Vibration analysis of skidding tractor with an operator during raising–lowering a tree

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Abstract. The aim of this article is to develop mathematical models that help at the design stage of design documentation for a skidder to determine the upcoming dynamic loads on the machine, the vibration effect on the machine and the operator, and scientifically based parameters to ensure their reduction. Vibration analysis and prediction of the skidding tractor with an operator allows predicting adverse events, prevent accidents, avoid costly and dangerous experiments, as well as optimize the design and operating modes. A particularly important degree of vibration loads affects the performance and health of the operator. The constant long-term effect of vibrations leads to increased operator fatigue and an increase in the number of errors in control. As a result, operator productivity significantly reduced. Baseline data that used in this article is related to the skidding trailer tractor TB-1M. So the results of this research may use as the foundation of future works for omitting vibration influence on the operator by designing active and smart dynamic vibration absorber for a different type of tractors. In addition, the effect of sitting stiffness and loading on the operator-tractor system have been investigated.

Keywords: Vibration analysis, Skidding tractor, Lagrange equation, Tractor-operator system, Mathematical modeling.

Introduction

The degree of universality of modern tractors is constantly increasing. Each modern tractor must be adapted to perform an increasing number of various traction, transport, and other works, therefore their designs become more and more complex. It is applied perfect-hinged equipment. In the case of skidding machines, feller, more and more manipulators are used. The speeds of starting and braking modes constantly increase when the hydraulic equipment of the tractor is working. In addition, in order to increase labor productivity, the electrical power of tractors is constantly increasing, and the speed of movement of tractor units increases. However, this inevitably leads to an increase in the dynamic loading of parts of the chassis and transmissions and an increase in the level of oscillations generated in the process, because of which the vibration load of the operator’s workplace increases.
Dynamic and vibration loads adversely affect the components and parts of the tractor itself, the environment and the operator. In the transmission and chassis, they cause permanent violations of the spatial location and laws of movement of parts, because of which fatigue damage accumulates in their material. Vibrations of the engine on its suspension lead to a deterioration in fuel efficiency. Vibration parts of the chassis have a detrimental effect on the structure of the soil and inhibit undergrowth. A particularly important degree of vibration loads affects the performance and health of the operator. The constant long-term effect of vibrations leads to increased operator fatigue and an increase in the number of errors in control. As a result, operator productivity significantly reduced. Operators often develop occupational diseases such as vibration disease. In addition, there are often disorders of the nervous system, metabolic disorders, prolapse and peptic ulcer, spinal deformity.

Nowadays, in all countries, the consideration of the need to ensure the safety and health of workers is one of the most important in the organization of labor. Despite ergonomic improvements, injuries and/or pain in the arm, neck, shoulder, legs, and lower back are common to mobile machine operators in the forest industry. These injuries are a material burden on employers, as the company subsidizes health care, as insurance premiums increase, and substitute workers are hired. As a result, if workers are injured, employers suffer large economic losses, as well as reduced prestige and confidence. Several factors influence the risk of injury by tractor operators, such as severe environmental conditions (low temperatures, etc.) and equipment (tractor, skidder, forwarder, harvester, etc.). In particular, the vibration of tractors, skidders and other equipment increases this risk.

Vibration analysis of the skidding tractor with an operator allows predicting adverse events, preventing accidents, avoiding costly and dangerous experiments, as well as optimizing the design and modes of operation. Objective. To develop mathematical models that at the design stage of design documentation for a skidder to determine the upcoming dynamic loads on the machine, the vibration effect on the machine and the operator, and scientifically based parameters to ensure their reduction.

In this paper, the vibration of skidding tractor – operator - tree system during raising – lowering a tree is considered. The Lagrange equation is then used to analyze the problem and obtain the results.

Review and Analysis of Researches of the Dynamics of Forestry Machines

Forest is the main raw material base of logging, woodworking and pulp and paper industry. All subsequent phases of production depend on successful work in the cutting area. In this stage, the task of mechanization and the increase of labor productivity on the felling and logging is the most important issue.

Traditionally, technological progress in the forest industry is associated with a continuous increase in productivity. This can be achieved in the design of new machines, by increasing the power of skidders, Feller and Feller machines. Increasing the power can increase the tip loads and operating speeds, which in turn leads to an inevitable increase in periodic, shock and other variable loads acting on the design of machines.

Previous studies [1-10] showed that the maximum dynamic loads in the elastic bonds and elastic bonds of forest machines occur in the starting - braking regimes of working.

Meanwhile, the growth of dynamic loads in the elastic bonds of the skidder or Feller – skidder leads to an increase in vibration effects on the driver or the operator [1, 2, 11].

Vibration destroys the human body, reduces visual acuity, which in turn leads to errors in the management of the machine, undesirable consequences (increased accident rate) and reduced productivity.

Therefore, in the development of new and modernization of commercially available skidders and felling and skidding machines, there is a problem of coordination of the machine design, production technologies of the logging process and the capabilities of the human driver or operator.
Mathematical Modeling of Skidding Tractor – Operator - Tree System

In this paper the vibration of the operator of a skidding tractor in the process of raising (lowering) a tree is considered. Fig. 1 shows the scheme of the biodynamic system “operator - skidder - tree”. Instead of a tree, we assume an external force in the vertical direction is applied to the operator - skidder system.

![Scheme of the biodynamic system “operator - skidder - tree”](image)

**Figure 1** Scheme of the biodynamic system “operator - skidder - tree”

Designated notation:
- $m_1, m_2, m_3, m_{01}, m_{02}$ are the masses of the sprung base, the boom, the manipulator with a gripping device, a pelvis with a part of the lower limbs, chest, head, shoulders and a part of the upper limbs, respectively.
- $I_1, I_2, I_3$ are moments of inertia of three moving links; the sprung base, the boom, the manipulator with a gripping device.
- $Y_{01}, Y_{02}$ are the generalized coordinates of the centers of the reduced masses $m_0, m_2, m_3, m_{01}, m_{02}$ respectively.
- $c_0, c_{ps}, c_s$ are the reduced stiffness’s of the elastic connections, respectively, of the tractor, suspension of the seat and spine of the operator.
- $F$ – gravity force of the tree.

We consider the joint configuration is fixed, so that gravity will have no effect on the vibration, as it is a constant force.

The Lagrange second order equation is then used to analyze the problem and obtain the dynamic equation of the system [12-16]:

$$\frac{d}{dt} \left( \frac{\partial K}{\partial \dot{q}_i} \right) + \frac{\partial K}{\partial q_i} + \frac{\partial U}{\partial q_i} = Q_i.$$ (1)
The kinetic energy of the system \( K(q_i, \dot{q}_i, t) \) should be represented as a function of generalized coordinates, velocities and (sometimes) obviously time; the potential energy \( U(q_i, t) \) describes the corresponding part of the force. The generalized forces \( Q_i \) are determined from the expression of the virtual work \( \delta A = \sum Q_i \delta q_i \) those forces that are not related to the potential energy [17-19].

The kinetic energy of the biodynamic system can be written as:

\[
K = 1/2(m_1 + m_2 + m_3)Y_1^2 + 1/2(I_1 + I_2 + I_3 + m_3 b_3^2 \sin \theta_2) \dot{\theta}_1^2 + ... + 1/2(I_2 + I_3 + m_3 b_3^2) \dot{\theta}_2^2 + 1/2 m_2 b_2^2 + 1/2 m_1 Y_0^1 + 1/2 m_{02} Y_{02}^2 \tag{2}
\]

The potential energy of the biodynamic system can be written as:

\[
U = 1/2 c_s Y_1^2 + 1/2 c_s (Y_1 - Y_0)^2 + 1/2 c_p s(Y_0^1 - Y_0)^2 \tag{3}
\]

Generalize forces are:

\[
\begin{align*}
Q_{0i} &= -F \sin \theta_2; \\
Q_{0i} &= -F b_3 \cos \theta_2; \\
Q_{0i} &= -F.
\end{align*}
\tag{4}
\]

After completing all the necessary actions in accordance with the Lagrange second order equation of the second kind, we obtain a system of equations that looks like:

\[
\begin{align*}
(m_1 + m_2 + m_3) \ddot{Y}_1 + (c_s + c_0) Y_1 &= c_s Y_{01} - F; \\
(I_1 + I_2 + I_3 + m_3 b_3^2 \sin \theta_2) \ddot{\theta}_1 &= 0; \\
(I_2 + I_3 + m_3 b_3^2) \ddot{\theta}_2 &= -F b_3 \cos \theta_2 + 1/2 m_2 b_2^2 \cos \theta_2 \dot{\theta}_2^2; \\
m_3 \ddot{b}_3 + (m_3 \sin \theta_2 \ddot{\theta}_2^2 + \dot{\theta}_2^2) b_3^2 &= -F \sin \theta_2; \\
m_{01} \ddot{Y}_0 + (c_{px} + c_s) Y_{01} &= c_s Y_1 - c_{px} Y_{02}; \\
m_{02} \ddot{Y}_{02} + c_{px} Y_{02} &= c_{px} Y_1.
\end{align*}
\tag{5}
\]

Next, for numerical calculation of system of Eq. 5, MATLAB has been used.

**Results**

Baseline data will apply in relation to the skidding tractor TB-1M, where the departure of the boom \( l \) is 6.5 m.

Fig. 2 shows vibration displacement of the operator's spinal column on the skidder tractor with sitting stiffness \( c_s = 1000 \) N/m. Other parameters set as follow: \( m_{01}=60 \) kg, \( m_{02}=28.5 \) kg, \( m_1=901 \) kg, \( m_2=246 \) kg, \( m_3=1180 \) kg, \( c_{px}=97000 \) N/m, \( F=10000 \) N, \( c_0=100000 \) N/m, \( I_2=65 \) kg.m\(^2\), \( I_3=295 \) kg.m\(^2\).
Figure 2  The vibration of the operator's spinal column on the skidder tractor

Fig. 3 shows vibration displacement of the operator's spinal column on the skidder with sitting stiffness $c_s = 1000 \text{ N/m}$ for different tree gravity force. Other parameters set as follow: $m_{01}=60 \text{ kg}$, $m_{02}=28.5 \text{ kg}$, $m_1=901 \text{ kg}$, $m_2=246 \text{ kg}$, $m_3=1180 \text{ kg}$, $c_{ps}=97000 \text{ N/m}$, $c_0=100000 \text{ N/m}$, $I_2=65 \text{ kg.m}^2$, $I_3=295 \text{ kg.m}^2$.

Figure 3  The vibration of the operator's spinal column on the skidder tractor for different tree gravity force; (a) $F = 500 \text{ N}$, (b) $F = 5000 \text{ N}$, (c) $F = 10000 \text{ N}$, and (d) $F = 16000 \text{ N}$

Fig. 4 shows vibration displacement of the operator's spinal column on the skidder tractor with different sitting stiffness. Other parameters set as follow: $m_{01}=60 \text{ kg}$, $m_{02}=28.5 \text{ kg}$, $m_1=901 \text{ kg}$, $m_2=246 \text{ kg}$, $m_3=1180 \text{ kg}$, $c_{ps}=97000 \text{ N/m}$, $c_0=100000 \text{ N/m}$, $I_2=65 \text{ kg.m}^2$, $I_3=295 \text{ kg.m}^2$, $F=10000 \text{ N}$.
As graphs in Fig. 3 and Fig. 4 show that by an increase of the weight of the tree (here gravity force of tree) and sitting stiffness the vibration of the operator's spinal column on the skidder tractor increases.

Conclusion

In this paper, the vibration of skidding tractor—operator—tree system during raising—lowering a tree has been investigated. The Lagrange equation has been used to analyze the problem and obtain the results. The effect of sitting stiffness and loading on the operator-tractor system have been studied.

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