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A METHOD TO ADD ENERGY TO RUNNING GAIT - POGOSUIT

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ABSTRACT

The human body is a mass spring system that oscillates up and down while running. We add energy to the running gait by oscillating a secondary mass in phase with the motion. A phase oscillator adds a bounded amount of energy to the limit cycle to make it easier to run. In an anti-phase oscillator, energy in the gait cycle is reduced and it is harder to run

INTRODUCTION

Control systems are needed to add energy and assist body motion in areas such as powered orthotics, prosthetics, and exoskeletons [1-9]. Systems can add energy based on negative damping [1], patterns based on phase angles [10, 11], and impedance control [12]. We developed a method to add energy to assist motion based on a phase angle.

1. The system adds a bounded amount of energy to create an oscillatory type of motion.
2. The control method has been shown to work on linear and rotary mechanical systems
3. An oscillating mass has been built and demonstrated using this new control method.

BACKGROUND

A standard, second order, mechanical system equation is given: m represents the mass, b represents the damping, k represents the stiffness.

$$m\ddot{x} + b\dot{x} + kx = 0 \tag{1}$$

Groups have added negative damping to the system to force the system to move, but the negative damping can become unstable because $c\dot{x}$ grows as the velocity gets larger.

$$m\ddot{x} + b\dot{x} + kx = c\dot{x} \tag{2}$$

We decided to add energy to the mechanical system by using a "phase oscillator". We use the sine of the phase angle, ϕ. In figure 1, the phase angle, ϕ, is defined.

$$m\ddot{x} + b\dot{x} + kx = c\sin(\emptyset) = \frac{c\dot{x}}{\sqrt{\dot{x}^2+x^2}} \tag{3}$$

If c is positive, the system oscillates back and forth. The energy is always bounded because as $\dot{x}$ gets large in the limit, the numerator and denominator cancel and just equal c, see figures 2 and 3.

If c is negative, the energy is damped, and the system state goes to zero, see figures 4 and 5.

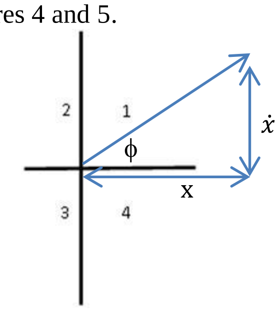

Fig. 1: Phase plot definition, horizontal axis is the position, x, and the vertical axis is the velocity, $\dot{x}$. The sine of the phase angle phi is given by the opposite over the hypotenuse. The hypotenuse is given by $\sqrt{\dot{x}^2 + x^2}$

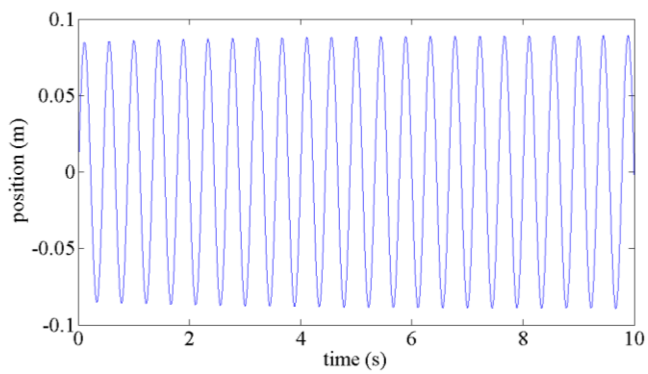

Fig. 2: The system position oscillates back and forth. m = 1 kg, k = 200 N/m, b = 0.6 Ns/m, c = 0.6. Initial velocity = 1.2 m/s, initial position = 0 m.

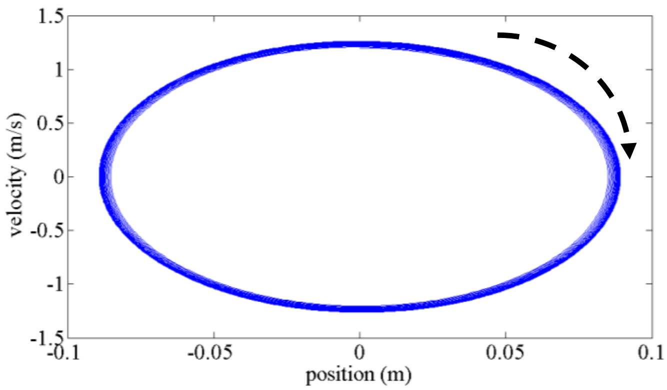

Fig. 3: The phase plot demonstrates a limit cycle as the system position oscillates back and forth. *m* = 1 kg, *k* = 200 N/m, *b* = 0.6 Ns/m, *c* = 0.6; Initial velocity = 1.2 m/s, initial position = 0 m.

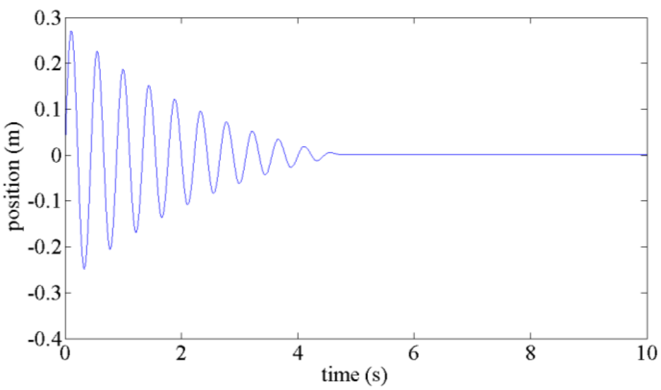

Fig. 4: The system damps to zero. *m* = 1 kg, *k* = 200 N/m; *b* = 0.6 Ns/m, *c* = -0.6. Initial velocity = 4 m/s, initial position = 0 m.

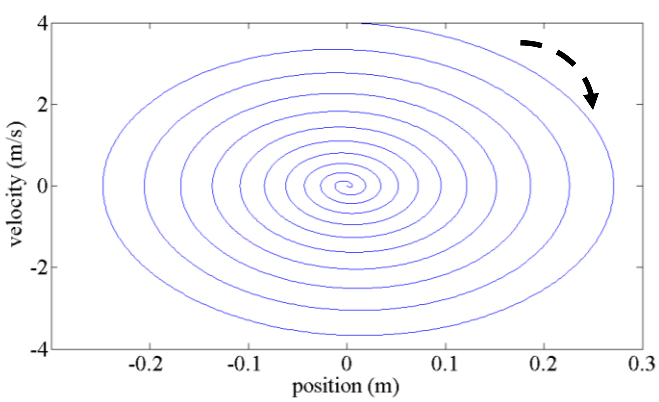

Fig. 5: The phase plot as the system position and velocity return back to 0. *m* = 1 kg, *k* = 200 N/m, *b* = 0.6 Ns/m, *c* = -0.6. Initial velocity = 4 m/s, initial position = 0 m.

In a simulated example, an external force is applied to a hopper based on the sine of the phase angle. The external force allows the system to oscillate up and down. The hopper has a mass of 80 kg and the leg stiffness and damping parameters equal 160,000 N/m and 4 N/(m/s) respectively. The leg stiffness and damping are only active when the hopper hits the ground and the leg is compressed. An external gravity field is present and drag reduces both the upward and downward velocity. Lastly, an external force is applied to the hopper based on sine of the phase angle.

$$m\ddot{x} + (b\dot{x} + kx) * e(t) + mg + D = c\sin(\emptyset) = \frac{c\dot{x}}{\sqrt{\dot{x}^2+x^2}} \quad (4)$$

$$e(t) = 1 \; when \; x < 0 \; and \; 0 \; otherwise \quad (5)$$

$$D = 0.5\rho C A v^2 \quad (6)$$

In the simulated example, *c* = 0.5, *m* = 80 kg, *b* = 4 N/(m/s), *k* = 160,000 N/m, ρ = 1.18 kg/m^3, *C* = 1, and *A* = 0.09 m^2.

The limit cycle is robust and a wide range of initial conditions converge to the hopping cycle defined by the constant *c*. The system oscillates up and down, see figure 6. The phase portrait of the system is shown in figure 7.

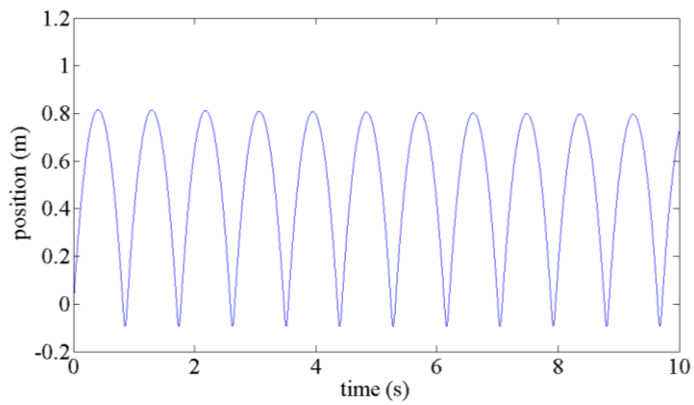

Fig. 6: The system oscillates up and down.

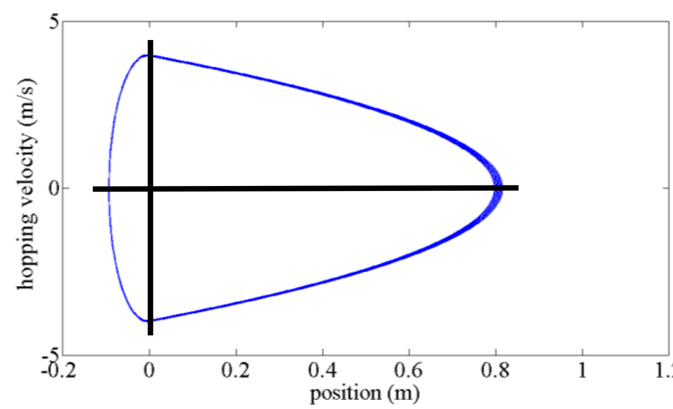

Fig. 7: The phase portrait of the system. To left of the vertical axis at 0, the hopper is touching the ground and the leg spring is compressed. To the right of the vertical axis at 0, the hopper is in the flight phase.

The damping of the leg and the air drag creates forces to slow the system down while the external force created by the sine of the phase angle assists the movement of the system. The external force created by the control signal (sine of the phase angle) is shown in figure 8.

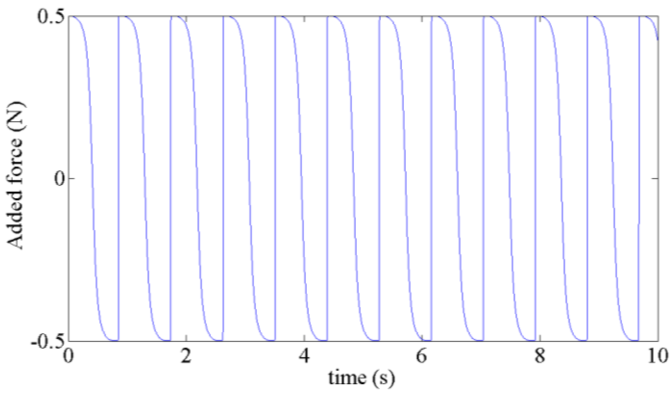

Fig. 8: The control force is continuous and is generated by the sine of the phase angle.

DEVELOPING A POGOSUIT

Our goal is then to enhance hopping by applying an external force based on the sine of the phase angle. We generate an external force by oscillating a secondary mass. The reaction force caused by accelerating the secondary mass creates the external force.

The leg of the human body can be assumed to be a pendulum-like structure with inertia, damping, and a spring stiffness [13-15]. To enhance the hopping motion, a parametric excitation force can be added. The direction of the force must be switched at the correct timing and frequency and should be tuned with the hopping frequency. A phase oscillating term based on the phase portrait determines the desired external force to add positive power to the system, see figure 9.

In figure 9, the phase portrait of a mass-spring-damper hopping model is shown. The hopping velocity is on the vertical axis and the hopping height is on the horizontal axis. The external force adds energy to the hopping cycle increasing the hopping height as the phase cycle increases to the right. The sign of the velocity and external force is given for each of the four quadrants.

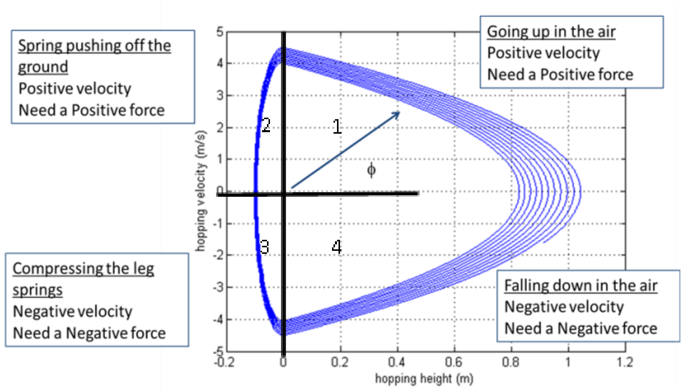

Figure 9: For hopping, the direction of the force is positive in quadrants 1 and 2 and it is negative in quadrants 3 and 4.

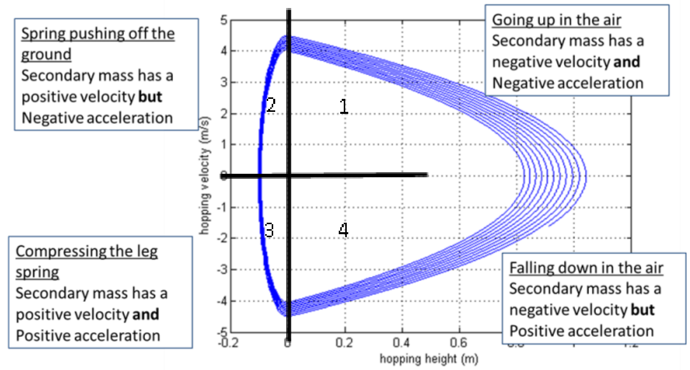

Figure 10: For hopping, the acceleration of the secondary mass in quadrants 1 and 2 is negative and it is positive in quadrants 3 and 4.

In figure 10, a secondary mass is oscillated up and down to create an external force acting on the primary mass, the trunk of the human. The secondary mass is accelerated up and down by a motor or a pneumatic cylinder. The reaction force to hold the motor in place creates the external force. If one runs with a non-motorized backpack, the weight oscillates up and down with incorrect phase and hinders the running motion. On the other hand, if the weight is oscillated based on the phase angle in the phase portrait, the running motion is enhanced due to energy pumping.

A small oscillating mass adds small positive power to the hopping motion enhancing hop height response. In a counter example, if the oscillating mass is moved in an anti-phase motion, the hop height is decreased and a resistance training device or “absorber/brake” is created.

A powered PogoSuit has been designed and built to enhance hopping, see figures 11 and 12. The control torque signal is used to trigger pneumatic valves or oscillate a motor to create a force at the trunk. One accelerometer is placed at the waist above the waist belt to determine the vertical acceleration of the trunk. The signal is pseudo-integrated to determine the trunk velocity and pseudo-integrated a second time to determine position. The sine of the phase angle is determined using the trunk position and velocity.

In one demonstration, hop height was increased by over four inches, see Figure 13.

The exoskeleton can seamlessly assist walking, running and the transitions from walking to running and back to walking. The seamless transitions are possible because a continuous control signal is generated and used as a triggering mechanism.

In the first year of work, preliminary testing was performed on the PogoSuit, see Table 1. Metabolic cost associated while running with a 5 kg powered-device was comparable to running with no device. This significant result shows that one can design a “metabolic augmentation device,” a device that does assist gait. When the device was turned off, the added 5 kg increased the metabolic cost by 9.3%. When the device motion is reversed resisting the movement of the user, the metabolic cost increased by 26.5%.

The goal of this work will be to design and build a mechanism to oscillate a large backpack (45kg) a very small amount (12.7 mm amplitude).

Table 1: Metabolic Cost when running with the PogoSuit on a Treadmill, Pilot work, one person, one trial

Test	Metabolic Cost
1. Running with No Device at 6 mph	30.1 mL.kg-1.min-1
2. Running with PogoSuit Powered On (additional 5 kg)	30.7
3. Running with PogoSuit Powered Off (additional 5 kg)	32.9 (9.3% increase compared to 30.1)
4. Running with PogoSuit Powered in Reverse	38.1 (26.5% increase compared to 30.1)

We have provisionally patented the idea of a PogoSuit. We are aware of the patents by Lightning Packs LLC. We believe that our methods are a similar but the idea is flipped. We are purposely trying to use energy from a battery to oscillate the backpack and give it to the user to reduce metabolic cost. On the other hand, they are trying to reduce backpack oscillations by harvesting energy for later use. We feel that these technologies are compatible and synergistic. Our method could be used to pump energy into the soldier when they are tired and their method could charge batteries when walking down hill for example.

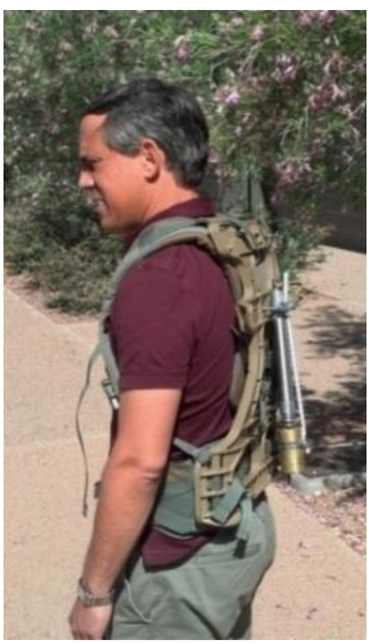

Fig 11: A powered PogoSuit is used to assist the hopping motion. A pneumatic cylinder oscillates the small mass up and down in phase with the user.

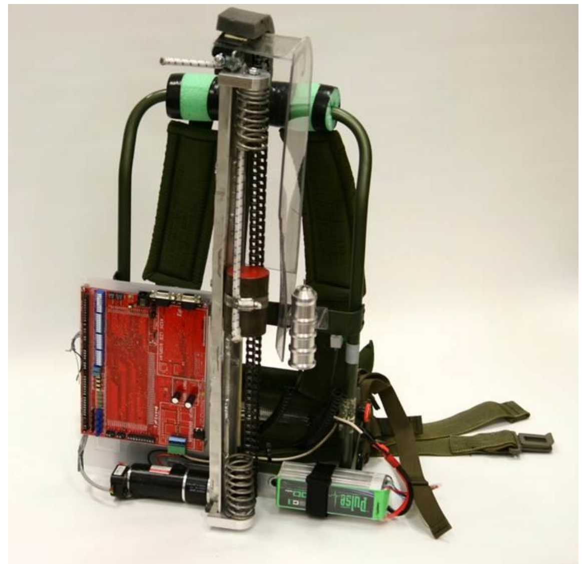

Fig 12: A powered PogoSuit is used to assist the hopping motion. A motor oscillates a mass up and down in phase with the user.

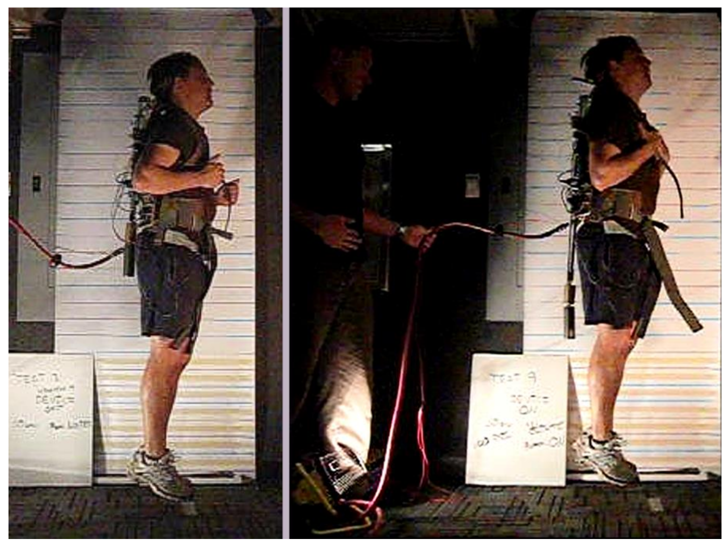

Fig 13: A powered PogoSuit is used to assist the hopping motion. Jump height increased 4 inches or 10.2 cm.

CONCLUSION

Our goal has been to develop a method to assist the hopping motion while walking and running. We developed a phase oscillator to develop a control signal that is bounded and creates a limit cycle. The control signal is small and oscillatory in nature that cancels out the damping in the system. The signal is continuous and is used to trigger the linear actuators in our PogoSuit.

The future goal is to design a powered backpack to assist load carriage.

DISCLOSURE

Matthew Holgate works at SpringActive, Inc., and Thomas Sugar is a part-owner of the company. A provisional patent application and a patent application on the phase oscillator have been filed. The application includes the design of an active backpack to assist load-carriage and pump energy into the gait cycle.

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