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Series and Parallel Elastic Actuation: Impact of natural dynamics on power and energy consumption

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ABSTRACT

This paper provides a detailed analysis of the power and mechanical/electrical energy consumption of Series Elastic Actuators (SEAs) and Parallel Elastic Actuators (PEAs). The study is done by imposing a sinusoidal motion to a pendulum load, such that the natural dynamics automatically present itself in the power and energy consumption. This allows to link the actuators' dynamics to their loss mechanisms, revealing interesting characteristics of series and parallel elastic elements in actuator designs. Simulations demonstrate that the SEA and PEA allow to decrease both peak power and energy consumption, provided that the stiffness of their elastic element is tuned properly. For the SEA, both are minimized by tuning the elastic element to the antiresonance frequency of the actuator. For the PEA, peak power is minimal at the link's resonance frequency, but the optimal stiffness for minimal electrical energy consumption cannot be determined by a theoretical resonance and needs to be calculated using a complete system model. If these guidelines are followed, both types of elastic actuators can provide significant energetic benefits at high frequencies. This was confirmed by experiments, which demonstrated energy reductions of up to 78% (SEA) and 20% (PEA) compared to rigid actuators.

1. Introduction

Recent developments in robotics have aimed to bring robots to our homes and working environments, focusing on human–robot interaction instead of carefully separating the robot's task space from the user. The requirement of close human–robot interaction results in an increasing relevance of soft or elastic robot designs [10,14,19], which can provide human safety through reacting by deformation in case of contact [10,14]. Further, elastic designs yield benefits in robotic motion assistance [1,11] and rehabilitation [15]. Besides improving human–robot interaction, elastic actuator designs can increase the energy efficiency of mobile (assistive) devices by adapting actuator elasticity to the operating state [29], e. g., by matching the natural behavior of the system with the trajectory frequency [3,4,27,30].

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Motivated by these promising examples, various concepts for actuators with fixed or variable elasticity have been proposed in recent years [28]. Many of those incorporate a series elastic element as a compliant coupling between drive and link in order to enable safe human–robot interaction. Such compliant couplings help to reduce the risk of injuries, since the robotic structure can deform upon impact with humans. This concept, which is generally known as Series Elastic Actuation (SEA), was introduced in the middle of the 1990s [18,22]. While the mechanical stiffness of the implementation in Ref. [22] is fixed, the stiffness of the concept from Ref. [18] can be varied. The actuator presented in this work can therefore also be considered as one of the first Variable Stiffness Actuators (VSAs) [28].

Regardless of stiffness variation capabilities, the configuration of elastic elements and motors has a significant impact on the dynamics and energy efficiency of elastic actuators. As mentioned before, most contemporary concepts utilize an elastic element in series with the actuator. Yet, Parallel Elastic Actuators (PEA) or actuators combining serial and parallel elastic elements can also yield advantageous power/energy characteristics [9,16,17,21] if the parallel spring is tuned considering task-specific requirements, e. g., by setting the appropriate equilibrium angle. Further, the analysis of dynamic properties like inertial or gravitational effects in elastic actuators shows that those have distinct influence on the natural dynamics [2,3]. Hence, a precise characterization and modeling is crucial to exploit natural dynamics by design and control. However, the dynamic interaction between motor and load is not sufficiently considered for dimensioning in many cases, e.g., Refs. [13,22,23,26,29,33]. Analyzing natural dynamics of Series Elastic Actuators considering the interaction of motor and load shows that natural and antiresonance modes can be exploited [3] and lead to significant decreases in energy consumption [2]. In conclusion, there seems to be a demand for a detailed comparison of the SEA and PEA concepts with respect to natural dynamics and power/energy consumption.

This paper compares the natural dynamics and power/energy characteristics of rigid actuation (RA), PEA, and SEA. To investigate mechanical and electrical energies, the dynamics of the whole system comprising load, actuator, kinematics/gear boxes and electronics are considered, including energy regeneration as suggested in Refs. [2,32]. In this regard, the paper differs from the work done by Grimmer et al. [9], which only compared the SEA and PEA in terms of mechanical peak power and mechanical energy consumption and, hence, did not take motor and gearbox properties into account. Furthermore, the work of Grimmer et al. presents a large set of simulations of a very specific application: a prosthetic ankle actuator at different walking and running speeds. In this work, the aim is to find the relationships between the dynamics of the actuators and their power and energy consumption in order to provide insight into the specific properties of series and parallel elastic elements. As such, the simulations and experiments apply to a very general case which allows to identify the natural dynamics of the actuator: a sinusoidal trajectory applied to a 1-DOF link.

The paper is structured as follows. Section 2 describes the investigated actuator types, corresponding models, and their dynamics. A power and energy analysis based on simulations is given in Section 3 to identify favorable operation modes and compare the different concepts at variable operating frequencies and stiffnesses. Experimental investigations with the test setup from Ref.[32] are used to evaluate the simulation results in a real system and shown in Section 4. Finally, the results of the paper are discussed in Section 5 and summarized in Section 6.

2. Actuator types and their dynamics

Fig. 1 presents schematics of the three studied actuator topologies, moving a one degree of freedom pendulum with a mass M and a length l (the distance between the rotation axis and the center of mass). Combined actuator and gearbox inertia is denoted as $J_m + J_{tr}$. As seen in Fig. 1a and b, the load inertia is J_l and angular positions of the pendulum are equal to those at the gearbox output in the RA and PEA cases. Pendulum motion corresponds to the reduced motor motion $\theta = n^{-1}\theta_m$, where θ and θ_m are the positions of the output and motor, respectively, and n is the gear ratio. The frontal view of the pendulum given in Fig. 1d defines the direction of θ as well as its maximum and minimum values $\pm\theta_{max}$. Motor torque T_m, as defined in Fig. 1a–c, is the sum of the torque available at the motor shaft and the torque required to accelerate the rotor inertia J_m.

The stiffness of the parallel elasticity in the PEA (Fig. 1b) is given by k_p. Considering a SEA with series stiffness k_s (Fig. 1c), inertias J_{l1} and J_{l2} are separated by the elastic element, and as a result, the positions of pendulum θ and gearbox output $n^{-1}\theta_m$ differ.

2.1. Rigid actuation

Considering the topology given in Fig. 1a and friction effects, the system's equations of motion are given by

$$T_m = (J_m + J_{tr})\, n\ddot{\theta} + \frac{C}{n} T_{load} \tag{1}$$

where T_{load} is defined as

$$T_{load} = J_l\ddot{\theta} + T_{c,\,l}\; sign\,(\dot{\theta}) + \nu_l\dot{\theta} + Mgl\sin\theta. \tag{2}$$

The first term on the right side of Eq. (1) represents the inertial torque due to rotating components in the gearbox and motor. T_{load} represents the torque due to the motion of the pendulum load. Essentially, it includes the gravitational and inertial