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A COMPARISON BETWEEN SERIES ELASTIC ACTUATORS FOR FOUR LEGGED DYNAMIC ROBOT APPLICATION

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Abstract. *Over the years, machine and drive systems are built to be as stiff as possible to increase bandwidth. The mechanical systems actuators are always rigidly connected to the load. However, the friction effect, impact damage and coupled actuator inertia begun to represent a great problem in some actuator's applications. To deal with these drawbacks, a series elastic actuator (SEA) which contains an elastic element in series with the mechanical energy source was created. 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. These properties allow the SEA to have major applications in dynamic robots. This paper describes a comparison between two types of SEA, an electric serial elastic actuator (ESEA) and a hydraulic serial elastic actuator (HSEA), for four legged dynamic robot application. The parameters employed in the comparison are bandwidth, output impedance, time response, power density, dynamic range. The results indicate the HSEA is the best actuator for a weight carrying four legged dynamic robot because of its higher power density and dynamic ratio with desirable output impedance, time response and bandwidth.*

Keywords: SEA, actuator, force control, dynamic robot

1. INTRODUCTION

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), 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 see (Pestana *et al*., 2010).

The SEA's components can be chosen and configured in many different ways, producing designs with various tradeoffs which affect the power output, volumetric size, weight, efficiency, backdrivability, impact resistance, passive energy storage, backlash, and torque ripple of a SEA. (Curran and Orin, 2008) propose rotary designs based primarily on commercially available off-the-shelf components. (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 (Kong *et al*., 2012) the authors place 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 backdrivable, 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 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 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 this paper, it was adopted such idea to develop the propose SEA controller.

In general, the SEAs can be actuated by electrical source, pneumatic cylinder, hydraulic cylinder. This 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 (Pratt *et al*., 2002) a hydraulic SEA has high output force with force and position controllability.

An application for serial elastic actuators is on robot links to improve its operation on non-structure environments. The SEA on the robot link can increase the shock tolerance, error rejection, low impedance and large dynamic range. Over the years many SEA were applied on robot links. (Brooks *et al*, 1999) applied a SEA on the COG robot which is a humanoid robot with torso and head. This robot has SEA on its arms and it gives the capability for hammering and turning cranks. (Robinson *et al*, 1999) developed the M2 which is a bipedal robot. This robot can walk on different conditions of terrain. The corndog was developed by (Krupp, 2000) which is a planar running robot.

In this paper a comparison between electric SEA and hydraulic SEA is developed. The HSEA's 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 (Tang *et al*.,2010). The ESEA developed by (Bento Filho *et al.*, 2014) is applied as basis of comparison. The comparison is made to decide the best serial elastic actuator for the implementation on a weight carrying four legged dynamic robot.

2. HYDRAULIC SERIES ELASTIC ACTUATOR

2.1 HSEA model design

The design of the hydraulic series elastic actuator can be divided in simple steps, presented in our previous work (Leal Junior et al., 2015):

Step 1: Select components of hydraulic part of the system, serial elastic element's components, specially the springs.

Step 2: Draw and assemble all the parts with Siemens Solid Edge.

Step 3: Develop actuator's dynamic system and apply it on Matlab/Simulink.

Following these steps, the actuator has the maximum output force with the most compact design. Also all the internal components are enclosed to avoid accidents, components contamination and make the actuator suitable to human interaction.

Figure 1 shows the prototype of the actuator. There is a hydraulic cylinder (1) that moves forward and dislocates the movable rod (2) fixed in it with a screwed connection. The model has two guides (6) and (8) fixed on the base tube and one guide (7) fixed on movable rod (2). There are two springs (4) and (5) fixed between the guides. A connection guide (10) is used to connect the hydraulic cylinder rod (1) to the base tube (3). The load terminal (9) is also connected directly on the base tube (3). The encapsulation tube (12) is the last part of the assembly. It is connected on the hydraulic cylinder (1) and base tube (3). A guide bolt (11) was applied to make the connection between the base tube (3) and the encapsulation tube (12), but without interfere on the base tube's (3) linear movement.

There are four guides (6), (7), (8), and (10) in this actuator model. The application of the four guides is to give to the system the necessary stability. Without the guides the movable rod (2) would oscillate creating additional forces on the springs instead of only an axial force. Moreover, the load terminal is connected with the base tube only.

The springs are responsible to the hydraulic SEA stiffness reduction. However this component has to be carefully assembled since it will stretch and compress depending on the movement of the actuator and the load attached to it.

Figure 1. HSEA's components: (1) hydraulic cylinder; (2) movable rod; (3) base tube; (4) and (5) springs; (6), (7) and (8) guides; (9) load terminal; (10) connection guide; (11) guide bolt; (12) encapsulation tube.

The prototype shows outstanding characteristics of output force and compactness. These characteristics are listed as follows:

- 200 mm length when retracted;
- 100 mm range;
- Maximum diameter of 26 mm;
- Maximum output force up to 4.9 kN;
- 100 bar of working pressure;
- Model structure material of carbon steel;
- Speed up to 5 cm/s;
- Estimated weight without hydraulic fluid of 1.5 kg.

2.2 HSEA dynamic model

Several assumptions had been made in this model according (Qian *et al*.,2014):

- Fluid properties are constant;
- Servo valves are not saturated;
- Supply pressure is much greater than the load pressure;
- Friction force can be modeled as viscous damping;
- Main stage spool opening is proportional to pilot stage flow.

Figure 2 presents the closed loop transfer function block diagram for the dynamic model. The controller was tuned by applying the pole placement and phase margin method (Tang et al., 2010) and achieves a robust control with large bandwidth.

Table 1 shows the parameters value of the entire system.

Table 1. HSEA's system parameters

Parameter	Value
Area (A)	4.91E-04 m^2
Damping (C1)	18.4 Ns/m
Mass (M)	1.5 kg
Bulk modulus (B)	1.23E+09 Pa
Leakage Coefficient (Cl)	2E-06 m^3s/kPa
Fluid volume (Vt)	2.60E-05 m^3
Load stiffness (KL)	3.30E+09 N/m
Load damping (CL)	8.08 Ns/m
Inner loop gain (Kp)	8.40E+02 s^{-1}
Valve pressure gain (Kc)	4.00E+06 m^3s/m
Valve flow gain (Kv)	6.24E-05 m^3s/m
Servo valve time constant (t)	0.0015 s

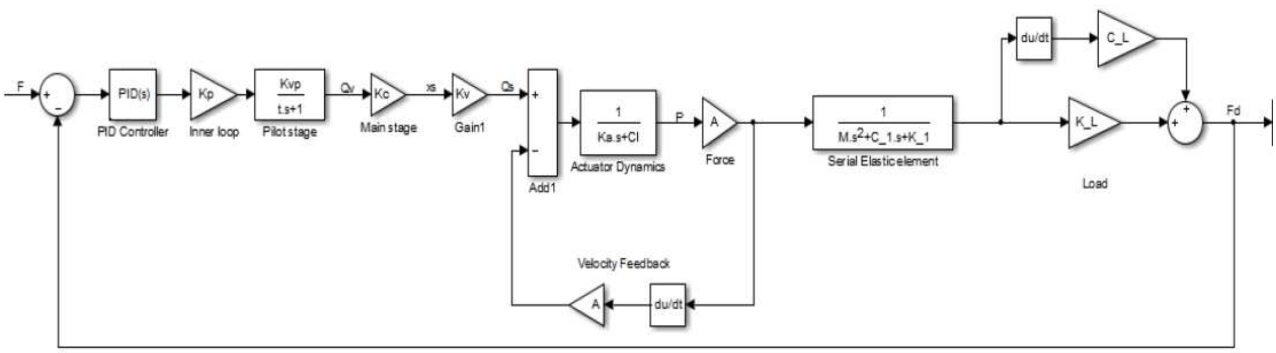

Figure 2. HSEA's closed loop transfer function block diagram

3. ELECTRIC SERIES ELASTIC ACTUATOR

3.1 ESEA model design

The ESEA presented here was developed in (Bento Filho *et al*., 2014). The characteristics desired for the actuator are enclosed internal components to avoid component contamination and accidents risks; size adequate for wearable robots, exoskeletons and prostheses applications, emulating natural muscles; Aesthetically suited to applications in wearable robots, exoskeletons and prostheses; Smart enough for applications in unstructured environment and four legged dynamic robots.

The actuator has a moving sub assembly connected to the planetary gearbox, and the ball screw which converts torque in force. The DC motor is a 60 mm, brushless, 400W and generates the torque; the gearbox is a planetary gearhead 62 mm diameter, 8-50N.m torque and the ball screw is a 10mm diameter and 3mm pitch rolled steel.

Figure 3 shows the actuator final design. The interactive digital prototyping design process done results in a set of desirable characteristics for the actuator, as follows:

- 425 mm long when retracted, with 130 mm range;
- Maximum diameter of 60 mm;
- Maximum load capacity up to 450 N;
- Standard rolled ball screw 10 mm diameter, 3 mm pitch;
- Main model structure of drawn carbon steel or aluminum alloy tubes;
- Estimated final weight of 3.70 kg;
- Estimated continuous speed: 13.40 cm/s;
- Operating voltage: 48 V.

3.2 ESEA dynamic model

The dynamic model of the actuator was constructed from the digital prototype data to run a simulation in order to verify its dynamic behavior, bandwidth and validate the project settings.

The actuator dynamic model equations are described with well-known DC motor equations and Newton's second law. Once described the actuator dynamic model equations, the closed loop PID transfer function block diagram in the frequency domain can be made, as shown in Fig. 4. The PID controller was tuned by applying pre-programmed Matlab routines.

Table 2 shows the parameters of the system.

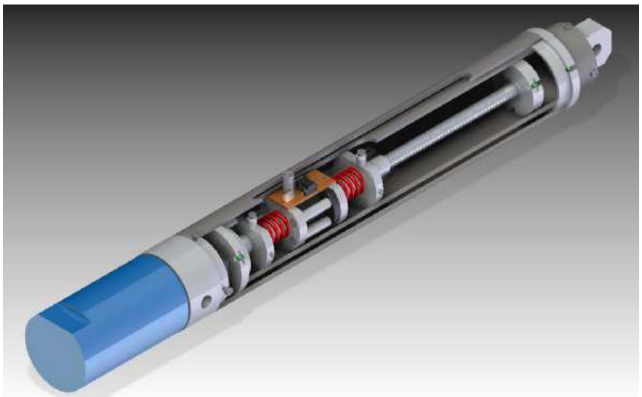

Figure 3. Electric SEA final design.

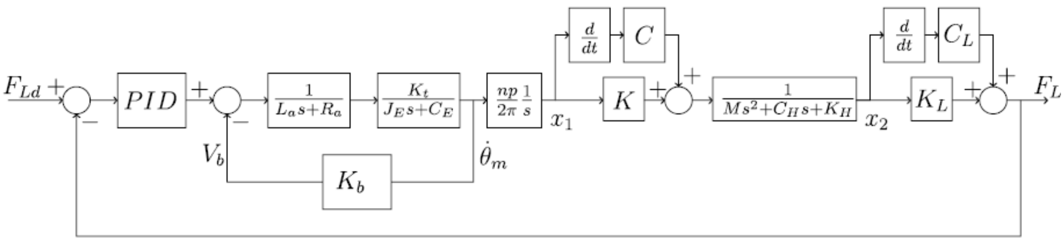

Figure 4. ESEA's PID closed loop transfer function block diagram.

Table 2. ESEA's system parameters.

Parameter	Value
Armature inductance (La)	8.2E-4 H
Armature resistance (Ra)	1.03 Ω
Back-EMF constant (Kb)	1.469E-1
Torque proportional constant (Kt)	1.470E-01
Movable arm sub assembly mass (M)	1.261 kg
Load interface viscous friction coefficient (C_L)	80.8 kgm/s
Load interface elastic constant (K_L)	3.3E6 N/m
the linear displacement of the movable arm reflected to motor axis rotation ($\frac{np}{2\pi}$)	4.7746E-6 m
Sub assembly inertia (J_E)	9.51E-5 kgm^2
Sub assembly viscous friction coefficient (C_E)	4.594E-5 kgm/s
Movable arm viscous friction coefficient (C_H)	81.6 kgm/s

4. RESULTS AND DISCUSSION

The two SEA presented in previous sections are compared based on the key parameters of the serial elastic actuators which are bandwidth, output impedance, time response, power density, dynamic range.

The spring stiffness affects all parameters presented above. In order to evaluate the differences between the two systems with the same parameter for the compliant sensor, the spring stiffness is 3.336E+03 kN/m for both actuators.

4.1 Bandwidth

Figure 5 shows the HSEA and ESEA Bode diagram which allows evaluating the two systems closed loop force bandwidth.

The ESEA frequency band is about 40Hz with a phase angle of 90º which is quite high. On the other hand, the HSEA has 30Hz but the phase angle is about 55º which is more appropriate for practical applications. Since a four leg robot works on small bandwidths, the smaller bandwidth range of the HSEA is not an issue for this application. In addition the two actuators present resonance frequency above 100Hz which is far enough of the required frequency.

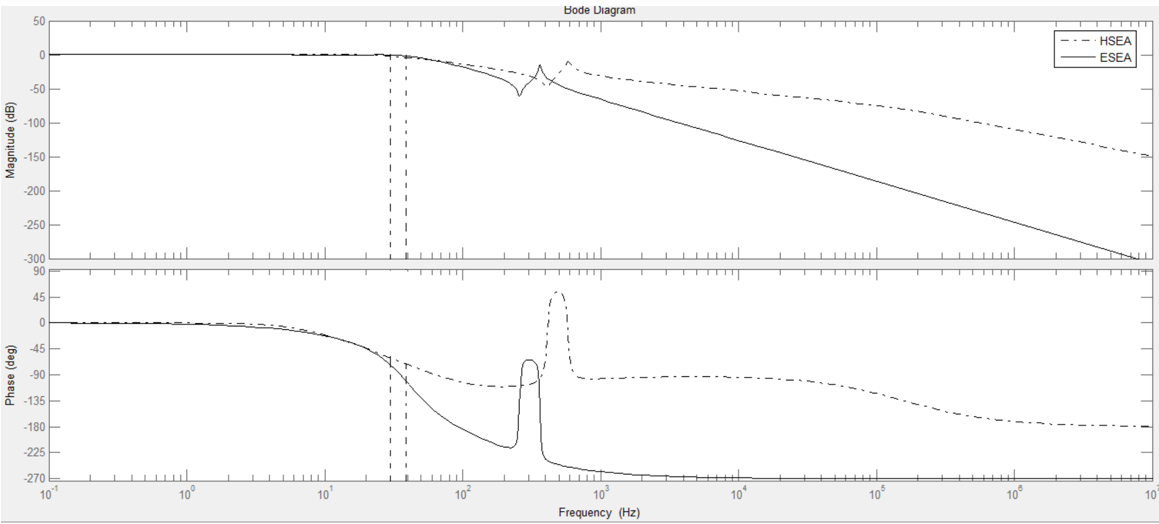

Figure 5. Closed Loop Bode diagram

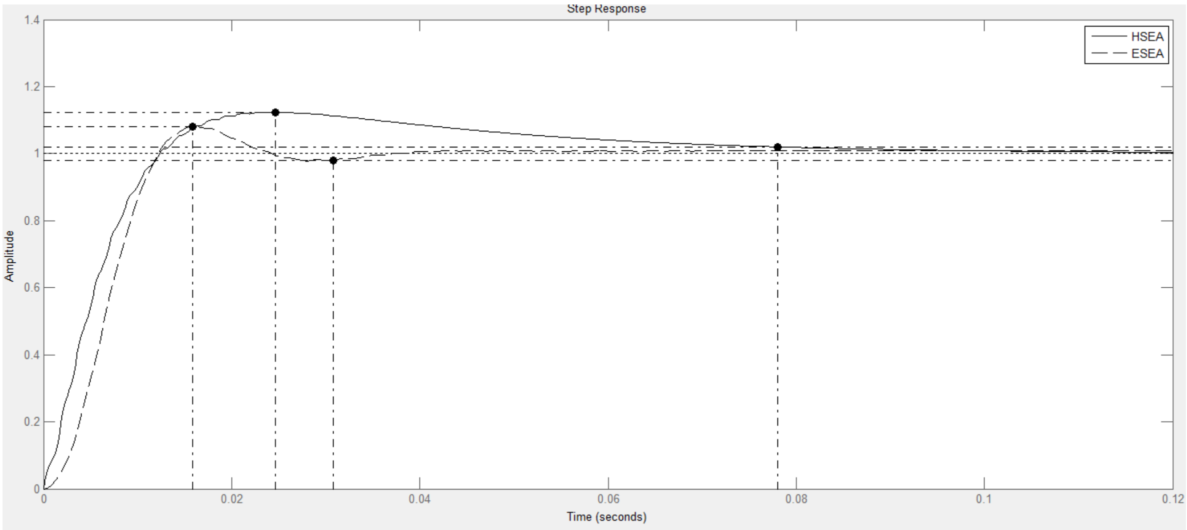

Figure 6. Time response of the actuators.

4.2 Time response

The time response for a unitary desired force is given on Fig. 6. ESEA shows an 8% overshoot and it settling time is 0.03 seconds which is very fast. While HSEA has an overshoot about 12% and a settling time of 0.07 seconds. Although HSEA has larger overshoot and settling time than ESEA, these two parameters are compatible with the reference works results (Paine *et al.*, 2013), (Robinson, 2000). Therefore, even in the HSEA case the settling time is tolerated.

4.3 Output Impedance

Since output impedance is the force at an actuator output given a moving load position, the impedance analysis was made by setting a load position with a constant desired force. An ideal actuator has zero impedance. In other words, the actuator is a pure force source. If this happens, the dynamics of the actuator are completely decoupled from the dynamics of the load motion (Robinson, 2000).

Although the compliant element of the series elastic actuator limits the bandwidth, it reduces the output impedance which is desirable for any actuator application (Pratt *et al.*, 2002).

Nevertheless, the two actuation systems have the same spring stiffness. Therefore the differences between the systems output impedance are due to the actuator's moving system which are the motor with gear reduction for the ESEA and for servo valve with hydraulic piston for the HSEA (Robinson, 2000).

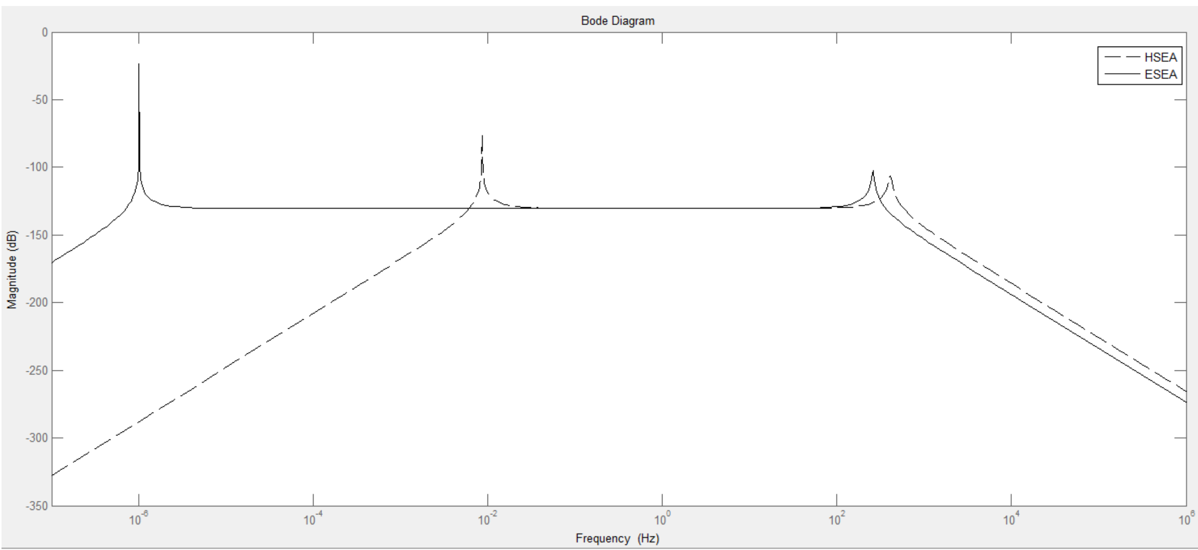

Figure 7. HSEA and ESEA output impedance.

Figure 7 shows the output impedance for both hydraulic and electric sources. The output impedance of the serial elastic actuator is small at low frequency and it achieves the spring stiffness magnitude (which is -130dB for the spring previous selected) when the frequency rises. This behavior was proved by simulations and physical SEA experiments (Robinson, 2000).

Because the both systems have the same compliant element, it achieves the same value with frequency increase. So the difference on the impedance is given by the curve slope. Examining the slope of the both curves, the HSEA has the smallest value of the impedance when the frequency increases. It can be seen two peaks of the magnitude, the first one due to controller gains and the second occurs in the systems resonance frequency.

4.4 Power density

Power density is the actuator power per mass unit. High power density actuators can delivery great power with a small package. It prevents over-burdening the actuator structure with excessive mass allowing a responsive robot performance. The lightweight structure with a quick performance is very important for a weight carrying dynamic robot because it provides a compact robot which is suited to a non-structured environment and has a great output force.

As shown in previous section, the hydraulic serial elastic actuator has more output force than the electric SEA. Moreover the ESEA is heavier than the HSEA.

The output force of the HSEA is 4.9kN and it weighs 1.5kg given the velocity of 0.5m/s, the HSEA has a power density about 1600W/kg which is a great performance. On the other hand, the ESEA has 450N of output force and weighs 3.7kg. The ESEA is also slower than HSEA, the electric SEA velocity is 13.4cm/s which gives a power density of 16W/kg. This result shows a poor performance of ESEA for weight carrying dynamic robot.

Even though the HSEA mass applied on the power density calculation did not include the mass of servo valve, reservoir, pump, hoses and pipes which are heavier than the ESEA batteries that also are not included on the electric SEA mass. The HSEA still has way more power density even with these items included.

4.5 Dynamic Range

Dynamic range is the ratio between the maximum output force and the minimum resolvable output force. It gives quantitative information of how sensitive the actuator is with respect of its maximum output force capability. It is a crucial parameter for dynamic robots because it allows the actuator to be used in sensitive activities such as human contact, equipment operation, non-structured environment exploration. Also the actuator with great dynamic range can do hard work activities such carrying, push or pull weights. In summary, high dynamic range is an important characteristic for the four legged dynamic robot application.

The minimum resolvable output force is evaluated by the resolution of the spring deflection sensor. Resolution gives the minimum spring deflection that can be detected. This deflection times the spring stiffness gives the actuator minimum resolvable force.

The both SEAs have the same spring stiffness in this comparison. Also, both actuators have the same spring deflection sensor which is a linear encoder. Therefore the minimum output force is the same for both which is 3N.

The HSEA dynamic range is 1500:1 while the ESEA range is 150:1. It shows that the hydraulic SEA has a range ten times bigger than electric one.

5. CONCLUSIONS

This paper presented a comparison between the two series elastic actuator (electric SEA and hydraulic SEA) for four legged dynamic application. The actuators were digitally prototyped in Universidade Federal do Espírito Santo (UFES). The comparison was made considering actuator's bandwidth, output impedance, time response, power density, dynamic range.

Although the ESEA has a better time response, both actuators have its responses within desired range for a dynamic robot application. The bandwidth also is not a problem for both actuators because all systems examined have large bandwidth compared with the given application. HSEA and ESEA presented good output impedance with a slightly better behavior from hydraulic SEA. Both actuators have two peaks on the output impedance, one peak due to controller gains and another due to the resonance frequency of the system.

Power density and dynamic range are the two key parameters that differs the weight carrying dynamic robot application from others dynamic robots applications. In these two parameters the HSEA showed a better performance than ESEA. The HSEA's power density is 100 times higher than the ESEA's. Moreover the dynamic range of hydraulic SEA is 10 times higher than the electric SEA dynamic range.

In summary, this paper presents the characteristics of a serial elastic actuator for a four legged dynamic robot application. The results showed the HSEA as the better serial elastic actuator for this task and it can contribute for the research of SEA applied on robot links.

Further work is a simulation of SEA, specially the HSEA, on a dynamic robot. With this simulation the advantages and drawbacks of the implementation can be analyzed and quantified. Also a construction of a real aluminum alloy based prototype and in testing its performance in a real time environment for evaluating the actuators performance under force, position, velocity and mixed controllers; development of tuning strategies between the spring stiffness – actuator bandwidth and elastic energy store relationship.

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