A Simple and Practical Vibration Control Method for Stacker Cranes Using Dynamic Interaction and Its Experimental Verification

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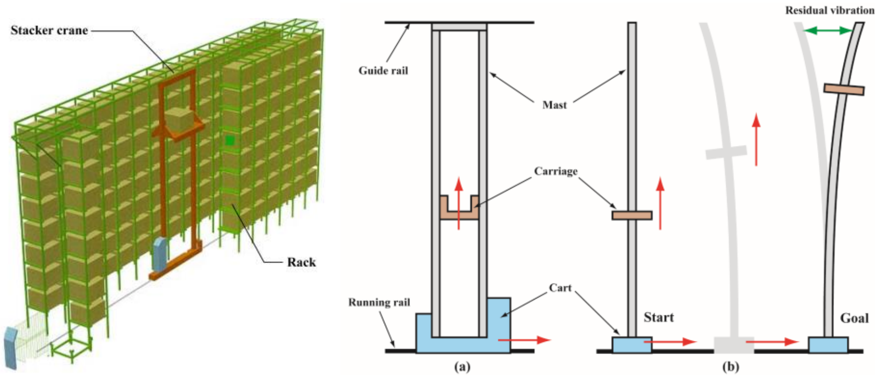
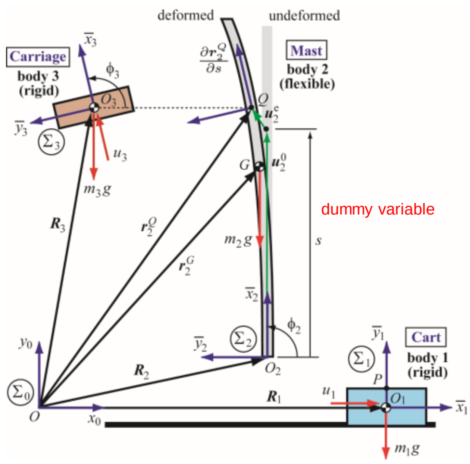
MD23_32

1. Introduction

- Stacker cranes used in automated warehouses are flexible multibody systems in which the elastic deformation of the mast cannot be ignored.
- We derive a dynamic model that strictly considers the coupling of motion and vibration of a stacker crane using flexible multibody dynamics.
- We propose a simple and practical residual vibration suppression method using B-spline functions and PSO.
- The validity and practicality of the proposed method are verified through both numerical simulation and experiment.



2. Dynamic model of stacker crane



Equation of motion of the mast:

$$\underbrace{\begin{bmatrix} M_2^{RR} & M_2^{R\phi} & M_2^{Rf} \\ & M_2^{\phi\phi} & M_2^{\phi f} \\ \text{Sym.} & & M_2^{ff} \end{bmatrix}}_{M_2}\underbrace{\begin{bmatrix} \ddot{R}_2 \\ \ddot{\phi}_2 \\ \ddot{q}_2^e \end{bmatrix}}_{\ddot{q}_2}+\underbrace{\begin{bmatrix} C_{q_2}^T \end{bmatrix}\lambda}_{C_{q_2}^T\lambda}=\underbrace{\begin{bmatrix} (Q_2^v)^R \\ (Q_2^v)^\phi \\ (Q_2^v)^f \end{bmatrix}}_{Q_2^v}+\underbrace{\begin{bmatrix} (Q_2^g)^R \\ (Q_2^g)^\phi \\ (Q_2^g)^f \end{bmatrix}}_{Q_2^g}+\underbrace{\begin{bmatrix} (Q_2^k)^R \\ (Q_2^k)^\phi \\ (Q_2^k)^f \end{bmatrix}}_{Q_2^k}$$

Combined constrains:

$$C(q,s)=\begin{bmatrix} C^1(q) \\ C^2(q) \\ C^3(q,s) \end{bmatrix}=0$$

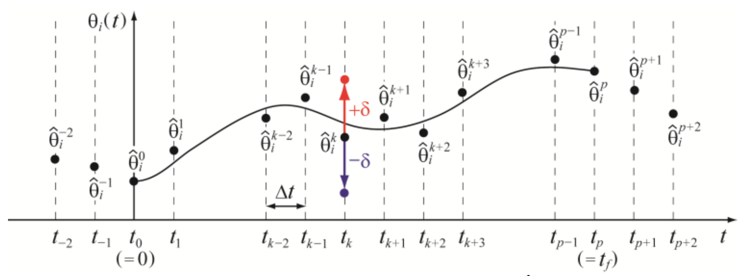
Differential-algebraic equation of the total system:

$$\begin{bmatrix} M_1 & 0 & 0 & 0 & C_{q_1}^T \\ 0 & M_2 & 0 & 0 & C_{q_2}^T \\ 0 & 0 & M_3 & 0 & C_{q_3}^T \\ 0 & 0 & 0 & 0 & C_s^T \\ C_{q_1} & C_{q_2} & C_{q_3} & C_s & 0 \end{bmatrix}\begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \\ \ddot{q}_3 \\ \ddot{s} \\ \lambda \end{bmatrix}=\begin{bmatrix} Q_1^g + H_1 u_1 \\ Q_2^v + Q_2^g + Q_2^k \\ Q_3^g + H_3 u_3 \\ 0 \\ \gamma \end{bmatrix}$$

The equation of motion of the mast, which is an elastic body, is formulated using the floating frame of reference formulation. Since the carriage runs on the mast, it becomes a problem of moving boundary conditions. Therefore, a dummy variable s is introduced to express the connection of both bodies. Using differential algebraic equation, dynamic model that considers the coupling of motion and vibration is obtain.

3. Residual vibration control method

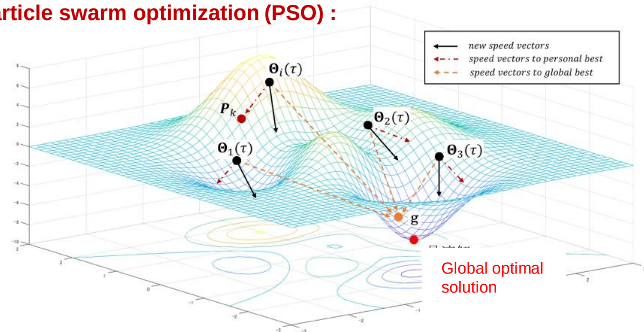
B-spline curve:



$$u_i = -K_{P_i}(x_i - \theta_i) - K_{D_i}(\dot{x}_i - \dot{\theta}_i)$$

Cart and Carriage are controlled by high gain PD control.
The reference trajectory θ is represented by B-spline curve.

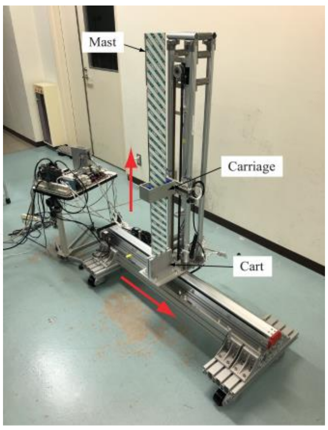
Particle swarm optimization (PSO) :

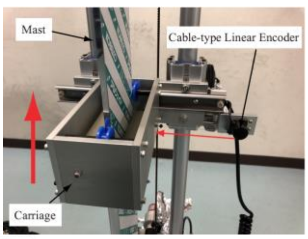


$$J(\Theta) = \frac{1}{2} q_2^{eT}(t_f) W_P q_2^e(t_f) + \frac{1}{2} \dot{q}_2^{eT}(t_f) W_D \dot{q}_2^e(t_f)$$

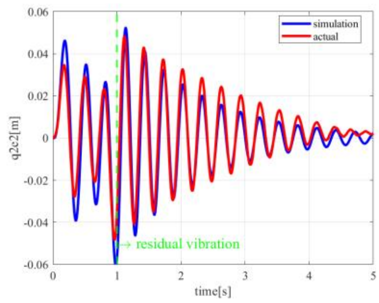
We use PSO to optimize the control points of the B-spline to minimize the elastic potential energy at the terminal time.

4. Experimental verification

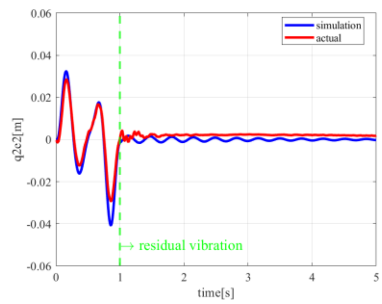




Before optimization



After optimization



In order to confirm the effectiveness of the proposed method, we built an experimental device for a stacker crane. These figures show the lateral deformation of the mast, where the blue line is the numerical simulation result and the red line is the experimental result. It can be confirmed that the numerical simulation and experimental results are in good agreement. It can also be confirmed that residual vibrations can be significantly suppressed by applying the proposed method.