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Damping Injection by Reset Control

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This paper presents a method for using reset control as an alternative way of obtaining dissipation for a class of port-Hamiltonian systems. One advantage of this approach is the simplicity of its implementation, which requires only a velocity observer. Another advantage is its robustness to modeling uncertainties, since it can be calculated independently of the plant structure. A gantry crane is selected as case study, yielding simulation and experimental results that show the good performance of this technique. [DOI: 10.1115/1.4005369]

1 Introduction

Reset control is a nonlinear-hybrid control strategy especially suited for plants subject to linear fundamental limitations. It is well known [1] that many control problems are subject to linearly unsolvable trade-offs between competing objectives, such as bandwidth versus robust stability. When properly tuned, a reset control system is able to produce a fast step response with limited overshoot, in a way that no linear controller is able to achieve. The original ideas can be dated back to the Clegg integrator [2] and to the first order reset element [3], where the design was addressed using Horowitz's quantitative feedback theory. These controllers are simple first order systems subject to a reset rule: the state is set to zero whenever the input crosses zero. In a subsequent contribution [4], the resetting was generalized to an n-dimensional state, subject to partial reset. These results showed the advantages of reset control, but raised attention to the fact that resetting might produce instability. Analysis and design results were presented based on the so-called H_β stability test, which is a passivity related condition. More recently, Refs. [5,6] have given extensions of the H_β condition to time-delay systems, or to reset systems with unstable base linear dynamics [7]. The passivity-based interpretation of stability conditions is presented in Ref. [8] and has been applied to teleoperation of systems with time delay in Ref. [9]. An application of reset to vibration control was presented in Ref. [10]. In Ref. [11], an approach to reset control was presented within the context of port-controlled Hamiltonian systems. The port-Hamiltonian framework [12] provides powerful techniques for modeling physical systems and for designing control laws based on principles of energy and interchanged power. Control by interconnection [13], which is closely related to impedance control [14], makes use of this framework and exploits the possibilities of interconnection of physical systems.

In this paper, we present a method for injecting dissipation, which is based on the port-controlled Hamiltonian approach. First, a continuous control law is designed based on potential energy shaping; then, reset is used to improve the bandwidth-versus-stability trade-off. The resetting event is based on a simple condition related to the maximum extracted energy. In this way, a robustly stable controller is obtained with fast and damped response.

A gantry crane is selected as the case study to illustrate this approach. Cranes have the interesting property that, if a fast reference tracking is forced, the payload swinging is excited. This is a fundamental limitation due to two open loop poles $\pm i\omega_0$ of the swinging dynamics (neglecting friction). A useful and simple idea for overcoming this limitation is to perform damping injection; here, instead of using the standard procedure in Ref. [12], we propose the use of resetting. Simulations and experiments confirm the validity of the proposed strategy.

The structure of this paper is as follows: first, the theoretical background is given in the Methods section, which includes Port-Controlled Hamiltonian Systems (Sec. 2.1), Interconnection and Damping Assignment-Passivity-Based Control (Sec. 2.2), Control by Interconnection (Sec. 2.3), and Reset Control (Sec. 2.4). In Secs. 2.1 and 2.2, the respective techniques are applied to a gantry crane as a case study. Then, in Sec. 3, we propose a procedure for damping by reset interconnection and apply it again to a gantry crane, providing simulation and experimental results. Finally, conclusions and guidelines for future work are given in Sec. 4.

2 Methods

2.1 Port-Controlled Hamiltonian Systems. The standard Euler–Lagrange equations are given as

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right) - \frac{\partial L}{\partial q} = \tau \tag{1}$$

where $q = (q_1, \ldots, q_n)$ are generalized configuration coordinates for the n degrees of freedom. The Lagrangian is $L = T - V$, where T is the kinetic energy and V the potential energy; and $\tau = (\tau_1, \ldots, \tau_n)$ is the vector of generalized forces. In standard mechanical systems, the kinetic energy is given by $T = \frac{1}{2}\dot{q}^\top M(q)\dot{q}$, where $M(q)$ is the $n \times n$ inertia matrix, which is symmetric and definite positive for all q. The vector of generalized momenta $p = (p_1, \ldots, p_n)$ is defined for as $p = \frac{\partial L}{\partial \dot{q}} = M(q)\dot{q}$. Defining the state vector as $x = (q, p)$, the n second order Lagrangian equations (1) transform into the $2n$ first order equations

$$\begin{aligned} \dot{q} &= \frac{\partial H}{\partial p} \\ \dot{p} &= -\frac{\partial H}{\partial q} + \tau \end{aligned} \tag{2}$$

where the energy is given by the Hamiltonian function,

$$H = \frac{1}{2}p^\top M^{-1}(q)p + V(q)$$

The system (2) is an example of a Hamiltonian system with collocated inputs and outputs, which is given more generally in the following form:

$$\begin{aligned} \dot{q} &= \frac{\partial H}{\partial p} \\ \dot{p} &= -\frac{\partial H}{\partial q} + B(q)u \\ y &= B^\top(q)\frac{\partial H}{\partial p} \end{aligned}$$

Here, $B(q)$ is the input force matrix, with $B(q)u$ representing the generalized forces resulting from the control inputs

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$u = (u_1, \ldots, u_m)$. Normally, $m < n$, in which case we speak of an under-actuated system. Using a more compact form, the $2n$ movement equations can be denoted as [15]

$$\begin{aligned} \dot{x} &= [J(x) - R(x)]\frac{\partial H}{\partial x} + G(x)u \\ y &= G^\top(x)\frac{\partial H}{\partial x} \end{aligned} \tag{3}$$

where $J(x) = -J^T(x)$ and $R(x) = R^T(x) \succeq 0$ are, respectively, the interconnection and damping matrices.

2.1.1 Case Study: Port-Hamiltonian Model of a Gantry Crane. Let us model a 2 degrees of freedom gantry crane, such as the one depicted in Fig. 1, in the way described by Eq. (3). The Hamiltonian state coordinates are $q = (r,\ \rho,\ \theta)$, $p = (p_r,\ p_\rho,\ p_\theta)$. The cart with mass m_c moves on the girder in the r direction under the actuating force F_r, so its position coordinate is given by r. The payload is represented by a point mass m_b hanging from a rope with variable length ρ. The payload and the cart are assumed to be connected by a massless, rigid rope, and the mass of the payload is assumed to be concentrated at a point. Adopting polar coordinates, with θ as the swing angle, the payload position is given by $r - \rho\hat{\rho}$ with $\hat{\rho} = (-\sin\theta, \cos\theta)^T$. Thus, the payload moves in the $\hat{\rho}$ direction under the actuating force F_ρ. The kinetic energy is given by $K = \frac{1}{2}(m_c\langle \dot{p}_c, \dot{p}_c\rangle + m_b\langle \dot{p}_b, \dot{p}_b\rangle)$, where $\langle *, *\rangle$ means scalar product, and the potential energy is $V = -m_b g\rho\cos\theta$, where g is the gravity acceleration. The Hamiltonian is $H(q,p) = \frac{1}{2}p^T M^{-1}(q)p + V(q)$, where $M(q) = \frac{\partial^2 K}{\partial \dot{q}_i \partial \dot{q}_j}$ is the mass matrix, and p is the momenta vector. As can be verified, $H(q, p)$ is not a strictly positive energy function for any desired equilibrium point $q_d = (r_d,\ \rho_d,\ 0)$. The Hessian matrix of the uncontrolled plant at the equilibrium point is thus

$$\frac{\partial^2 H(x)}{\partial x_i \partial x_j} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & g m_c \rho_d & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{2}{m_c} & 0 & \frac{2}{m_c \rho_d} \\ 0 & 0 & 0 & 0 & \frac{2}{m_b} & 0 \\ 0 & 0 & 0 & \frac{2}{m_c \rho_d} & 0 & \frac{2(m_c + m_b)}{m_c m_b \rho_d^2} \end{pmatrix}$$

The movement equations can be derived easily, obtaining Eq. (3) with

$$J = \begin{bmatrix} 0_3 & I_3 \\ -I_3 & 0_3 \end{bmatrix}, \quad R = \begin{bmatrix} 0_3 & 0_3 \\ 0_3 & 0_3 \end{bmatrix}, \quad G = \begin{bmatrix} 0_{3\times 2} \\ \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix} \end{bmatrix} \tag{4}$$

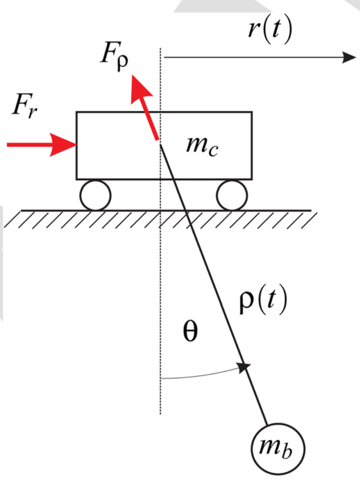

Fig. 1 2D overhead crane arrangement

2.2 Interconnection and Damping Assignment-Passivity-Based Control. Let x_d be a desired configuration in the state space for a plant described in the port-Hamiltonian framework as in Eq. (3). The control goal is to find a state feedback law $u = \beta(x)$ such that the dynamics of the resulting closed loop system is given by

$$\dot{x} = [J_d(x) - R_d(x)]\frac{\partial H_d}{\partial x}$$

where $J_d(x)$ and $R_d(x) \succ 0$ are desired interconnection and damping matrices, respectively. This desired energy function $H_d(q, p)$ can be represented as

$$H_d(q,p) = \frac{1}{2}p^T M_d^{-1}(q)p + V_d(q) \tag{5}$$

The plant can be regulated to x_d in a passive way if the desired energy function $H_d(x)$ has a minimum in the state space. This procedure is called interconnection and damping assignment (IDA), and it can be applied jointly with passivity-based control (PBC) [13]. In PBC, the control input is naturally decomposed into two terms, $u = u_{es}(q, p) + u_{di}(q, p)$, where

$$u_{di}(q,p) = -K_v G^T \frac{\partial H_d}{\partial p} \tag{6}$$

with $K_v \succ 0$ responsible for damping injection. Energy shaping is obtained with $u_{es} = (G^T G)^{-1} G^T\left(\frac{\partial V}{\partial q} - \frac{\partial V_d}{\partial q}\right)$ as in Ref. [12].

2.2.1 Case Study: IDA-PBC of a Gantry Crane. Let us now apply this procedure to our gantry crane. The energy function must be shaped in the r and ρ coordinates, which can be accomplished by shaping the potential energy. The desired closed loop dynamics in Eq. (5) are chosen so that $M_d(q, p) = M(q, p)$ and

$$V_d(q) = \frac{1}{2}\left(\gamma_r(r - r_d)^2 + \gamma_\rho(\rho - \rho_d)^2\right)$$

with $\gamma_x > 0$, $\gamma_\rho > 0$ and where r_d, ρ_d with $\theta = 0$ defines the desired equilibrium point. The θ configuration coordinate cannot be shaped with this procedure since it is not an actuated variable. After the shaping, the Hamiltonian exhibits the Hessian matrix

$$\frac{\partial^2 H_d(x)}{\partial x_i \partial x_j} = \begin{pmatrix} \gamma_r & 0 & 0 & 0 & 0 & 0 \\ 0 & \gamma_\rho & 0 & 0 & 0 & 0 \\ 0 & 0 & g m_c \rho_d & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{2}{m_c} & 0 & \frac{2}{m_c \rho_d} \\ 0 & 0 & 0 & 0 & \frac{2}{m_b} & 0 \\ 0 & 0 & 0 & \frac{2}{m_c \rho_d} & 0 & \frac{2(m_c + m_b)}{m_c m_b \rho_d^2} \end{pmatrix}$$

at the desired equilibrium point $x_d = (r_d,\ \rho_d,\ 0,\ 0,\ 0,\ 0)$.

2.3 Control by Interconnection. Consider a port-controlled Hamiltonian system given by Eq. (3), regarded as a plant system to be controlled. Recall the well-known result that the standard feedback interconnection of two passive systems is again a passive system [15]. A method to shape the energy function via interconnection was first proposed and developed in Ref. [13]. The main idea of this method is to interconnect the plant system (3) with a source system given by

$$\begin{aligned} \dot{\xi} &= J_c(\xi)\frac{\partial H_c}{\partial \xi} + G_c(\xi)u_c \\ y_c &= G_c^\top(\xi)\frac{\partial H_c}{\partial \xi} \end{aligned} \tag{7}$$

regarded as the controller system, via the standard feedback interconnection

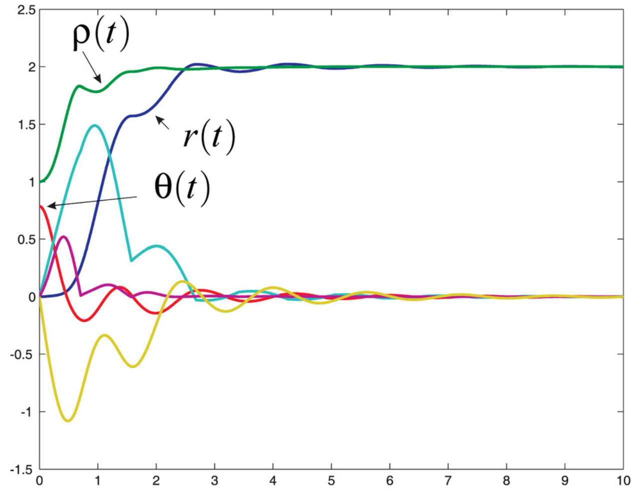

Fig. 2 Evolution of the crane states (simulation)

$$u = -y_c + e$$
$$u_c = y + e_c$$

Assuming that there are no external disturbances ($e=0$, $e_c=0$), the closed loop takes the form

$$\begin{pmatrix} \dot{x} \\ \dot{\xi} \end{pmatrix} = \begin{pmatrix} J(x) & -G(x)G_c^\top(\xi) \\ G_c(\xi)G^\top(x) & J_c(\xi) \end{pmatrix} \begin{pmatrix} \dfrac{\partial H}{\partial x} \\ \dfrac{\partial H_c}{\partial \xi} \end{pmatrix}$$

$$\begin{pmatrix} y \\ y_c \end{pmatrix} = \begin{pmatrix} G(x) & 0 \\ 0 & G_c(\xi) \end{pmatrix} \begin{pmatrix} \dfrac{\partial H}{\partial x} \\ \dfrac{\partial H_c}{\partial \xi} \end{pmatrix}$$

and the closed loop energy function is

$$H_{cl}(x,\xi) = H(x) + H_c(\xi)$$

2.4 Reset Control. A resetting differential equation consists of three elements:

(1) A continuous-time dynamical equation, which governs the motion of the system between resetting events.
(2) A difference equation, which governs the way the states are instantaneously changed when a resetting event occurs.
(3) A criterion for determining when the states of the system are to be reset.

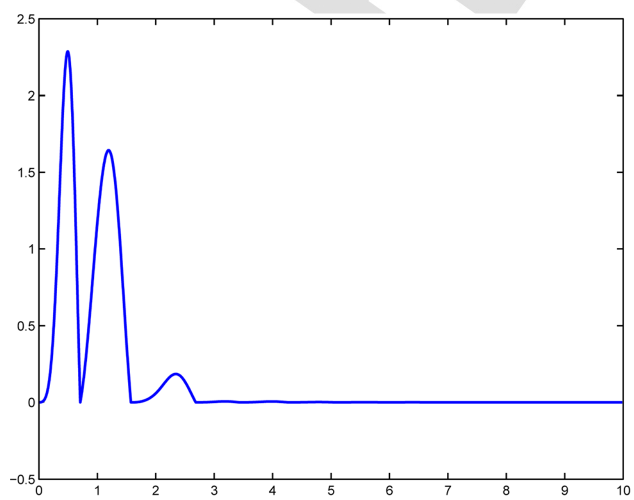

Fig. 3 Evolution of the controller energy flow (simulation)

Fig. 4 Experimental plant: the Inteco 3DCrane

Thus, a resetting differential equation has the form

$$\begin{aligned} \dot{x}(t) &= f(x(t)), (t, x(t)) \notin \mathbf{S} \\ \Delta x(t) &= \rho(x(t)), (t, x(t)) \in \mathbf{S} \end{aligned} \quad (8)$$

where $t \geq 0$, $x(t) \in \mathbf{R}^n$, f: $\mathbf{R}^n \to \mathbf{R}^n$ is Lipschitz continuous and satisfies $f(0)=0$; ρ: $\mathbf{R}^n \to \mathbf{R}^n$ is such that $\rho(0)=0$ and $\mathbf{S} \subset [0,\infty) \times \mathbf{R}^n$ is the resetting set. We refer to the first equation in Eq. (8) as the continuous-time dynamics, and to the second equation in Eq. (8) as the resetting law. For our purposes, the following result for the stability of the zero solution is needed.

Theorem 1. *Suppose there exists a continuously differentiable function V: $\mathbf{R}^n \to [0,\infty)$ satisfying $V(0)=0$, $V(x)>0$, $x \neq 0$, and*

$$\begin{aligned} \frac{\partial V}{\partial x} f(x) &\leq 0, x \notin \mathbf{S} \\ V(x+\rho(x)) - V(x) &\leq 0, x \in \mathbf{S} \end{aligned} \quad (9)$$

Then the zero solution of Eq. (8) is Lyapunov stable. Furthermore, if the inequality in Eq. (9) is strict for $x \neq 0$, then the zero solution is asymptotically stable [16].

3 Damping by Reset Interconnection

In this section, it is shown how, by interconnecting the plant to a reset controller, it is possible to achieve the desired damping injection effect. Instead of using Eq. (6), the dissipation is injected through an energy absorber device, characterized by a resetting oscillator. The controller system interconnected with the plant is given by Eq. (7), with the energy function being

$$H_c = \frac{1}{2}\left(q_c^\top K_c q_c + p_c^\top M_c^{-1} p_c\right)$$

This controller corresponds physically to a mass–spring system, with K_c and M_c being the (constant, definite positive) virtual rigidity and mass controller matrices. Since it is a reset controller, its dynamic equations corresponding to Eq. (8) are

$$\begin{aligned} \dot{q}_c &= M_c^{-1} p_c \\ \dot{p}_c &= -K_c q_c + y, (q_c, p_c) \notin \mathbf{S} \\ u_c &= K_c q_c \\ \Delta q_c &= -q_c \\ \Delta p_c &= -p_c, (q_c, p_c) \in \mathbf{S} \\ u_c &= K_c q_c \end{aligned}$$

Notice that, without taking reset into consideration, the controller does not include any energy-dissipating elements. The set $\mathbf{S}$ is characterized as those (q_c, p_c) for which $\frac{dH_c(q_c,p_c)}{dt} < 0$. As stated in Theorem 1, this resetting controller asymptotically stabilizes the

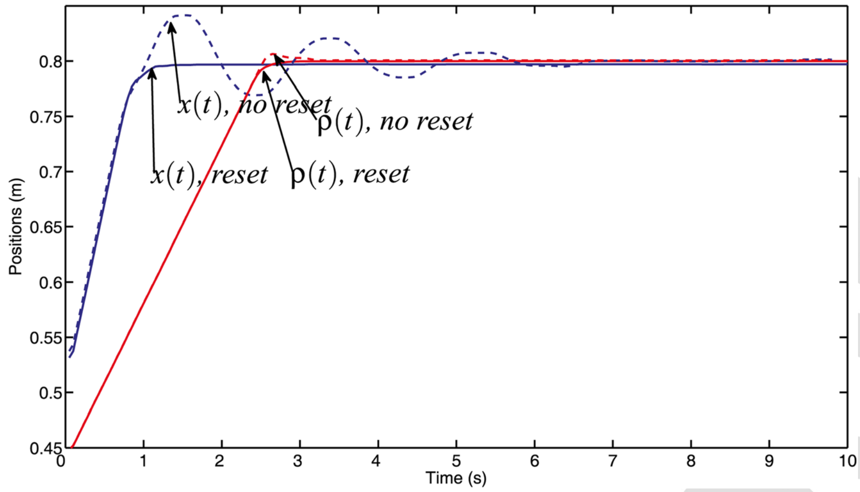

Fig. 5 Evolution of the crane's cart positions (experiments)

plant for $V(x,\xi) = H_d(x) + H_c(\xi)$. Deriving along an orbit $\dot{V}(x,\xi) = \dot{H}_d(x) + \dot{H}_c(\xi)$ and calculating the theorem conditions, we obtain

$$(x,\xi) \notin \mathbf{S} \Rightarrow \dot{V}(x,\xi) = 0, \text{(lossless)}$$
$$(x,\xi) \in \mathbf{S} \Rightarrow \Delta V(x,\xi) = -H_c(\xi) < 0, \forall \xi \neq 0$$

Notice that, since the flow is lossless, the first inequality in Eq. (9) is not strict and we cannot prove asymptotic stability. However, in practice, we have found that the dissipation is complete and asymptotic stability is achieved, as intuitively expected. A rigorous prove of this property deserves further research.

3.1 Case Study: Damping by Resetting for a Gantry Crane. We show now how the procedure can be applied to our case study. For the gantry crane, $q_c = (r_c, \rho_c)$ are the controller configuration variables and $p_c = (p_{r_c}, p_{\rho_c})$ its momenta. The resetting law is calculated with

$$\frac{dH_c}{dt} = \frac{2((m_{22}\dot{r} - m_{12}\dot{\rho})p_{r_{c_1}} + (m_{11}\dot{\rho} - m_{12}\dot{r})p_{r_{c_2}})}{m_{11}m_{22} - m_{12}^2} \quad (10)$$

We perform simulations using the values $m_c = 1.155$, $m_b = 0.5 g = 9.8$, $K_r = 3$; $K_\rho = 2$; $K_{s_r} = 1$; $K_{s\rho} = 1$, with initial conditions $r_0 = 0$, $\rho_0 = 1$, $\theta_0 = \pi/4$, $p_r = 0$, $p_\rho = 0$, $p_\theta = 0$. The desired equilibrium point ($r_d = 2$, $\rho_d = 2$, $\theta_0 = 0$), and the controller parameters are

$$K_c = \begin{pmatrix} 2 & 0 \\ 0 & 1 \end{pmatrix}, M_c = \begin{pmatrix} 2 & 0 \\ 0 & 1 \end{pmatrix} \quad (11)$$

The simulation results in Fig. 2 show the good performance of the adopted solution. In Fig. 3, the evolution of the plant's energy is plotted.

It should be noticed that the use of dissipation injection as given in Eq. (6), that is,

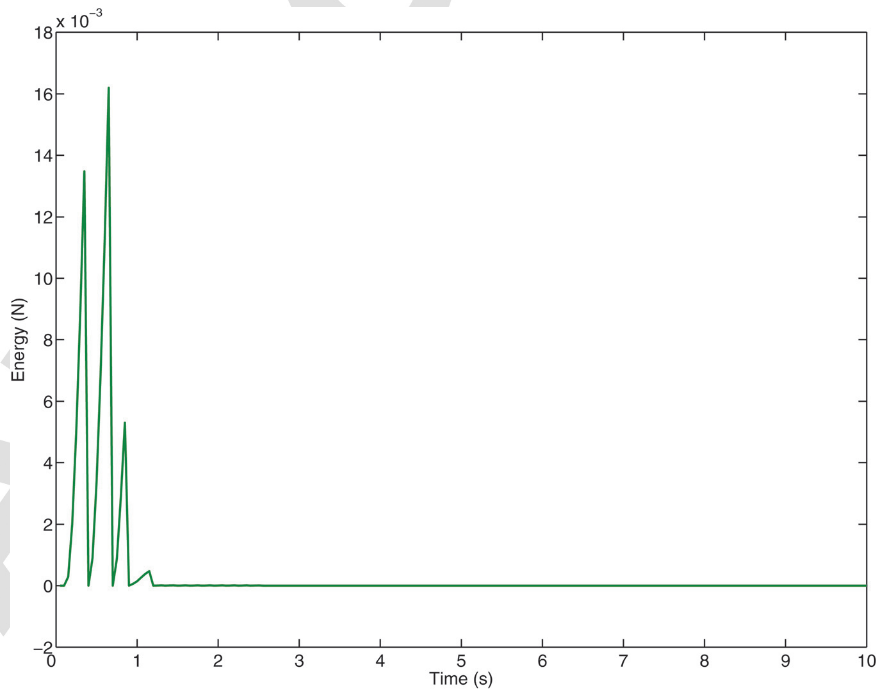

Fig. 6 Evolution of the controller energy flow (experiments)

$$u_{di} = \begin{bmatrix} [2K_r \dfrac{(\cos\theta p_\theta + (p_r + p_\rho \sin\theta)\rho)}{m_c \rho} \\ \dfrac{2K_\rho}{m_b m_c \rho}(m_b p_\theta \sin(2\theta) + ((2m_c - m_b(1-\cos(2\theta))p_\rho + 2m_b p_r \sin\theta)\rho)] \end{bmatrix}$$

requires to know precise values for the momenta, entailing the adoption of a full state observer. As can be concluded from the use of the resetting controller, only the plant velocities $(\dot{r}, \dot{\rho})$ are needed for its implementation; thus, only a velocity observer is required [17]. The dissipation injection as given by Eq. (11) has two tuning parameters (K_r, K_ρ) while the resetting controller has a richer parameter space (K_c, M_c) to enhance transient characteristics.

The controller has also been applied to a real gantry crane, Inteco's 3DCrane model (depicted in Fig. 4, see also http://www.inteco.com.pl/ for details). Experimental results can be found in Fig. 5, where the evolution of the (r, ρ) coordinates (cart position and cable length) are plotted both for the case that no reset is applied (dashed lines) and for the resetted controller (solid lines). The evolution of the controller's energy is pictured in Fig. 6, where the abrupt changes due to reset of the controller states can be noticed.

4 Conclusions

In this paper, a new strategy for injecting dissipation into port-controlled Hamiltonian systems has been designed. The controller synthesis procedure is as follows: first, a physical controller is developed, which is characterized as a port-Hamiltonian system itself. This controller has in principle no damping terms, and it is connected to the plant to be controlled in an energy-conserving way. Dissipation is then achieved by resetting the controller states every time that the controller's energy is going to decrease. It has been shown that the effect of this reset (and hence, nonlinear) controller is equivalent to injecting damping to the plant at some required moments, thus leading to performance improvements. An advantage of this alternative way of performing damping injection is the simplicity of its implementation.

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