High Load Capacity Crane Analysis for Real-Time Applications Using Arbitrary Eulerian-Lagrangian Modal Approach

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Wire rope segments, made of strands of metal wires twisted into a helix, are commonly used for lifting and hoisting in cranes and elevators. Dynamic modeling of the wire ropes is challenging as its elastic behavior is complex and many phenomena, like a taut-string effect coupling axial strain and transverse vibrations, need to be addressed [1]. Furthermore, the cranes are commonly used in human-in-the-loop systems, e.g. as training simulators, where the real-time efficiency and good physical accuracy are required [2].

This paper present the case study of the crane model with multiple wire rope spans modeled using recently introduced wire rope model for a real-time applications. The concept of the wire rope segment used in study is proposed by Escalona [3] and it takes the current form of the *Arbitrary Lagrangian-Eulerian Modal* (ALEM) wire rope in a recent work by Escalona et al. [4]. In the ALEM approach, a segment coordinates are divided into three groups:

$$\boldsymbol{q} = \begin{bmatrix} \boldsymbol{q}_a^T & \boldsymbol{q}_m^T & \boldsymbol{q}_s^T \end{bmatrix}^T \tag{1}$$

where $\boldsymbol{q}_a^T = \begin{bmatrix} \boldsymbol{r}_1^T & \boldsymbol{r}_2^T \end{bmatrix}$ is a vector of absolute position coordinates of segment end points 1 and 2, $\boldsymbol{q}_m$ is vector of relative modal amplitudes in transverse directions and $\boldsymbol{q}_s^T = \begin{bmatrix} s_1 & s_2 \end{bmatrix}$ is a vector of longitudinal coordinates of the segment end points with respect to reference straight and undeformed configuration. Vector $\boldsymbol{q}_m$ contains nm modal amplitudes for both local y and z directions, comprising of $2 \times nm$ components.

The position of an arbitrary particle P on the segment, as shown in Fig. 1a, can be written as:

$$\boldsymbol{r} = \boldsymbol{r}_a + \boldsymbol{u}_t = \mathbf{N}\boldsymbol{q}_a + \mathbf{A}\bar{\boldsymbol{u}}_t = \mathbf{N}\boldsymbol{q}_a + \mathbf{A}\mathbf{S}\boldsymbol{q}_m \tag{2}$$

where $\boldsymbol{r}_a = \mathbf{N}\boldsymbol{q}_a$ is absolute position of the point on the segment center-line and $\boldsymbol{u}_t = \mathbf{A}\bar{\boldsymbol{u}}_t$ is transverse displacement. In Eq. (2) $\mathbf{N}(s, \boldsymbol{q}_s)$ is a linear function that interpolates nodal positions, and s is longitudinal coordinate associated with a point on the segment. Coordinate $s \in \langle s_1, s_2 \rangle$ is measured in straight and undeformed configuration and in general it does not coincide with arc-length of a deformed segment $\bar{s}$ shown in Fig. 1a. A rotation matrix $\mathbf{A}(\boldsymbol{q}_a)$ is associated with fixed segment frame $x_e y_e z_e$ and $\mathbf{S}(s, \boldsymbol{q}_s)$ is a shape functions matrix representing the transverse vibrations of a string as sines with different angular frequencies.

The equations of motion of the ALEM wire rope segment can be written as follows:

$$\mathbf{M}\ddot{\boldsymbol{q}} = \boldsymbol{Q}_v + \boldsymbol{Q}_{elas} + \boldsymbol{Q}_{ex} + \boldsymbol{Q}_{rec} + \boldsymbol{L} \tag{3}$$

where $\mathbf{M}$ is mass matrix, $\boldsymbol{Q}_v$ is vector of velocity dependent inertia forces, $\boldsymbol{Q}_{elas}$ are elastic forces, $\boldsymbol{Q}_{ex}$ are externally applied forces, including gravity, $\boldsymbol{Q}_{rec}$ are reaction forces due to kinematic constraints, and $\boldsymbol{L}$ are inertia forces related to the material flow through the nodes. The elastic forces account for axial, bending and so-called taut-string deformation energies (resulting in transverse displacement and axial load coupling). Torsion and contact between pulleys and ropes are not considered. In addition, reeving system modeling requires a nonlinear constraints that ensures equal axial force in the wires connected by pulley.

Despite the complex kinematic description, the main advantage of the ALEM is the small number of segments required to model the crane system as, in general, one segment per span can be used. The accuracy of the transverse deformations can be adjusted by the number of used modal coordinates. Therefore, the ALEM is a good candidate for a wire rope modeling in real-time applications. To shed a light on the application of the ALEM in modeling

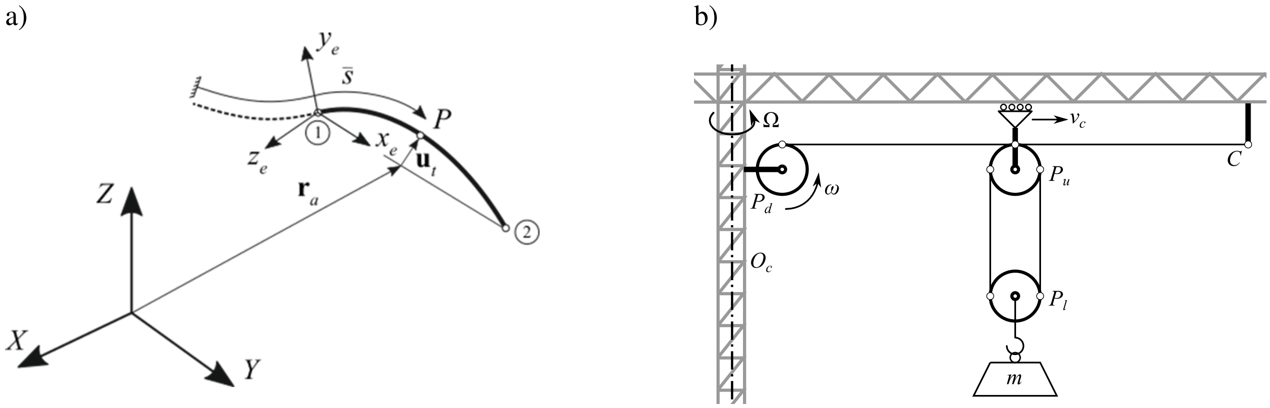

Fig. 1: a) Body frame and arbitrary displacement vectors in an ALEM segment. b) Simplified crane model.

complex reeving systems in real-time, the simplified crane model shown in Fig. 1b is analyzed. Crane consists of tree pulleys (P_d, P_u and P_l) between which wire ropes are located. Additional wire rope can be found between pulley P_u and point C. To test a wire rope system with multiple segments (that also handles larger masses) there are nVR ropes on both sides between pulleys P_u and P_l. The total number or wire ropes in the system is $n = 2nVR + 2$. Pulley P_d is attached to the crane frame and it can wind and unwind the rope with rotational velocity ω. Pulley P_u is also attached to the crane frame and it can move horizontally with velocity v_c. In addition, the whole crane can rotate around its axis O_c with rotational velocity Ω.

To obtain a reference results, the system is solved with full inertia description using coordinate partitioning and implicit integration methods with automated time stepping and error checking. Different motion patterns of the crane are considered. Next, the influence of different simplifications made to inertia forces in Eq. (3) is examined. For the solution of the equations of motion, the methods that are more suitable for real-time application are considered: Baumgarte stabilization and penalty formulation, used with constant step integration procedures like fourth order Runge-Kutta or midpoint rule [5]. Due to large stiffness of the system, a careful analysis has to be provided. The linear kinematic constraints are eliminated at the preprocessing stage. Next, the scalability of the system with increasing number of wire rope segments and more complex description of the transverse displacement is tested. Finally, the parallel co-simulation of the system is considered, where the wire rope system is separated from the crane dynamics, in order to ensure the real-time efficiency of the system with increasing complexity by exploiting computations on many nodes.

Preliminary tests shows that due to relatively low system velocities, carefully simplified inertia forces does not influence the results significantly. For example, the forces resulting from a material flow can be safely neglected together with some terms in velocity description. Those simplifications result in the significant savings in simulation time without compromising the accuracy. Moreover, the bending term of the elastic energy forces adds a little contribution in typical crane motion pattern. Scalability tests shows that system scales well, approximately linearly with an increase in the number of wire rope segments, but far more insight is required. Also the setup and reliability of the co-simulation has to be examined in details.

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