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# Identification, design and kinematic analysis of an earthmoving mechanism

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**Abstract**

Earthmoving mechanisms in motor graders are critical components for earthwork, compaction and re-handling, and yet they have not received much attention by mechanical engineering research in recent times. In this paper, a comprehensive analysis, from mechanism identification and innovative design to kinematic analysis, is presented. First, the mechanism analysis and synthesis method based on multibody system dynamics is carried out through the analysis of the system topology and connectivity. We conclude that the earthmoving multibody system is a spatial hybrid mechanism, which consists of a spatial parallel mechanism and a spatial serial mechanism. Second, a number of new spatial parallel mechanisms, which are advantageous with respect to the original one under certain conditions, are generated. The kinematic characteristics of the parallel mechanism family are investigated in terms of constraint equations formulated in natural coordinates. Third and last, kinematic simulations and optimization processes are carried out to evaluate the advantages of the presented spatial parallel mechanisms. Simulation results show that these mechanisms can provide better kinematic performance.


*Keywords:* Motor grader; Earthmoving mechanism; Multibody systems; 3RRPS-S mechanism; Natural coordinates

## 1. Introduction

Motor graders are pieces of construction machinery usually equipped with a blade operation device. They can be used to prepare a wide flat surface, set native soil foundation pads, produce inclined surfaces, and provide drainage ditches with shallow V-shaped cross sections in construction, mining, agriculture and military engineering. An overview of an example motor grader is shown in Fig. 1.

The earthmoving mechanism is a key component of motor graders. A typical structure of an earthmoving mechanism is shown in Fig. 2. It operates directly with earth and plays a crucial role during earthwork, compaction and re-handling. The mechanism can be considered as a complex multibody system (MBS). In order to ensure rigid construction, simple operation and efficient performance, innovative design and kinematic and dynamic analyses can be used.

The earthmoving mechanism consists of an overhead frame, a swing frame, a traction frame, a turntable, several rod forks and several blade positioning cylinders. The blade yaw angle is commanded by a subsystem containing components with relative translations and rotations. The overhead frame is a large-scale, box-type welding part, which bears heavy loads resulting from the imposed joint constraints. As can be seen in Fig. 2, the swing frame connects the overhead frame arms through axis pins, which

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**Nomenclature**

| | | | |
|---|---|---|---|
| $\Delta H^{*}$ | minimum delta lifting height | $\mathbf{q}$ | generalized coordinates |
| $\Delta H^{\circ}$ | maximum delta lifting height | $\mathbf{r}$ | Cartesian positions |
| $\gamma$ | roll angle | $\mathbf{u}$ | Cartesian components of unit vectors |
| $D(\mathbf{x})$ | combined membership function | $\mathbf{x}$ | design parameters |
| $H$ | lifting height | $H^{*}$ | maximum lifting height |
| $k$ | membership function index | $H^{\circ}$ | minimum lifting height |
| $w$ | weighting factor | $N(\mathbf{x})$ | membership function |
| $\mathbf{\Phi}$ | constraint equations | $s$ | known distance depending on points |
| $\Delta H$ | delta lifting height | $\mathbf{\Phi}_t$ | constraint equations partial derivative |
| $\mathbf{F}(\mathbf{x})$ | optimization objectives | $\mathbf{\Phi_q}$ | Jacobian matrix |
| $\mathbf{l}$ | driven coordinates | | |

means that the relative position is adjusted before operations according to work conditions. Hence, they can be modeled as a single fixed part during system operation.

Rod forks are relatively small components. They bear high forces coming from the swing frame and cylinders. In fact, fatigue cracks or failure in the rod fork are some of the most common mechanism failures according to customer feedback questionnaires. Hydraulic cylinders connect the overhead frame to the traction frame, and they are used to lift the blade and rotate it. The traction frame is a welding part and works as a moving platform to lift and rotate the blade and propagate traction forces.

Finally, the turntable has internal teeth and an internal motor so that it can rotate with respect to the traction frame. It also supports the subsystem that adjusts the cutting angle and lateral motion. This subsystem contains a blade, two angle regulators, and several fasteners and cylinders. The motor inside the turntable controls the blade yaw angle around the vehicle's vertical axis.

Research on the kinematics and dynamics of earthmoving equipment, especially within hydraulic excavators and wheel loaders, has received significant attention recently. In most cases, it is very difficult or even impossible to determine dynamic solutions using analytical methods. Furthermore, real tests on physical prototypes are too laborious and pricey. Consequently, numerical simulations are often regarded as better alternatives to solve the dynamic problems.

Hemami (1992, 1993) introduced an analysis and modeling technique for the automatic scooping and loading of a loader excavating machine and discussed the optimal motion of a loader bucket. Vähä and Skibniewski (1993) described a dynamic model of an excavator based on Newton–Euler's equations in a local coordinate frame. Koivo (1994, 1996) presented a dynamic model and a systematic procedure to obtain an excavator's kinematic and dynamic performance. Fox et al. (2002) developed a dynamic model of digging operations based on a multibody system approach. Towarek (2003) discussed the dynamics of a spatial model of a single-bucket excavator considering the strain of soil foundation. Takahashi et al. (2004) proposed a concept of advanced load-haul-dump with a vessel (ALV) and described its kinematics and dynamics. Frimpong et al. (2005), Frimpong and Li (2005), Li and Frimpong (2008) and Frimpong et al. (2008) developed a dynamics model and a hybrid virtual prototype toward an intelligent shovel excavator, and they also analyzed its dynamic characteristics. Fales and Kelkar (2009) introduced two $H_{\infty}$-based robust control designs for a wheel loader bucket leveling mechanism, on the basis of a multi-input, multi-output nonlinear linkage model. Chen et al. (2014) described an optimal method for backhoe excavators including digging paths.

Based on the known dynamic characteristics of earthmoving equipment, some researchers have also presented finite element and fatigue analyses to calculate structural

Fig. 1. Motor grader overview.