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Energy-based Safety in Series Elastic Actuation

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***Abstract*— This work presents the concept of energy-based safety for series-elastic actuation. Generic actuation passivity and safety is treated, defining several energy storage and power flow properties related to passivity. Safe behaviour is not guaranteed by passivity, but can be guaranteed by energy and power limits that adapt the nominal behaviour of an impedance controller. A discussion on power flows in series-elastic actuation is presented and an appropriate controller is developed. Experimental results validate the effectiveness of the energy-based safety in elastic actuation.**

I. Introduction

With the increased interest in collaborative robots, the area of truly safe and stable interaction between humans and robots has seen significant development in the past years. Many developments have taken place to increase the level of safety, using various control techniques [1] and novel mechanical implementations [2]. All of these show a paradigm shift from rigid high-bandwidth, highly accurate position controlled systems to compliant and softer interaction controlled systems. Series-elastic actuation uses a physical elastic element to decouple the motor side from the link side of the actuator or joint. This actuation is able to store and release energy, having merits in energy efficient actuation. However, when energy is put in the elastic element and no locking mechanism exists to keep the energy stored, it is immediately released and, thereby, possibly causing undesired behaviour in the intended application.

In physical systems, the property of passivity is an energy-based measure of stability. It is a special case of dissipativity, as introduced in [3], that arises naturally in physical dynamical systems. Intuitively stated, and considering the energetic connection of two system Σ_1 and Σ_2 by power port (e, f) as shown in Fig. 1, system Σ_2 is said to be passive *with respect to the port* (e, f) if the stored energy of Σ_2 is never more than what has been added through (e, f) plus the energy initially present in Σ_2. System Σ_1 can be thought of as an actuator that delivers power to a mechanism Σ_2. In general, existing literature does not explicitly deal with discrete time control implementations and their performance implications, even though it cannot be guaranteed that a stable continuous time control system remains stable when it is implemented in a discrete time computer. A passive system, however, does remain stable.

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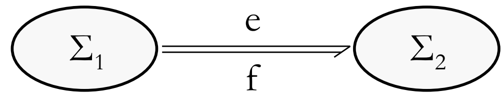

Fig. 1: Two systems Σ_1 and Σ_2 connected by an energy transferring power port with associated dual power variables effort e and flow f.

One way to enforce passivity of an actuated system is the Embedded Energy-Aware Actuation method as presented in the previous work [4], [5]. In this framework, passivity is enforced at the interface between continuous time dynamics and discrete time control systems: at the actuation, where it is exactly determined how much energy is injected into a system. This is contrary to other techniques that strive to dissipate excess energy above the passive energy level, such as the Passivity Observer/Controller (POPC) approach [6], [7], energy tank based approaches [8], or methods that passivate a system using a passive setpoint modulation [9].

However, safe behaviour is not guaranteed by passivity. Passivity puts no limit on the total energy content as long as it was injected at some point, or on the rate of energy flow (power). In general, safety criteria are directly or indirectly dependent on energy transfers. In this work, total energy content, passivity, and rate of energy flow (that is, power) at the interaction port are explicitly controlled.

Torque and impedance control of series-elastic actuators has been discussed thoroughly in literature [10]–[13]. While many algorithms are either passive or passivity-based, most do not consider safety issues that may arise in spite of passivity. The main contribution of this paper is to combine the concept of energy-based safety with series elastic actuation, to ensure passive or strictly dissipative *and* safe behaviour through modulated impedance control.

The remainder of the paper is structured as follows. Sec. II elaborates on the properties of passivity and requirements for safety. Sec. III presents the contribution of energy-awareness in series elastic actuators, and experimental results are presented in Sec. IV. The results and limitations are discussed in Sec. V and the paper concludes with Sec. VI.

II. Generic Actuation Passivity and Safety

General passivity can be mathematically described by considering a system with a storage function $V(s(t)) : S \to \mathbb{R}$, in which the state $s \in S$, such that:

$$V(s(t_1)) \;\leq\; V(s(t_0)) + \int_{t_0}^{t_1} P(\sigma)\,\mathrm{d}\sigma \quad \forall\, t_1 \geq t_0, \qquad (1)$$

where $P(\sigma)$ is a supply function to the system with stored energy $V(s(t))$. This is visualized in the generic model of

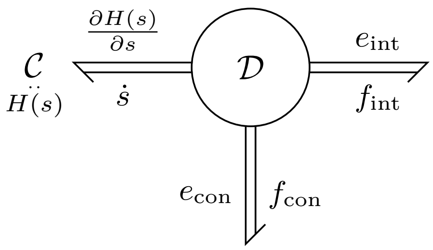

Fig. 2: Visualization of a generic port-Hamiltonian model, with storage port $\left(\frac{\partial H(s)}{\partial s}, \dot{s}\right)$, control port $(e_{\text{con}}, f_{\text{con}})$ and interaction port $(e_{\text{int}}, f_{\text{int}})$. Note that a dissipation port $\mathcal{R}$ with $(e_{\text{dis}}, f_{\text{dis}})$ can be included to model irreversible energy dissipation.

a physical dynamical system in Fig. 2 (in which the time-dependence notation is dropped), with storage $\mathcal{C}$ and associated Hamiltonian storage function $H(s) \equiv V(s)$, control port $(e_{\text{con}}, f_{\text{con}})$ and associated supply function that can be defined as the duality product of effort e_{con} and flow f_{con} according to $P_{\text{con}} := \langle e_{\text{con}}, f_{\text{con}} \rangle$. Moreover, an interaction port $(e_{\text{int}}, f_{\text{int}})$ is shown, with corresponding power flow $P_{\text{int}} := \langle e_{\text{int}}, f_{\text{int}} \rangle$. A natural choice for the storage function $V(s(t))$ in (1) is the total energy in the system. The supply function is the supplied power through the control port of the system, for example the duality product of mechanical force F and velocity v, i.e., $P = \langle F, v \rangle$. Systems that contain only passive physical elements, e.g. masses, springs, and dampers, cannot contain more energy than what was initially present. Consequently, the energy is bounded and thus a system that is overall passive is always stable [14], [15].

A. Energy storage properties

Eq. (1) states the condition for a passive system. If a system can be described such that strictly the equality holds, the system is conservative, i.e., non-dissipative. This means that exactly all supplied energy is stored, and none is dissipated. A dissipative system always stores less energy than was supplied, i.e., only the inequality holds in (1). If a system is designed to only extract energy from an attached system through a power port at any time instance, i.e., the power flow through that port is negative or zero, it is defined here to be *strictly dissipative*. Hence, strictly dissipative systems cannot supply any energy. These properties define special cases of passive systems.

On the other hand, if (1) does not hold at all, the system is defined as being active. Formally, physical systems are always passive, and energy cannot be created or destroyed according to the first law of thermodynamics. An active system may arise when certain physical energetic connections are not present in the mathematical description of the system. In that way, the systems seem to be able to increase their stored energy without having exchanged or received that energy through a considered power port, which can be considered the generation of energy. For example, a naive controller implementation on a system that does not consider and limit supplied actuation power may render a system active and unstable [4]. Similar to (1), the various energy storing behaviours are mathematically defined by:

$$
\begin{aligned}
\textbf{Passive:} \quad & V(s(t_1)) \leq V(s(t_0)) + \int_{t_0}^{t_1} P(\sigma)\, \mathrm{d}\sigma \\
\text{Conservative:} \quad & V(s(t_1)) = V(s(t_0)) + \int_{t_0}^{t_1} P(\sigma)\, \mathrm{d}\sigma \\
\text{Dissipative:} \quad & V(s(t_1)) < V(s(t_0)) + \int_{t_0}^{t_1} P(\sigma)\, \mathrm{d}\sigma \\
\text{Strictly Dissipative:} \quad & P(t) \leq 0 \;\; \forall\, t \\
\textbf{Active:} \quad & V(s(t_1)) > V(s(t_0)) + \int_{t_0}^{t_1} P(\sigma)\, \mathrm{d}\sigma, \quad (2)
\end{aligned}
$$

for all $t_1 > t_0$. Note that the definition of strictly dissipative systems only places a constraint on the power flow at a considered port, and does not define a constraint on the stored energy.

B. Passivity and safety

Although passivity guarantees the stability of a system, it implies nothing about the safety of the system with respect to itself or the environment. Safe behaviour of a system is often loosely stated as behaviour that causes no damage to the system itself or to the environment with which energy is exchanged, i.e., interaction. A more formal rating can be obtained with the definition of various safety criteria, like the Head Injury Criterion, Maximum Power Index, and Maximum Mean Strain Injury Criterion. To meet these criteria, the amount of energy, power, force, and/or acceleration that is transferred to the environment needs to be limited [16]. In general, all safety criteria are directly or indirectly dependent on energy transfers, making energy and power a reasonable focus for safety considerations [17], [18].

Safe behaviour of a robot has been treated in [19], where it was proposed that when unwanted energy in an impedance controlled system is identified, the controller drains energy by being more compliant and when unsafe power output is detected, the controller increases the damping on its output. The former prevents possible suffocating forces to be applied by a robotic system to the environment, e.g., a person, while the latter prevents a high-energy, large momentum movement having the risk of causing a potentially harmful collision.

Safety can also be established at the actuation level of a system using an actuation energy budget, as shown in previous work [4], [5]. This budget is the amount of energy that can be injected by the actuator in a system. By allocating energy needed for task execution to the budget, safety is achieved because the amount of energy in the system can be chosen to never be outside of safe limits, while still allowing enough for task execution.

This paper proposes to ensure safety by imposing conditions on the actuation energy storage and output power, varying it between strictly dissipative and passive depending on the set safety limits. In the former, energy in a connected system is only ever extracted, meaning that no energy can be released into the robot and the environment causing potential

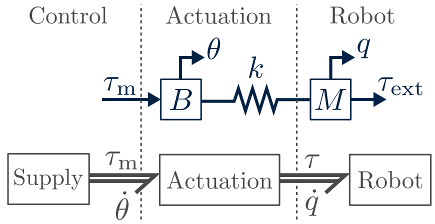

Fig. 3: Linear dynamics model of series-elastic actuation.

harm. In the latter, energy may be stored up to a safe limit and only released at a safe rate.

III. Energy-based Safe Elastic Actuation

One of the main differences between stiff actuation and elastic actuation is indirect coupling of the control input to the control variable. In stiff actuation the mechanical forces following control inputs are directly applied to the robot. Hence, the choice of control effort directly determines power flow into the system. Conversely, in elastic actuation only motor-side states can be directly influenced, which are indirectly coupled to the robot-side states. The consequence is that the choice of control effort at the motor-side does not directly influence power flow out of the elastic element into the robot dynamics. At a particular point in time, stored elastic energy may be injected into the robot, even though the control power may be negative.

As an example, to provide damping (i.e. negative power) at the output (actuation port), some deflection in the elastic element is required, to generate the desired torque. This may momentarily require *positive* power at the control port to create the required deflection, even though power at the actuation port is nonpositive. Interestingly, for *any* nonzero power to be generated at the actuation port, nonzero energy must be present in the system in the form of elastic energy.

A. Modelling and energy flows

Consider the linear model of an elastic actuator with load in Fig. 3, with motor and load inertiae B and M, with positions θ and q, respectively, coupled by an elastic element with stiffness k. The input torque as generated by the motor is denoted by τ_{m}, and external interaction torques are denoted as τ_{ext}. Its dynamics are given by:

$$B\,\ddot\theta = \tau_{\mathrm{m}} - k\,(\theta - q)\,, \tag{3}$$
$$M\,\ddot q = \tau_{\mathrm{ext}} + k\,(\theta - q)\,. \tag{4}$$

The output torque that is applied to the robot is defined as $\tau := k\,(\theta - q)$. The dashed vertical lines in Fig. 3 depict the control port $(e_{\mathrm{con}}, f_{\mathrm{con}}) := (\tau_{\mathrm{m}}, \dot\theta)$ and actuation output port $(e_{\mathrm{act}}, f_{\mathrm{act}}) := (\tau, \dot q)$. Focusing on the actuation subsystem, its total storage function is given by:

$$V(\mathbf{s}) = \frac{1}{2}\,B\,\dot\theta^2 + \frac{1}{2}\,k\Delta^2, \tag{5}$$

with the state $\mathbf{s}$ defined as:

$$\mathbf{s} = \begin{bmatrix}\dot\theta\\ \Delta\end{bmatrix}, \tag{6}$$

and where elastic element deflection $\Delta = (\theta - q)$. The rate of change of stored energy is the sum of the power flowing through the ports, which is represented by the duality product of the collocated output and input port variables $\mathbf{y}$ and $\mathbf{u}$:

$$\begin{aligned}\dot V(\mathbf{s}) &= \langle \mathbf{y}, \mathbf{u}\rangle = \mathbf{y}^{\mathrm{T}}\mathbf{u}\\ &= \tau_{\mathrm{m}}\,\dot\theta - \tau\,\dot q\\ &= P_{\mathrm{con}} - P_{\mathrm{act}}.\end{aligned}$$

Hence, the change in actuation energy storage is the energy supplied via the control port minus the energy released via the actuation output port.

1) Shaping energy exchange: As was shown, the energy flow out of the actuation into the robot is defined by the actuation port $(\tau, \dot q)$ and its corresponding power $P_{\mathrm{act}} = \langle \tau, \dot q\rangle$. Thus, shaping the relationship between τ and $\dot q$ implies shaping the energy exchange between the two systems. Consider the following first-order impedance relationship:

$$\tau = \tau_{\mathrm{imp}} := -K\,q - D\dot q, \tag{7}$$

with corresponding storage function given by $V_{\mathrm{imp}} = \frac{1}{2}Kq^2$. Taking the derivative and computing $P_{\mathrm{act}} = \tau\,\dot q$ using (7) yields[1]:

$$\dot V_{\mathrm{imp}} = K\,q\,\dot q \quad \leq \quad -P_{\mathrm{act}} = K\,q\,\dot q + D\dot q^2,$$

for $K, D \geq 0$, which is a sufficient condition for passivity cf. (2). In fact, the actuation port is dissipative for any $D > 0$. However, it is only strictly dissipative $\forall\ q, \dot q$ if $K = 0$ and $D \geq 0$, in which case $P_{\mathrm{act}} = -D\,\dot q^2 \leq 0$ (cf. (2)), i.e. the actuator can only absorb power from the robot. Hence, realising the torque dynamics $\tau = \tau_{\mathrm{imp}}$ above, the system can be made either passive, dissipative, or strictly dissipative w.r.t. the actuation port by choosing K and D.

While the desired impedance (7) can theoretically be realised by control (as will be shown in the next section), not all required higher-order signals can be obtained exactly, as in practice they need to be approximated by numerical methods or estimators. Secondly, aspects such as discrete-time digital control and delays of any realisable system will reduce performance. Thus, in practice, even control algorithms that are theoretically passive in continuous time cannot be fully guaranteed to be passive in practice. Hence, actively monitoring the energy flow out of an actuator into the actuated system is necessary, to take appropriate action so that safety can be guaranteed at all times.

B. Control

As discussed above, the goal is to realise the following behaviour:

$$\tau \to \tau^* = K\,(q^* - q) + D\,(\dot q^* - \dot q) + \tau_{\mathrm{id}}, \tag{8}$$

where * denotes reference configurations and velocities, K and D denote impedance stiffness and damping, and τ_{id} denotes a link-side inverse dynamics based term to achieve

[1] The minus sign stems from the positive direction of P_{act} to be energy flow *out* of the actuator, hence energy supplied to the actuator is $-P_{\mathrm{act}}$.

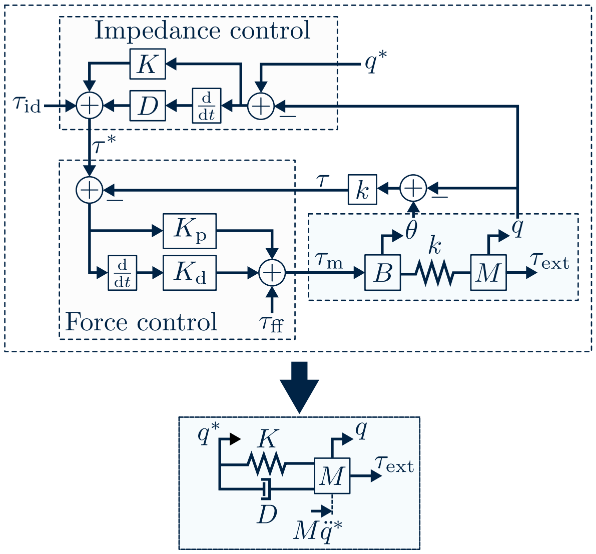

Fig. 4: Cascaded impedance and force control with feed-forward terms.

exact link-side tracking, given by $\tau_{\text{id}} = M\,\ddot{q}^*$ in the considered case. Notice that (8) is equal to (7) for the regulation case $q^* \equiv \dot{q}^* \equiv \ddot{q}^* \equiv 0$, fulfilling the earlier conditions for passivity and (strict) dissipativity at the port $(\tau, \dot{q})$.

1) Torque feedback and feed-forward terms: Suppose a torque control law of the form:

$$\tau_{\text{m}} = K_{\text{p}}\,(\tau^* - \tau) + K_{\text{d}}\,(\dot{\tau}^* - \dot{\tau}) + \tau_{\text{ff}}, \tag{9}$$

where τ_{ff} denotes feed-forward terms. The resulting control structure is shown in Fig. 4, constituting a well-known cascaded control scheme augmented with feed-forward terms.

To obtain the feed-forward terms, we recall $k\,(\theta - q) =: \tau$, set $\tau = \tau^*$, and solve for the motor-side coordinate θ:

$$\theta = q + k^{-1}\,\underbrace{(K\,e_q + D\,\dot{e}_q + M\,\ddot{q}^*)}_{\tau^*}, \tag{10}$$

where $e_q = q^* - q$ denotes the link-side tracking error. Substituting into (3) and solving for τ_{m}, we obtain

$$\tau_{\text{ff}} = k^{-1}\,B\,\underbrace{\left(K\,\ddot{e}_q + D\,e_q^{(3)} + M\,q^{(4)*}\right)}_{\ddot{\tau}^*} + \underbrace{B\,\ddot{q}}_{\ddot{\theta}=\ddot{q}} + \underbrace{K\,e_q + D\,\dot{e}_q + M\,\ddot{q}^*}_{\tau^*}. \tag{11}$$

Lastly, substituting (8), (9), and (11) into (4) leads to the following link-side dynamics, expressed in the tracking error dynamics:

$$M\,\ddot{e}_q + D\,\dot{e}_q + K\,e_q = \tau_{\text{ext}}, \tag{12}$$

which for $M, D, K > 0$ and $\tau_{\text{ext}} = 0$ has the unique equilibrium $\ddot{e}_q = \dot{e}_q = e_q = 0$, thus creating an actuator impedance as specified by (7), with the addition of a reference position input $q^*(t) \in \mathcal{C}^4$ and its derivatives[2,3], as shown in Fig. 4. However, notice that the feed-forward terms (11) require measurements of $\dot{q}, \ddot{q}, q^{(3)}$. To partially reduce this burden a specific choice for K can be made.

2) Rendering intrinsic stiffness: Consider a truly elastic actuator, that is, one with a physical stiffness close to what should be rendered at the output. In such a case it is useful to render the actuator's intrinsic stiffness exactly, i.e. $K = k$. The motor-side coordinate θ then simplifies to

$$\theta = q^* + k^{-1}\,(D\,\dot{e}_q + M\,\ddot{q}^*)\,, \tag{13}$$

which is equal to $\theta = -k^{-1}\,D\,\dot{q}$ in the regulation case $\ddot{q}^* \equiv \dot{q}^* \equiv q^* \equiv 0$. The motor position is only adjusted to produce the desired link-side damping, as the desired link-side stiffness is already produced by the physical stiffness. The feed-forward terms reduce to

$$\tau_{\text{ff}} = k^{-1}\,B\left(D\,e_q^{(3)} + M\,q^{(4)*}\right) + \underbrace{B\,\ddot{q}^*}_{\ddot{\theta}=\ddot{q}^*} + \underbrace{k\,e_q + D\,\dot{e}_q + M\,\ddot{q}^*}_{\tau^*}, \tag{14}$$

which for the regulation case is equal to

$$\tau_{\text{ff}} = \underbrace{-k^{-1}\,B\,D\,q^{(3)}}_{B\ddot{\theta}}\underbrace{-D\,\dot{q} - k\,q}_{\tau^*}. \tag{15}$$

where the first term can be recognised as motor acceleration feed-forward given the desired motor-side coordinate above, and the second term compensates for spring force. Hence, choosing $K = k$ simplifies required motor dynamics as well as control terms. This choice also demonstrates how the central design idea in [12] is effectively a special case of the conventional cascaded impedance control scheme[4] with $K = k$. Notice that compared to (11), (14) does not depend on $\ddot{q}$. The earlier mentioned work [12] neglected the remaining $q^{(3)}$ term, seemingly without significant loss in performance.

C. Energy-based impedance modulation for safety

The strategy for ensuring safety, as discussed in Sec. III-A, relies on modulation of rendered impedance parameters K and D that allow to vary the system between passive and strictly dissipative. The technique proposed in [19] is employed, with some minor modifications.

1) Limiting energy storage: The energy stored in the controlled actuation system is defined by the virtual potential energy in the impedance stiffness:

$$E_{\text{p}} = \frac{1}{2}\,K\,q^2. \tag{16}$$

where $q^* \equiv 0$ was assumed without loss of generality. Hence, modulation of K can be utilised to limit the stored virtual energy below a maximum $E_{\text{p}} \leq E_{\text{p}}^{\text{max}}$. Setting K as follows:

$$K = \begin{cases} \frac{2\,E_{\text{p}}^{\text{max}}}{q^2} & \frac{1}{2}\,k\,q^2 > E_{\text{p}}^{\text{max}} \\ k & \text{Otherwise,} \end{cases} \tag{17}$$

reduces the impedance stiffness down from k as it is brought further out of equilibrium – effectively absorbing any energy injected through the actuation port above the threshold of $E_{\text{p}}^{\text{max}}$ via the control port.

[2] $\mathcal{C}^k$ denotes the set of k times continuously differentiable functions.

[3] Note that assuming finite control inputs, τ_{ext} has to be at least $\in \mathcal{C}^1$ to ensure finite $q^{(3)}$.

[4] Including the feed-forward terms (14), however with the exception of the $k\,e_q$ term, leading to the rendered stiffness being a series connection of the physical stiffness and motor proportional gain in their case.

2) Limiting output power: Contrary to stored energy, output power is a function of both impedance parameters K and D. First, recall $P_{\text{act}} = -K\,q\,\dot{q} - D\,\dot{q}^2$, with K now given by (17). Secondly, define the nominal impedance damping $\bar{D}$ as

$$\bar{D} = 2\,M\,\zeta\,\sqrt{K/M} \tag{18}$$

where ζ defines the damping ratio of the load. Notice $\bar{D}$ decreases with decreasing K given by (17), to maintain the desired damping ratio. Now, setting D as follows:

$$D = \begin{cases} -\frac{K\,q\,\dot{q} + P_{\text{act}}^{\text{max}}}{\dot{q}^2} & -K\,q\,\dot{q} - \bar{D}\,\dot{q}^2 > P_{\text{act}}^{\text{max}} \\ \bar{D} & \text{Otherwise} \end{cases}, \tag{19}$$

increases $D > \bar{D}$ if necessary, to ensure $P_{\text{act}} \leq P_{\text{act}}^{\text{max}}$.

3) Choosing safety parameters: From the physical interpretation of a spring-damper for the rendered impedance, it becomes clear that not every combination of $E_{\text{p}}^{\text{max}}$ and $P_{\text{act}}^{\text{max}}$ is desirable. Consider Table I, which shows that either both parameters need to be zero for strict dissipativity, or both must be positive for passive operation (with limited energy storage and output power for finite values). Other combinations result in conflicting energy storage and release requirements. With regards to passive operation, the two parameters are not independent: a system with large energy storage will generally tend towards high power output, and forcing small power output requires large and rapid changes in damping[5].

IV. Experimental Results

A. Experimental setup

To validate the effectiveness of the proposed approach, experiments were performed with a compliant actuation setup as shown in Fig. 5. It consists of a DC motor connected to a flywheel through a belt drive mechanism, with combined inertia B, which drives a load inertia M through a flexible shaft with stiffness k. Because the flexible shaft is considerably more compliant than the belt drive, parasitic belt drive compliance is neglected. Optical incremental encoders on the motor and load allow angular position measurements. The motor is driven by a current controlled power amplifier, and control and data acquisition run on an embedded FPGA board. Physical and control parameters are listed in Table II.

B. Results

Two experiments were performed, with impedance modulation switched off and on, respectively. In both cases, the load was brought out of its equilibrium position by approx. ± 2 rad, and then released. Due to limitations in the software implementation the sample rate was set to 200 Hz; together with filtering of the encoder signals, this necessitated lowering the nominal stiffness to $K = \frac{1}{2}k$ to ensure satisfactory performance. Higher order derivatives were neglected as the relatively low encoder resolution makes numerical approximation infeasible.

Results without impedance modulation are shown in Fig. 6 and 7. In Fig. 6 it can be observed that upon release at 4.5 s and 9.7 s, the motor inertia first moves in the opposite direction to generate desired damping torques, after which both inertiae converge asymptotically ($\zeta = 1.0$) to the equilibrium position. Up to approx. 0.7 J of energy is stored due to the large deflection, corresponding to a torque of approx. 0.66 Nm. Upon release of the load this energy is released, resulting in a peak actuation power of over 3.3 W, as shown in Fig. 7. Most of this energy is then re-absorbed and dissipated by the actuation to dampen the load in its equilibrium position.

Next experiments were performed with impedance modulation enabled. The safety parameters were set to $E_{\text{p}}^{\text{max}} = 0.25$ J and $P_{\text{act}}^{\text{max}} = 0.25$ W, respectively, i.e. passive be-

[5]A useful guideline appears to be choosing $E_{\text{p}}^{\text{max}}$ and $P_{\text{act}}^{\text{max}}$ relatively as function of the time constant of the physical spring and load combination.

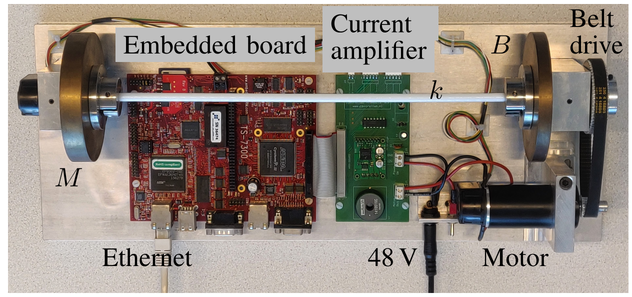

Fig. 5: The compliant actuation experimental setup used for testing the controller performance.

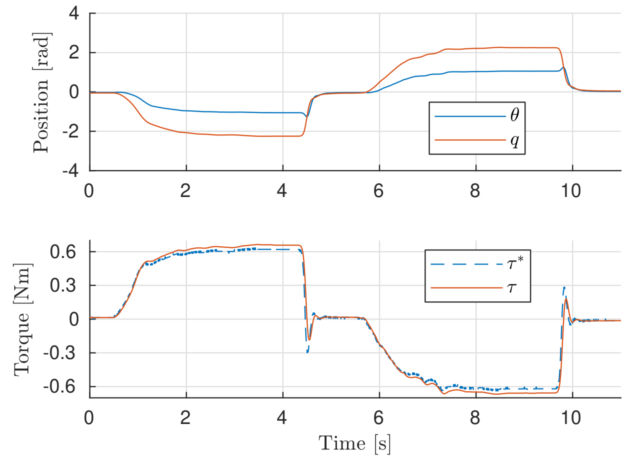

Fig. 6: Experiment, safety off: Position and torques.

TABLE I: Choosing safety parameters.

	$E_{\text{p}}^{\text{max}} = 0$	$E_{\text{p}}^{\text{max}} > 0$
$P_{\text{act}}^{\text{max}} = 0$	Strictly dissipative	Undesirable (Energy may be stored but not released)
$P_{\text{act}}^{\text{max}} > 0$	Undesirable (No energy is stored, but may be released)	Passive

TABLE II: Physical and control parameters of the experimental setup.

Component	**Value**	**Unit**
Flexible shaft stiffness k	0.551	Nm / rad
Load flywheel inertia M	$1.37 \cdot 10^{-3}$	kg m^2
Motor+flywheel inertia B	$1.02 \cdot 10^{-3}$	kg m^2
Belt drive speed reduction ratio	$\frac{60}{16}$	–
Encoder resolution	2000	counts/rev
Control sample rate	200	Hz

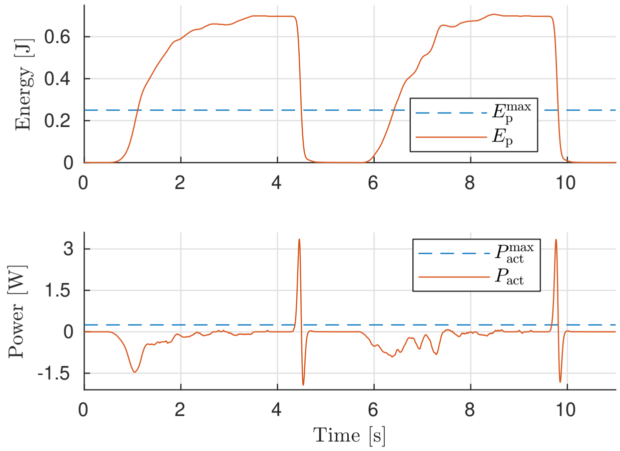

Fig. 7: Experiment, safety off: Energy and power.

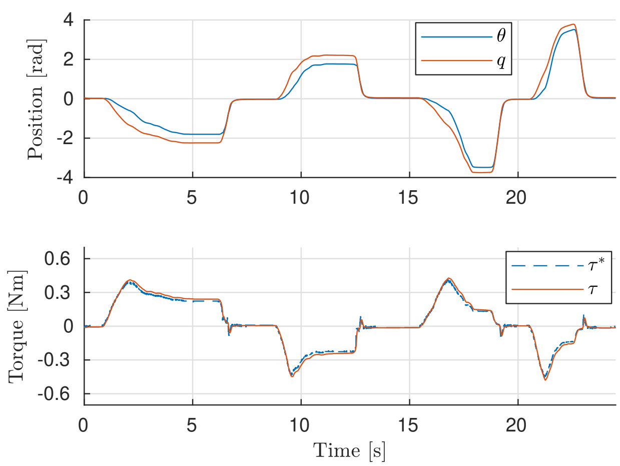

Fig. 8: Experiment, safety on: Position and torques.

haviour with limits on energy content and actuation power output. The results are shown in Fig. 8–10. In the first part, the load is again brought to approx. ± 2 rad and released. However, the stored energy is limited to 0.25 J (Fig. 9), due to the modulation of impedance stiffness as shown in Fig. 10. Even when brought to almost ± 4 rad (from 15 s), the energy is limited appropriately. This is reflected in lower torques shown in Fig. 8. The actuation power shown in Fig. 9 shows that the system does not manage to stay within the imposed limit just after release, but converges quickly. This is attributed to insufficiently accurate torque tracking as the reference changes rapidly. However, the peak of almost 0.6 W is a significant reduction over the earlier $>$3.3 W without impedance modulation.

V. Discussion

Although some issues were observed in the experimental results, they validate the effectiveness of the energy-based safety concept. While Sec. III-B.1 showed that rendering the desired (modulated) impedance in principle requires higher order derivatives of system states, the results indicate that satisfactory performance can be achieved without them. Indeed, the system was able to enforce the safety limits to a large extent. Control performance was mainly limited by

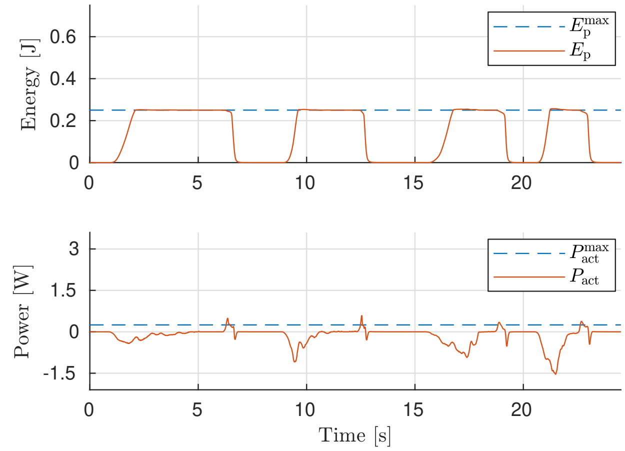

Fig. 9: Experiment, safety on: Energy and power.

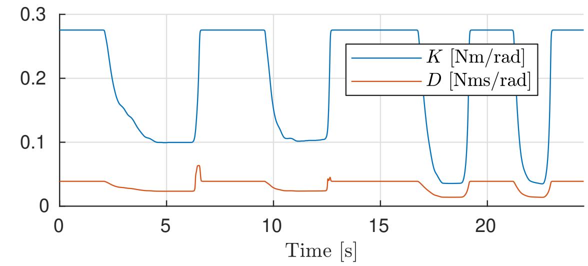

Fig. 10: Experiment, safety on: Impedance parameters.

sample rate and encoder resolution, which are straightforward avenues to increase performance further.

The current safety implementation imposes fixed limits on energy storage and actuation power. The choice of these limits at the moment is heuristic and would benefit from further future investigation. Furthermore, execution of tasks may (momentarily) require larger energy content or output power. For such situations temporarily increasing the safety limits or implementing actuation budgeting may prove useful further developments to this strategy.

VI. Conclusions

This paper presented the implementation of energy-based safety in series-elastic actuation. Generic actuation passivity and safety were treated, defining several energy storage properties. It was concluded that passivity is not a sufficient condition for safety, and that limitations on energy content and output power, or even strict dissipativity, are necessary. The developed controller for an elastic actuation system shows impedance regulating behaviour to realise safety limits based on energy and power. The experimental results validate the theoretical foundations of the proposed approach.

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