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Modelling Friction Phenomena in the Dynamics Analysis of Forest Cranes

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A dynamics analysis of a forest crane, with a special consideration of friction in joints, is considered. The LuGre friction model is applied in all revolute and prismatic joints of the crane. A load handling simulation is performed for a typical operation. Various friction factors and loading conditions are examined. As shown, friction phenomena plays a significant role when defining loads acting on crane elements.

Key words: friction, stick-slip motion, crane dynamics.

1. Introduction

Friction, which always occur in a machine and mechanism joints will generate an impact on many operational aspects during the exploatation. In some cases, for example in a car steering system, the friction plays a positive role by limiting the vibration transferred from an uneven road into the steering wheel. In many cases, however, designers will have to solve some friction-related issues. A jamming problem is one of the most evident example where the friction can stop the motion and serious consequences may arise. Another common example emerges in control applications where one struggles with precise motion of a robot and it is the friction that needs to be compensated. And, not for the last, the designer must take into account additional friction loads when selecting drive components.

The mathematical model of a forest crane is a complex multibody model and inclusion of the friction entails some additional steps to be considered. Many friction models and approaches are developed in literature. In this work the LuGre friction model [1] is applied. This friction model is more universal (captures stick-slip, hysteresis, the Stribeck effects) than the most commonly used the Coulomb model. When developing the numerical and mathematical models, it is important how the friction formulation can be integrated into existing models and equations.

2. Simplified model of the crane

A forest crane, considered in this paper is presented schematically in Fig. 1. It consists of eight rigid bodies connected by revolute or translational joints. The platform is supported on eight legs modelled as 3D linear spring-damping elements (displacements along global $\hat{\mathbf{x}}_0\hat{\mathbf{y}}_0\hat{\mathbf{z}}_0$ axes are considered in points s_i, $i = 1, \ldots, 8$).

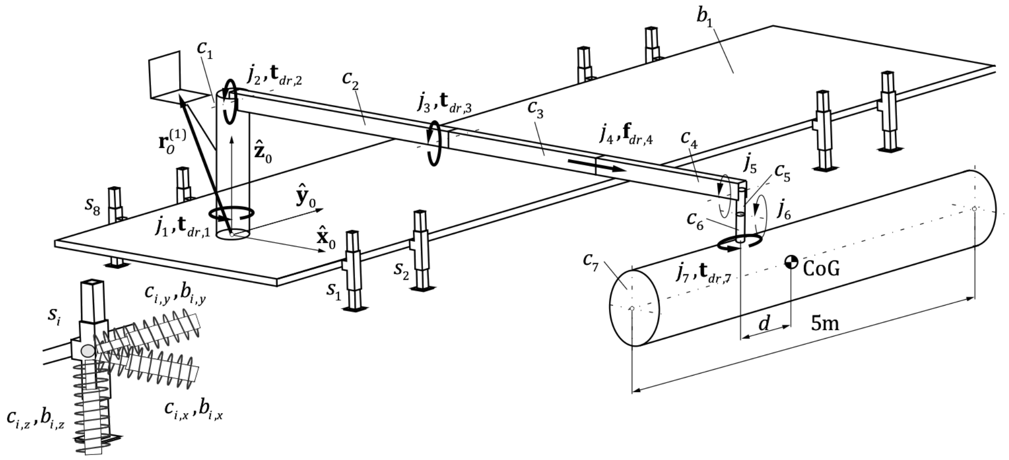

Fig. 1. Simplified scheme of the grab crane.

Joint coordinates and homogeneous transformation matrices are used to describe the geometry of the crane [2]. The generalized coordinates of the model are presented for the following vector:

$$\mathbf{q} = [\mathbf{q}_b^T \;\; \mathbf{q}_c^T]^T, \tag{2.1}$$

where

$$\mathbf{q}_b = (q_{b,i})_{i=1,\ldots,6} = \begin{bmatrix} x_{b,1} & y_{b,1} & z_{b,1} & \psi_{b,1} & \theta_{b,1} & \varphi_{b,1} \end{bmatrix}^T,$$

$$\mathbf{q}_c = (q_{c,i})_{i=1,\ldots,7} = \begin{bmatrix} \psi_{c,1} & \psi_{c,2} & \psi_{c,3} & z_{c,4} & \psi_{c,5} & \psi_{c,6} & \psi_{c,7} \end{bmatrix}^T.$$

The equations of motions are derived from the Lagrange equations of the second order. Since the LuGre friction model requires additional first order ordinary differential equations to be solved, the whole set of equations can be written in the form (detailed expressions for matrices $\mathbf{A}$ and $\mathbf{f}$ can be found in paper [3]):

$$\left\{\begin{array}{l}\mathbf{A}\ddot{\mathbf{q}} = \mathbf{f}\left(t, \mathbf{q}, \dot{\mathbf{q}}\right),\\ \dot{\mathbf{z}} = \mathbf{h}\left(t, \dot{\mathbf{q}}_c, \mathbf{z}\right),\end{array}\right. \tag{2.2}$$

where $\mathbf{A} = \mathbf{A}(\mathbf{q})$ is the inertia matrix, $\mathbf{f}(t, \mathbf{q}, \dot{\mathbf{q}})$ is the right side vector of generalized forces, Coriolis forces, potential and dissipation elements, $\mathbf{z} = (z_i)_{i=1,\ldots,7}$ is the vector of the LuGre model state variables, $\mathbf{h} = (h_i)_{i=1,\ldots,7}$ is the vector of the LuGre model right side components.

The LuGre friction model forms the $\mathbf{h}$ vector in Eqs. (2.2) i.e.:

$$(h_i)_{i=1,\ldots,7} = v_{c,i} - \sigma_{0,i}\frac{|v_{c,i}|}{g\left(v_{c,i}\right)}z_i, \tag{2.3}$$

where $v_{c,i}$ is the relative velocity of contacting surfaces (forming the joint), $g\left(v_{c,i}\right) = f_{C,i} + \left(f_{S,i} - f_{C,i}\right) e^{-\left|\frac{v_{c,i}}{v_{S,i}}\right|^{\alpha}}$, $f_{C,i}$ and $f_{S,i}$ are the Coulomb and stiction forces, $v_{S,i}$ is the transition velocity between friction regimes, α is a parameter depending on the joint material.

The components of the vector $\mathbf{f}$ from (2.2) contain necessary relations due to friction torques and force in joints. Its definition follows:

$$\left.\begin{array}{l}(t_{f,i})_{i=1,2,3,5,6,7}\\ (f_{f,i})_{i=4}\end{array}\right\} = \sigma_{0,i}z_i + \sigma_{1,i}\dot{z}_i + \sigma_{2,i}v_{c,i}, \tag{2.4}$$

where $\sigma_{0,i}$, $\sigma_{1,i}$, $\sigma_{2,i}$ are friction model constants (stiffness, damping and viscosity terms).

The Eqs. (2.2) are numerically integrated by the fixed-step Runge-Kutta 4th order method with time step $\Delta t = 10^{-5}$ s. Each step of integration involves also determination of the joint reaction forces, required to calculated friction forces and moments. This can be solved by the application of the recursive Newton-Euler algorithm as proposed in [2].

The accelerations on the operator's seat foundation will be presented in the next section. The location vector (refer to Fig. 1) defined as:

$$\mathbf{r}_O^{(1)} = \left[\begin{array}{cccc} x_O^{(1)} & y_O^{(1)} & z_O^{(1)} & 1\end{array}\right]^T = \left[\begin{array}{cccc} -0.5 & -0.5 & 1.5 & 1\end{array}\right]^T \ [\mathrm{m}] \tag{2.5}$$

is considered to describe a point (belonging to the column, body c_1). For simplicity, the seat is considered without any suspension elements that normally improve operator comfort.

3. Example analysis

The geometrical and mass parameters are similar to the crane presented in [3]. The body c_7, however, is assumed to be a wooden trunk of 5 m length having a mass of approx. 970 kg. The trunk is taken from the ground assuming an offset between its CoG (assumed in the geometric centre) and the grab (Fig. 1), i.e. three cases are assumed: $d = 0$ cm, $d = 10$ cm and $d = 20$ cm.

Drive functions are assumed as in Fig. 2. Drive functions $\psi_{dr,3}(t) = \psi_{dr,7}(t) =$ const maintains the respective angles of the links during the analysis.

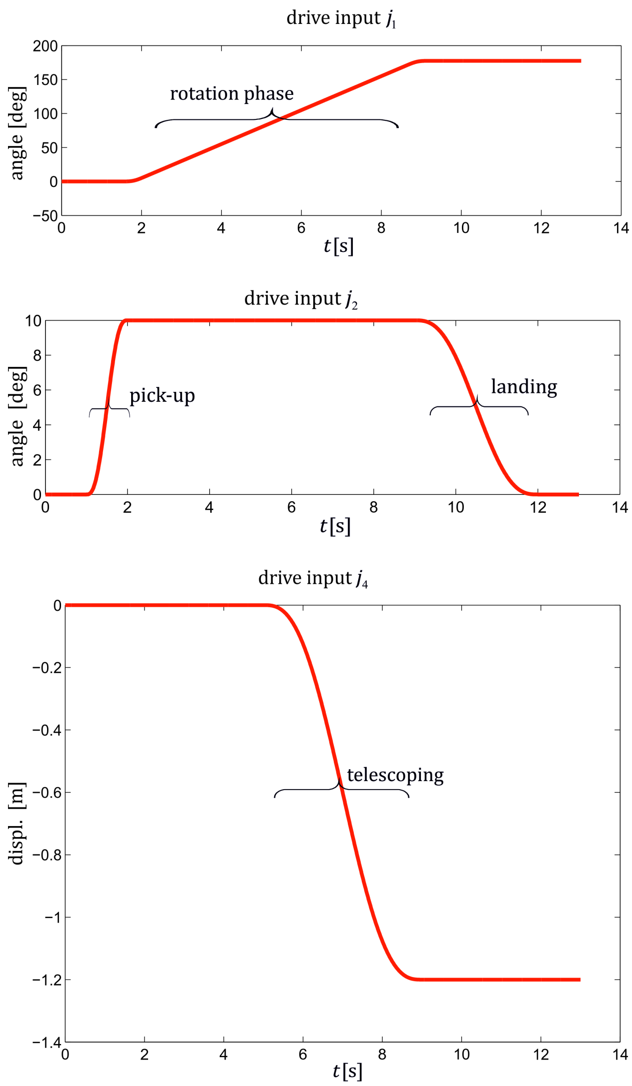

Fig. 2. Drive functions, joints j_1, j_2, j_4.

Table 1 and Fig. 3 show geometrical and friction joint properties. The two sets of friction factors represent different conditions of joints (normal and non-greased).

Table 1. Joint parameters, geometrical and friction (SI units).

j_k	a	a_A, a_B	d_A, d_B	d_C	σ_0	σ_1	σ_2	α	v_S	Set 1		Set 2	
										μ_k	μ_s	μ_k	μ_s
1	0.2	0.04	0.085	0.10	10^5	5	0	2	0.005	0.15	0.20	0.07	0.10
2	0.15	0.03	0.055	0.06	10^5	5	0	2	0.005	0.10	0.15	0.07	0.10
3	0.15	0.03	0.055	0.06	10^5	5	0	2	0.005	0.10	0.20	0.05	0.15
4	–	–	–	–	10^7	5	0	2	0.005	0.10	0.20	0.20	0.30
5, 6	0.10	0.02	0.040	0.05	10^5	5	0	2	0.005	0.15	0.20	0.20	0.35
7	0.25	0.05	0.065	0.05	10^5	5	0	2	0.005	0.15	0.20	0.10	0.15

a) b)

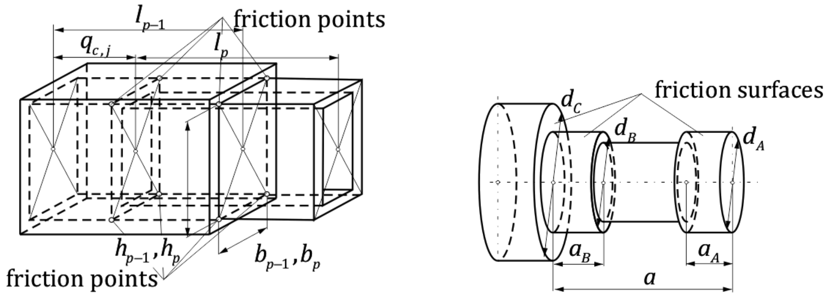

FIG. 3. Geometrical parameters of revolute (a) and prismatic (b) joint.

Normal forces in joints have been calculated as described in the work [1].

4. Results

Despite the trajectory of the body c_7 (its CoG) is not that much affected by the frictional parameters, the acceleration presented in Fig. 4 shows a large influence of different friction factors as well as the effect of the mass centre offset d.

Figure 5 presents the vertical velocity of the body c_7. As the offset d increases, the friction in joint increases and oscillations evident in case $d = 0$ cm vanishes.

The influence on drive force (joint j_4) and torque needed to orient the last body (joint j_7) are presented in Fig. 6. As these plots show the required reaction force to obtain the assumed drive functions, these reflect loads coming from all

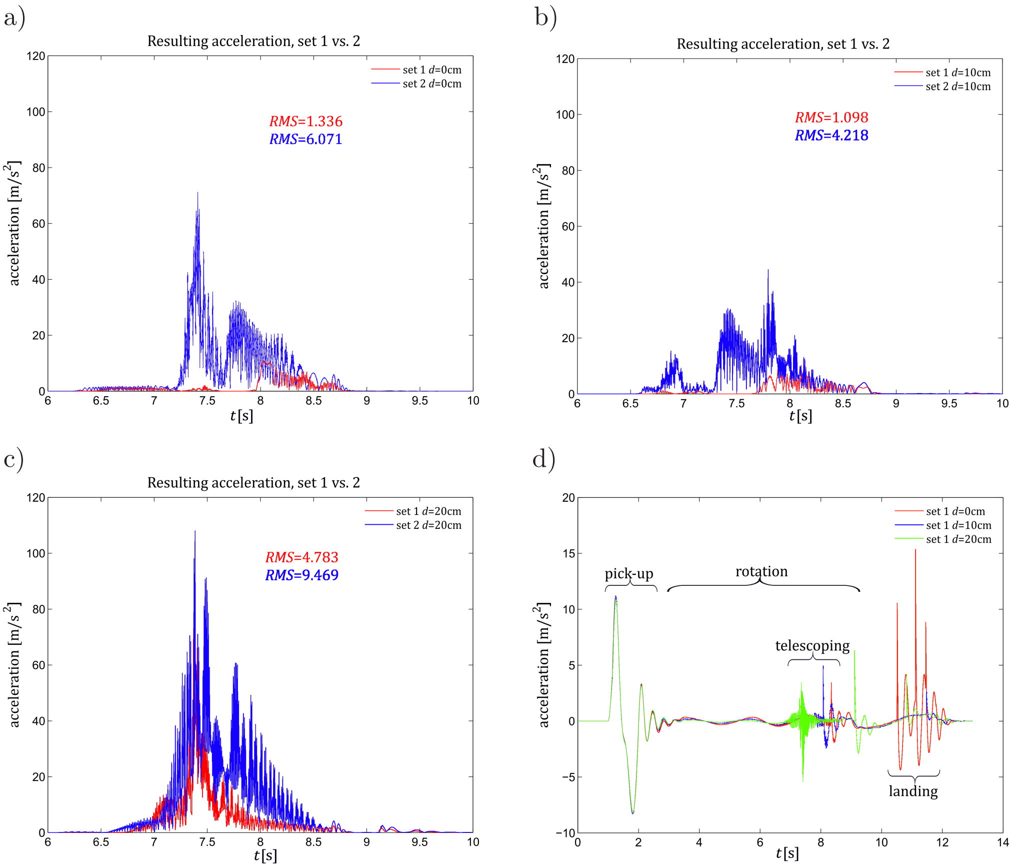

FIG. 4. Resulting acceleration on seat support for two different friction sets (a)–(c) and vertical acceleration on the body c_7 CoG location (d).

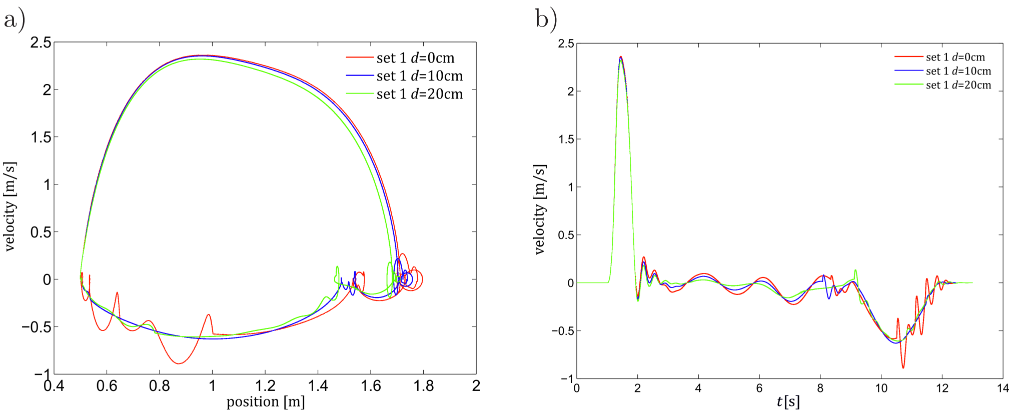

FIG. 5. Phase portrait for vertical coordinate of c_7 mass centre (a) and velocity time history (b).

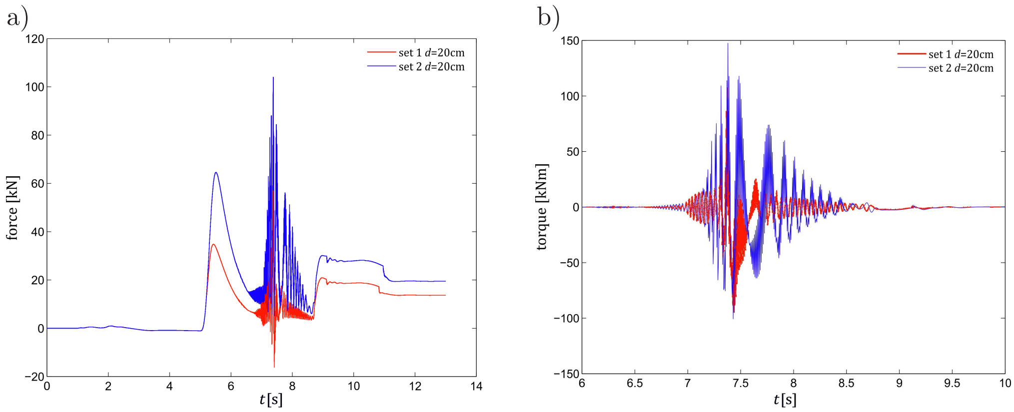

FIG. 6. Drive reaction force $f_{dr,4}$ (a) and reaction moment $t_{dr,7}$ (b).

sources. Large peaks are occurring when the telescopic jib is activated. As the jib becomes shorter, the driving force required reduces significantly.

5. SUMMARY

The results obtained indicate strong influence of friction in joints. The applied LuGre model of friction allows to be relatively easily implemented in a multibody dynamic model. However, the size of the system equations increases (by one equation for each joint) as well as high frequency oscillations may be generated due to frictional model properties (stiff system). This requires a careful choice of integration method and integration steps. On the other hand, one can obtain the results with friction phenomenon, which cannot be neglected in a careful design of cranes.

A typical forest crane would be driven by hydraulic motors and cylinders. Simplifications of such elements, introduced in the mathematical model presented, should be evaluated in future work. Friction in kinematic pairs proposed in this work should be regarded as an approximate description. Obtained loads must be transformed to a real geometry of the system. Despite these drawbacks, the model gives important information about the loads and general response in a user-defined load handling scenario.

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