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Linear Serial Elastic Hydraulic Actuator: Digital Prototyping and Force Control

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Abstract: In aggressive environments for humans, such as those present in the offshore industry, the main alternative is to replace human labor by remotely controlled robots, and some cases completely autonomous robots. The environment affects directly on robots tasks. When a robot works in a structured environment, its automation is easier since the environment can be modeled by dynamics equations. However if the environment is non-structured this modeling is quite difficult and presents a high computational effort. To overcome this difficult, over the years series elastic actuator (SEA) has been applied in non-structured environments. Actuators of the mechanical systems are always rigidly connected to the load to be moved. This can be observed in the hydraulic systems of agricultural, highway construction and mining equipment and in elevation and cargo transportation, among others. Unlike rigid actuators, a SEA contains an elastic element in series with the mechanical energy source. Such an elastic element gives SEA's several unique properties compared to rigid actuators, including tolerance to impact loads, low mechanical output impedance, passive mechanical energy storage, and increased peak power output. However it is not trivial to select the correct spring for the system. The spring has to be able to support the loads, but the spring cannot be too stiff, otherwise system impedance will be high. Iterative methods are needed to select the spring, which fits in impedance and bandwidth parameters. The resonance frequency is another issue for SEAs. This paper describes an entire digital prototyping of a linear serial elastic hydraulic actuator. It is done a digital prototyping of a tubular actuator design, which encapsulates the mechanical and electrical components and sensors. The digital prototype dimensions, mass and inertia properties are used to build the dynamic model for simulations and implementation of a controller. Moreover the methodology adopted results in a good response actuator with a compact and high force design.

Keywords: SEA, hydraulic actuators, servo hydraulics, PID control, force control.

1. INTRODUCTION

Trends in the oil and gas industry to improve safety and efficiency and reduce environmental impact suggest the use of industrial robotics. New developments in regions difficult or dangerous for humans to work in could be enabled with maintenance, inspection and repairs carried out by remotely controlled industrial robots. This new application area highlights some difficulties with today's robots, as they do not adapt well to dynamic environments. Therefore, new decision models, methods of control, actuators need to be developed.

Series elastic actuator (SEA) has been successfully used in a number of applications for almost 20 years (Pratt and Williamson, 1995). As widely reported by a number of researchers (see (Pratt and Williamson, 1995), (Arumugom et al. 2009), (Paluska and Herr, 2006) and (Paine et al, 2013)) series elastic actuators provide many benefits in force control of robots. Unlike rigid actuators, SEA's contain an elastic element in series with the mechanical energy source. Such as elastic element gives SEA's several unique properties compared to rigid actuators including low mechanical output impedance, tolerance to impact loads, increased peak power output, and passive mechanical energy storage. These properties are well aligned with requirements on legged actuation systems; as a result, SEA's have been widely adopted in the fields of legged robotics and human orthotics (Parietti et al., 2011)).

The SEA's components can be chosen and configured in many different ways, producing designs with various trade-offs which affect the power output, volumetric size, weight, efficiency, back drivability, impact resistance, passive energy storage, backlash, and torque ripple of a SEA. (Kong et al, 2009), and (Ragonesi et al., 2011) propose rotary designs based primarily on commercially available off-the-shelf components. (Lagoda et al., 2010) and (Diftler et al., 2011) design a compact rotary SEA using a harmonic drive and a high-stiffness planar spring.(Hutter et al. 2011) use linear springs coupled to rotary shafts between the motor and the chassis ground to achieve compact actuator packaging with low spring stiffness. In (Taylor, 2011), the authors placed the spring within the reduction phase. This arrangement reduces the torque requirement on the spring compared to designs with the spring at the actuator output. (Pratt and Pratt, 1998) propose a prismatic designs which use ball screws as the primary reduction mechanism followed by a cable drive to remotely drive a revolute joint. Ball screws are highly efficient, even for large speed reductions (85–90%), are back

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drivable, are tolerant to impact loads, and do not introduce torque ripple. (Paine et al., 2013) is a good review of some recent progress in series elastic actuators. In this paper it is presented a different design of a SEA. In order to avoid accidents risks and components contamination, the internal components were encapsulated in a unique hollow tubular structure. That allows substitute the heavy structure of solid steel tubes of the reference model (Pratt et al., 2002), permitting the applications in wearable robots, exoskeletons and prostheses.

Different control architectures have been proposed for controlling series elastic actuators. The variation of controller design is related to the different physical characteristics of the hardware. For example, force can be observed either by measuring spring deflection and applying Hooke's law in (Kong et al., 2010), or by measuring change in resistance, as is accomplished using strain gauges, as shown in (Pratt and Williamson, 1995). If friction and backlash are too large, a pure high-gain PID approach can suffer from stability issues. In order to avoid this issue, (Pratt et al., 2004) suggest using position feedback as the innermost control structure for force control. This idea is adopted in others researches see (Lagoda et al., 2010), treating force control as a position or velocity-tracking problem.

In general, the SEAs can be actuated by electrical source, pneumatic cylinder, hydraulic cylinder. The hydraulic SEA is similar to a SEA with electrical source replacing the electrical source, which is a motor with a recirculating ball screw by a hydraulic cylinder. According (Prat et al., 2002) a hydraulic SEA has high output force with force and position controllability.

In this paper the digital prototyping of a hydraulic SEA is developed. The methodology showed in (Robinson and Pratt, 2000) is used specially to choose the spring stiffness. The dynamic model has to contemplate the hydraulic cylinder internal leakage (Qian et al., 2014) and a PID controller has to be designed by pole placement and phase margin (Tang et al., 2010).

The hydraulic SEA developed here is a contribution for robot's desing for non-structured enviorement, in special for oil and gas aplication since this industry applies robots on drilling platforms which uses the Remotely Operated Vehicle (ROV). The ROVs have two actuators on each ROV manipulator which can be replaced by two hydraulic SEAs for more force with less weight. The impact tolerance provides one of the major advantages of a hydraulic SEA increasing actuator durability and smooth contact which makes the actuator suitable to operating valve. The serial elastic element provides that impact tolerance and it makes the possibility of contact inspection on pipe by spring deflection analysis for example.

2. METHODOLOGY

A basic model of a serial elastic hydraulic actuator has the serial element i.e. a rod with the spring's arrangement and a hydraulic circuit which contains the hydraulic cylinder and the servo valve.

The actuator may be understood as a combination of two parts. The first one is the serial elastic element presented in Figure 1. The other one is the hydraulic circuit which has some alternatives of construction as well.

With the components of the actuator defined, the next step is to select the correct component based on the application. This decision is made defining a condition for this system. In this case the condition was the actuator with an output force up to 5000N.

To achieve the output force required, the springs were selected based on consolidate knowledge presented by mechanical engineering design bibliography. Moreover, the rod had to be able to support the load without buckling. Therefore, the knowledge presented by the solid mechanics bibliography is able to help with the design of the desirable rod by considering the systems behavior with all loads.

A special attention must be given to the actuator's springs because they affect system's impedance and bandwidth. After setting these two parameters, iteration could be necessary to evaluate the desirable spring constant.

Knowing the rod and the spring, it is possible to use the force caused by the spring as the force output of the hydraulic cylinder. This force and the maximum speed of 0.5 m/s (as defined by Robinson and Pratt (2000) led to the selection of the correct cylinder by a commercial catalogue, otherwise would be possible to manufacture a custom cylinder.

After design the parts it is assembled in a digital prototyping environment. The parts are drawn using the Siemens Solid Edge software which allows obtaining inertial properties of the assembly.

The actuator's dynamic model was developed from well-known mass-spring-damping system and the actuator's hydraulic part, which is the most challenging, was developed by all hydraulic system components analysis with linearization and simplification as defined in (Qian et al.,2014).

The PID control was obtained by a method based on pole placement and phase margin as defined in (Tang et al., 2010). After the tuning, the time response and the bode diagram of the system were analysed in order to describe system's characteristics of force control.

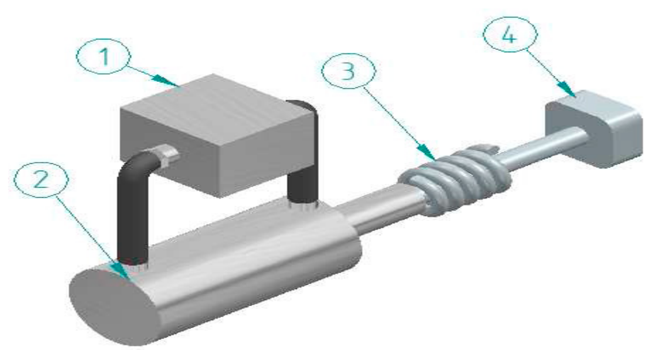

Fig.1. Single rod hydraulic serial elastic actuator schematics: (1) servo valve; (2) hydraulic cylinder; (3) spring; (4) load.