Biomimetic Hopping Strategy for Robots

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Abstract: In this paper, we present biomimetic hopping strategy which is more human-like for legged robot through stiffness modulation. Stiffness value is calculated from the motion of body center of gravity. This method enable to reduce impact force on touch-down, adaption on ground stiffness change and height modulation. Simple selected models will be used to validate this method. For general model, singular perturbation is used for control and simulation using stiffness modulation is presented.

Keywords: biomimetic, hopping, stiffness

1. Introduction

Humanoid robot research is one of the most interested areas to robot engineers these days. Until now, rapid improvements of humanoid technology makes it possible that humanoid can walk, go up and down stairs, co-work with human, and do hazardous work instead of human. Nowadays humanoid researchers endeavor to improve the humanoids which can do work more independently and move faster.

Technologies being developed and has been developed to make faster humanoid are divided into hardware and software area. Hardware design for walking and running has been totally different. Most of the walking robots have been constructed using motor and gear combination and most of them are directly connected to the joint without elastic material(Of course, there are some designs which have visco-elastic material in joint, but it is not enough for running or hopping). Hopping robot designs have been also different from those of walking. Most of them have telescopic legs and use pneumatic actuator. Recently, researches on legged hopping robot have been done in some papers [1, 2]. (There is also typical walking robot that has hardware design enough for running or hopping [3]).

Software Strategy is also different between walking and hopping. Most of walking robots use ZMP(Zero Moment Point) trajectory for dynamically stable walking, but hopping robots use COG(Center of Gravity) path planning to jump enough height or prevent flip-over . Anyhow, for legged(not telescopic) humanoids to run or hop, we must explore new way such as new actuator, new design or new control strategy, different from previous.

Research about the locomotion of human and robot has been developed in biomechanics and robotics respectively. And main idea of paper is biomimetic approach and comes from biomechanics field. Common problem for locomotion of human or robot is impact during gait change or landing motion. In biomechanics point of view human reduces effect from impact by two ways of motion. One is retracting his body when he touches down on landing, the other is reducing approaching speed for ground(obstacle). But how do we plan a path for contracting our body? What is his consistent strategy for action? In biomechanics, human hopping or jumping is described using variation of his leg(body) stiffness [4]. When human hops continually, leg stiffness value increases from touch-down to take-off with same initial value on every instant.

Below equation is for leg stiffness of human body(leg) when he modulates its value.

$$k_{leg} = \frac{F_{peak}}{\Delta L} \tag{1}$$

(F_{peak} : peak reaction force in the force platform when human jumps onto that, ΔL : vertical displacement of body center of mass)

Human also uses this leg stiffness modulation on terrain adaptation. It is known that human makes a stiffness adaptation according to change in terrain condition [5]. In this paper, we apply this fact(stiffness modulation) to robot hopping through simulations and verify its effectiveness.

This method uses not only passive compliance through materials(rubber, spring, etc) which is used in previous ways, but also active structure compliance to come over initial impact by reducing its stiffness and provides methodology for continuous hopping. This paper is composed of simulation through stiffness modulation about simple models.

In Section 2, we will select one model for hopping and try continuous hopping using simplified model. In Section 3, we will develop control method about selected design and explore the method about applying stiffness modulation method to general legged robot. And finally, we will provide summary of this paper.

2. Hopping through Stiffness Modulation

2.1. Simple Model Application

In this section, we propose a biomimetic hopping control method, the stiffness modulation which was found in biomechanics. By modulating spring stiffness character, we can take advantage in reducing impact force. Until now, most of the hopping strategies have origin on Raibert's method [6] that one calculates energy at the lowermost point and compensates energy difference between desired and present energy level. Here, we propose a strategy named stiffness modulation method(STIMM). Here, stiffness means the whole system's spring-like fashion behavior in vertical direction. By stiffness modulation, we can make the system behave like the one which has less or more spring constant than its original one. In other words, less spring constant means lowering the center of gravity of system more rapidly as if it has low stiffness character. But initial impact peak force is not reduced if the legged system was not contracting before impact(This part is not treated in this paper). After the first peak, the second peak force(not a second contact) can be

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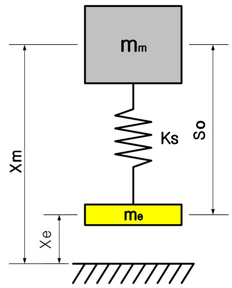
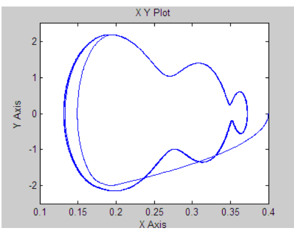
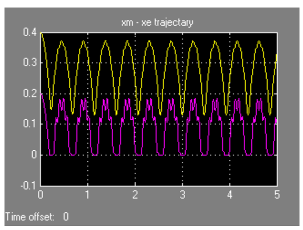


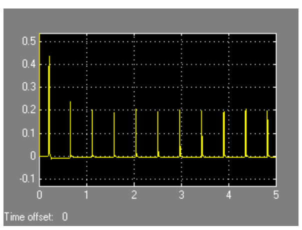
Fig. 1. Simple model for stiffness modulation - Model I



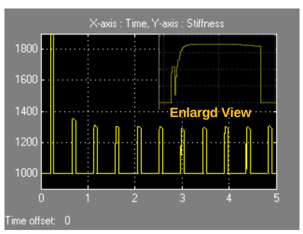
(a) Limit cycle behavior, x_m vs $\dot{x}_m$



(b) x_m, x_e continuous hopping graph



(c) Energy difference, Initial - Present



(d) Stiffness modulation result

Fig. 2. Stiffness modulation simulation

reduced because of low stiffness behavior through stiffness modulation. This method also uses energy compensation philosophy like Raibert's. But it is more advantageous to controlling robot's hopping or running behavior because this method can handle impact situation actively. Let's think of simple model(Fig 1) composed of two masses and spring between them. By modulating spring stiffness k_s, continuous hopping can be possible (Ground is spring-damper modelling). Controller(Eq. (2)) for energy compensation, is a simple PI-type(I-control is used for null-out energy difference more rapidly). Suitable choice of gain will produce moderate stiffness increase to compensate energy difference.

$$k_s = K_P(TE_i - TE_p) + K_I \int_{t_1}^{t_2} (TE_i - TE_p)dt \quad (2)$$

(where TE_i : initial total energy, TE_p : present total energy, k_s : spring stiffness, t_1 : impact beginning time, t_2 : impact ending time)

Simulation is performed at 0.4m height, initial x_m(S_0 : 0.2, initial free length of spring). The spring constant is 2000(N/m). It's result is in Fig 2.

2.1.1 Limit cycle behavior

We can identify the limit cycle behavior through stiffness modulation method. Stiffness is controlled only in impact regime and is maintained in flight phase at initial value(Fig 2(d)). Energy is modulated near initial level(Fig 2(c)). If we carefully examine Fig 2(a), we can find out that value of x_m does not get an equal height as initial's. It is because some part of a total energy is transformed into spring potential in the form of vibration. Fig 3 shows total energy and the others(gravity potential energy, kinetic energy and spring potential energy). From this graph, we can identify that energy compensation has been accomplished through stiffness modulation method.

2.1.2 Adaptation during ground condition change

Now, let's check out stiffness change according to the change of ground stiffness condition. In Fig 4, there are graphs of stiffness modulation result with changing ground condition. Ground stiffness value is changed from 3000(kN/m) to 30(kN/m) at 3.0(sec). We can see that terrain adaption is fulfilled through stiffness modulation method. Energy compensation is kept well which we can see in Fig 4(c) and stiffness modulation was performed to adapt to ground stiffness change. It is identified that total stiffness (hopper + ground) is almost same at two different environments, 5589.6(N/m) and 6190.5(kN/m) (the difference comes from damping characteristic of ground model). In [4], there is similar fact from human that "*When human hop in place or run forward, leg stiffness is increased to offset reductions in surface stiffness, allowing the global kinematics and mechanics to remain the same on all surface*" and "*The total stiffness of the series combination of the legs and the surface remains the same regardless of surface stiffness*". Using same strategy with human, hopper is adapted to ground stiffness change. In Fig 5(a), hopping height is changed during ground adaptation. It is because vibration is reduced as the ground is changed more softly(Fig 5(b)).

2.1.3 Impact force reduction

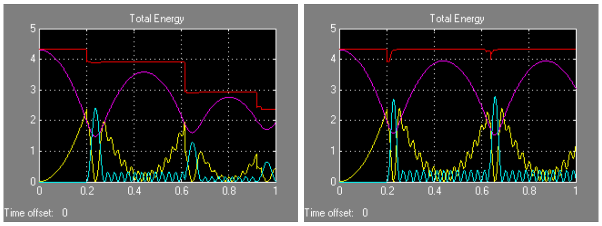
Ground reaction force can be reduced through stiffness modulation method. Fig 6 is the simulation result with respect to change in initial spring stiffness value(the value that system has before impact). Fig 6(a) & (b) are results of 2(kN/m) in initial spring stiffness value and Fig 6(c) & (d) are for the 4(kN/m) value. For low initial spring stiffness case, initial peak and ground force are small compared to the higher stiffness case.

2.1.4 Change in hopping height

We can also identify the changing ability through stiffness modulation method in hopping.

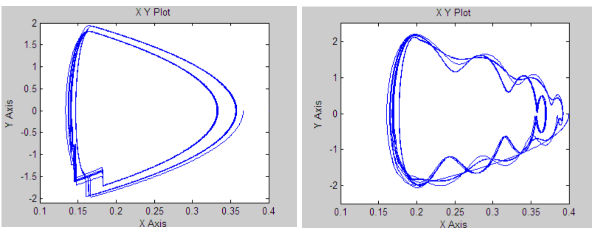
3. Control more realistic model with stiffness modulation method

In this section, we develop an application of stiffness modulation method to more realistic model(Model-II). At first, application model is selected as the one which has all essential elements to construct legged running robot(motor, spring, ball-screw, etc). The model has fixed physical stiffness value in spring and we can not change real stiffness value. So, stiffness modulation method is applied in stiffness modulated fashion. In other words, it moves

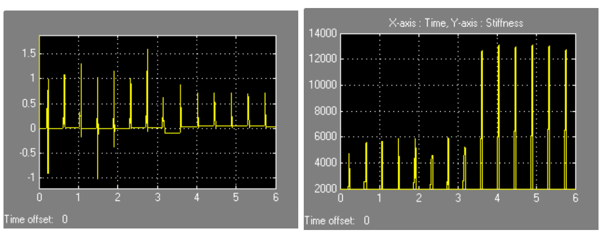


(a) Energy at free fall (b) Energy at modulated

Fig. 3. Energy magnitude comparison

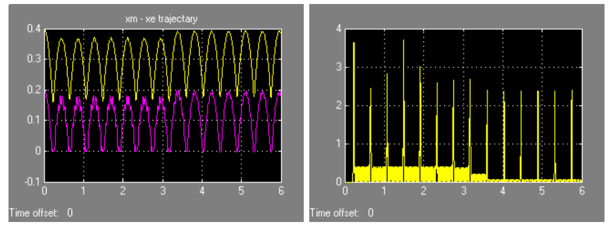


(a) Limit cycle behavior, COG vs COG velocity (b) Limit cycle behavior, x_m vs $\dot{x}_m$



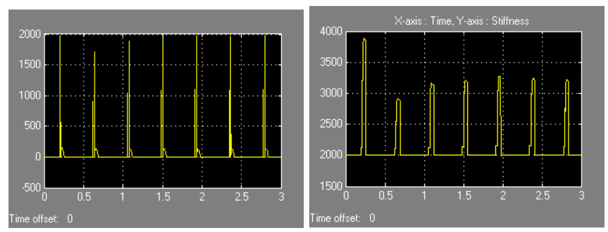
(c) Energy difference, (Initial - Present) (d) Stiffness modulation change result

Fig. 4. Ground stiffness change example

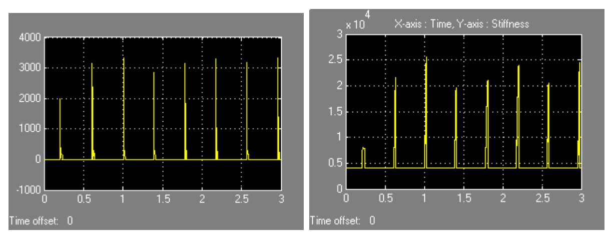


(a) Continuous hopping with changing ground (b) Spring potential energy change

Fig. 5. Varying hopping height



(a) Ground force at 2(kN/m) on initial (b) Modulated spring stiffness 2(kN/m) on initial



(c) Ground force at 4(kN/m) on initial (d) Modulated spring stiffness 4(kN/m) on initial

Fig. 6. Ground force with initial stiffness change

as if it can vary its stiffness value. To control at impact regime, we use simplified model and develop control method for this model because the system of Model-II is similar to the one which has compliant base joint at that time. It is performed through singular perturbation [7] because the system's motion can be analyzed into fast motion in spring due to parasitic parameter and gross(slow) motion of upper mass. From the controller design of simplified model, we apply stiffness modulation method for Model-II.

3.1. Hopping model

In this section, we select suitable realistic model for running or hopping analysis.

To run or hop for legged robot(not a telescopic one), we must consider impact phenomena through a design that can endure and temper the effect from impact in order that the robot can move along its desired motion. General approach for this is attaching passive compliance(damping element on foot or elastic joint mechanism). But most of these approaches are for the slow walking and rarely for running or fast walking which causes large impact force. We need to develop more realistic method or robot structure design which can reduce impact force.

Selected model is shown in Fig 8. It has spring serially connected to motor and ball-screw connection. It is called series elastic actuator [3] and is used several times in hoping analysis in some other papers. Because of spring deflection, we can protect system from damage. Spring force, output force of system can be measured from spring deflection(Spring has a fixed physical value) (B_0 : initial length between x_b and x_e, S_0 : initial length between x_m and x_b)

3.2. Simplified Model Control

Let's think about simplified model to control Model-II which is shown in (Fig 9). This model is composed of two masses and spring on end. In this section, we will try to control with respect to desired x_m signal. Slow variable for singular perturbation formulation is x_m and fast variable is spring force, z. Small variable is selected as an inverse of spring constant($1/\varepsilon^2 = k_s$). Dynamic equation from above formulation is shown below.

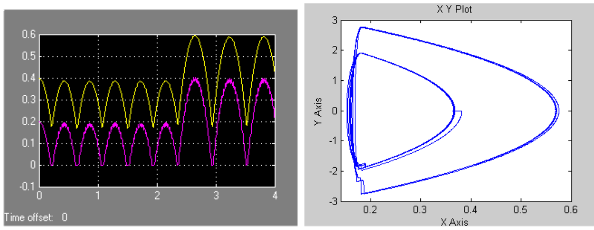
$$\begin{bmatrix} m_m + J_{eff} & -J_{eff} \\ -J_{eff} & m_b + J_{eff} \end{bmatrix} \begin{bmatrix} \ddot{x}_m \\ \varepsilon^2 \ddot{z} \end{bmatrix} + \begin{bmatrix} m_m \\ m_b \end{bmatrix} g + \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_m \\ z \end{bmatrix} = \begin{bmatrix} u \\ -u \end{bmatrix}$$

(J_{eff} : Effective Inertia, $J/k_m/k_m$, k_m : ball-screw constant, $x_m - x_b - S_0 = k_m\theta$, u : torque from motor, g : gravity acceleration)

It is an actuator form that fast variable behavior can determine slow variable behavior, and it is true in this system. This system can be divided into slow dynamics that describes slow motion of mass and fast dynamics for fast motion of spring. If we make $\varepsilon \rightarrow 0$, we can get a slow dynamics and a slow manifold.

- Slow Dynamics

$$(J_{eff} + m_m)\ddot{x}_m = -g\, m_m + u_s \qquad (3)$$



(a) Hopping height change from 0.4m to 0.6m (b) Limit cycle change in COG for height change

Fig. 7. Hopping Height Change through STIMM

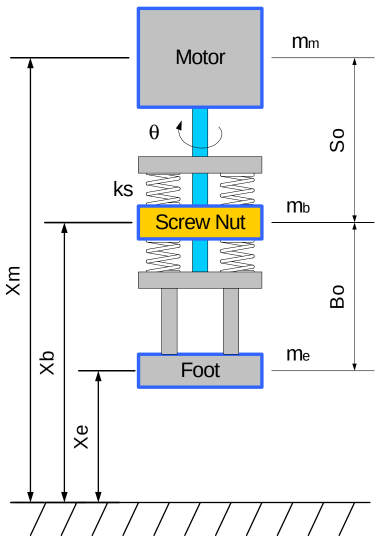


Fig. 8. Hopping model, Model - II

- Slow Manifold

$$z_0 = \frac{-g(m_b M_m + J_{eff}(m_b + m_m)) - m_m u_s}{J_{eff} + m_m} \tag{4}$$

Slow subsystem controller is constructed through computed torque and gravity compensation. This controller results in error dynamics Eq. (6) and it is stable.

- Slow controller

$$\begin{aligned} u_s &= g\, m_m + (J_{eff} + m_m)\ddot{x}_{md} \\ &+ K_p(x_{md} - x_m) + K_d(\dot{x}_m d - \dot{x}_m) \end{aligned} \tag{5}$$

$$(J_{eff} + m_m)\ddot{e} + K_p e + K_d \dot{e} = 0 \tag{6}$$

At last, we can make the fast dynamics using $\zeta = z - z_0$.

- Fast Dynamics

$$\varepsilon^2 \ddot{\zeta} = -\frac{f_2}{f_1}\zeta - \frac{f_3}{f_1}u_f \tag{7}$$

$(f_1 = m_b m_m + J_{eff}(m_b + m_m),\ f_2 = J_{eff} + m_m, f_3 = m_m)$ Fast subsystem controller can be proposed as Eq. (8). If we apply this controller, the fast subsystem is transformed into the 2nd order differential equation whose coefficients are all positive, which is asymptotically stable.

$$u_f = K_1 \zeta + K_2 \dot{\zeta} \tag{8}$$

$$\varepsilon^2 \ddot{\zeta} + \frac{f_3 K_2}{f_1}\dot{\zeta} + \frac{K_1 f_3 + f_2}{f_1}\zeta = 0 \tag{9}$$

$$\frac{d^2\zeta}{d\tau^2} + \frac{f_3 K_2}{f_1}\frac{1}{\varepsilon}\frac{d\zeta}{d\tau} + \frac{K_1 f_3 + f_2}{f_1}\zeta = 0 \quad (t = \varepsilon\tau) \tag{10}$$

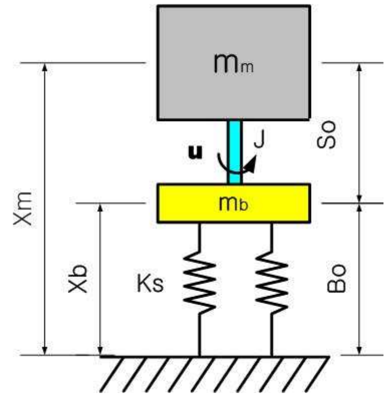


Fig. 9. Simplified model dynamics from singular perturbation formulation

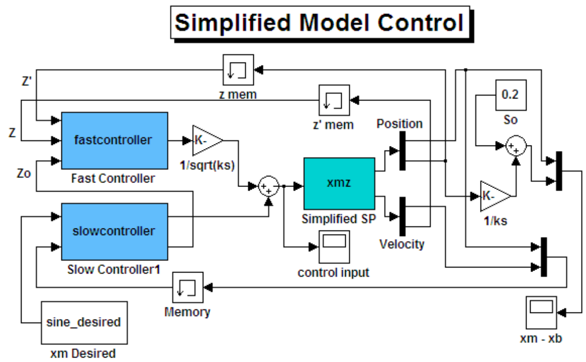


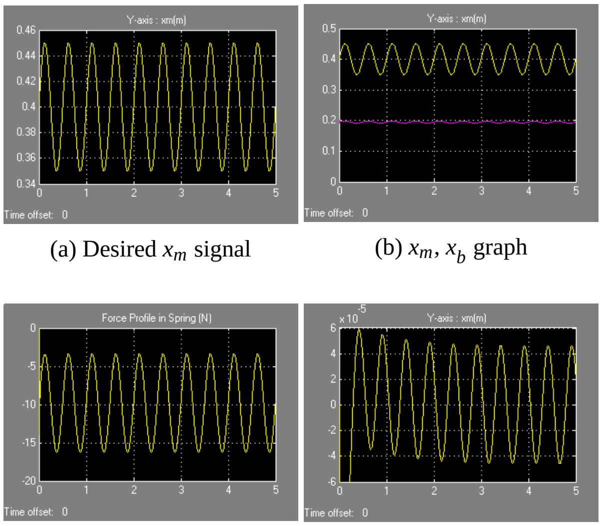
Fig. 10. Simplified model, control block

Simulation is for the desired sine signal whose frequency is 2Hz and 5cm amplitude. Spring is assumed as 2000N/m. From simulation result, we can see that singular perturbation method shows good performance in simplified model. Fig 9(b) shows trajectory of x_m and x_b. Steady-state error is within 0.05mm, 0.1N error in spring force.

3.3. Hopping Control of Model - II

In this section, we apply stiffness modulation method to Model-II. Spring and ball-screw mass is neglected but m_m, m_b and m_e are considered. The aim is making the model behave as stiffness modulated fashion. On controlling model, we assume that there is no control at flight phase but we apply the result of previously built controller in simplified model only at impact regime. To control at impact regime, desired x_m and x_b trajectories are required to behave like stiffness modulated fashion. In this process, we compare Model-II with Model-I(virtual model) of Section 2. This process is used not only in this example, but also in more complex legged model. Detail process is in Fig 12.

First, we calculate energy difference between initial and present time. From this, we can form energy controller which determines desired stiffness so that the system can have equal energy as much as initial's. From desired stiffness, we calculate desired x_m and x_b through simple similarity relation between two models. Similarity relation is that mass center position of upper two of Model-II must be equal to the upper mass position of virtual model. The other is that spring forces must be equal although spring deformations are different. From present x_m and x_b position, velocity, acceleration



(a) Desired x_m signal (b) x_m, x_b graph

(c) Forces in spring (d) Error in x_m

Fig. 11. Simplified model control trough singular perturbation

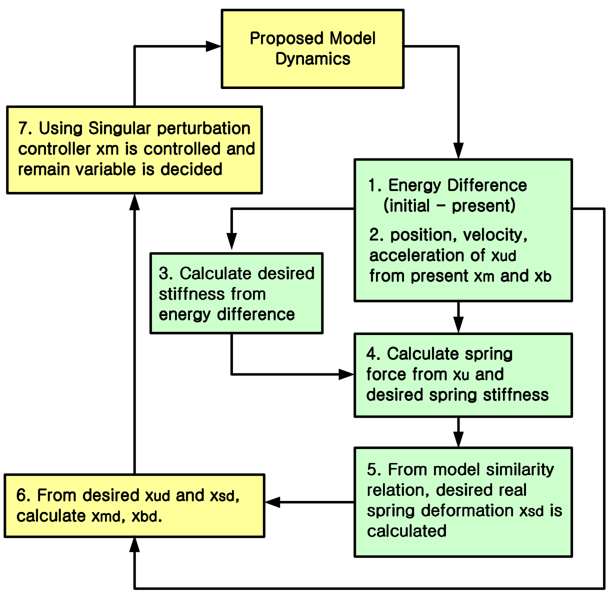


Fig. 12. Calculation flowchart

information, we can calculate those of x_u(x_u : lumped upper mass position of Model-II). From similarity fact, we can calculate desired spring deformation value using below equation.

$$x_{sv}k_{sv} = k_s x_{sd} \tag{11}$$

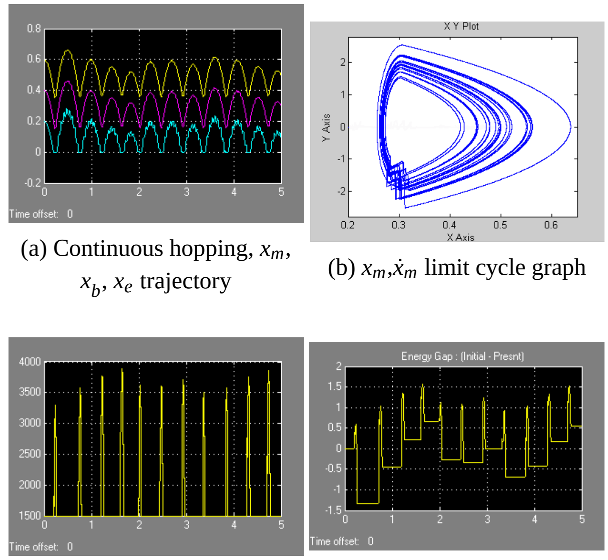
(k_s : given spring stiffness Model-II, it does not change. x_{sd} : desired spring deformation value, x_{sv} : spring deformation of virtual model, k_{sv} : calculated spring stiffness of virtual model, $m_u = m_m + m_b$)

From the above x_{sd} value, again we can get desired x_{bd} and x_{md} value using below equations.

$$x_{bd} = x_{sd} + B_0 \tag{12}$$

$$x_{md} = \frac{1}{m_m}(m_u x_{ud} - m_b x_{bd}) \tag{13}$$

Desired x_{bd} and x_{md} velocity and acceleration can be calculated through similar process. Until now, we can calculate desired trajectories from energy difference and modulated stiffness. To control



(a) Continuous hopping, x_m, x_b, x_e trajectory (b) x_m,$\dot{x}_m$ limit cycle graph

(c) Stiffness modulation (d) Energy difference

Fig. 13. Hopping simulation of Model-II

the model for desired trajectory, we use singular perturbation result of simplified model again. At impact regime, proposed model can be assumed as simplified model proposed in previous section. In controlling proposed model in impact regime, there is some vagueness. Control input matrix and target control variable is 2-dimension and it is actuated from one control input. If we inspect system carefully, this control target can be fulfilled through control of only one variable x_m, because x_m and x_b show dependent behavior.

In order words, For satisfying both of desired x_m, x_b values, x_b can be spontaneously satisfied along the desired trajectory by controlling only one variable, x_m. This fact can be identified through summing upper and lower equations of Model-II dynamics, so that there remains only one equation for x_m and x_b. Also it means that to control x_m along desired trajectory x_b is to be fixed according to x_m, and there is unique control input to control x_m along fixed desired trajectory.

In Fig 13, we can see control results. Comparing with Model-I, there is irregular shape in limit cycle graph. It is because of assumption that in controlling Model-II, system is assumed as simplified model in contact regime and there is difference in end effector information. There is post-impact after initial impact with ground and it causes difference. In this simulation example, we validate that stiffness modulation method can be applied to the system which has not variable stiffness element. Real shock absorption is happened at real fixed spring and motion of lumped upper mass represents stiffness modulated-fashioned motion of center of mass.

4. Conclusions

In this paper, we have shown hopping simulation through stiffness modulation method. Using this, we could make continuous hopping and it was usefully applied to terrain adaptation, impact force reduction and hopping height change of hopper. Procedures to apply this method to the system which has fixed stiffness element have been developed and result from this can be applied to the humanoid(legged) robots. The validity was demonstrated by the numerical examples.

References

[1] K. Y. K. K. S. Kajita, T. Nagasaki and K. Tanie, "Running pattern generation for a humanoid robot," in *ICRA 2002*, May 2002.

[2] T. M. K. Arkawa, "Design of multi-dof jumping robot," in *ICRA 2002*, May 2002.

[3] D. J.Paluska, "Design of a humanoid biped for walking research," 2000.

[4] E. B. Poul. Dyhre-Poulsen and M. Voigt, "Dynamic control of muscle stiffness and h-reflex modulation during hopping and jumping in man," *Journal of Physiology*, vol. 437, pp. 287–304, 1991.

[5] C. V. S. Claire T. Farley, Han H.P.Houdijk and M. Louie, "Mechanism of leg stiffness adjustment for hopping on surface of different stiffnesses," *American Physiological Society*, vol. 85, no. 3, pp. 1044–1055, 1998.

[6] M. H.Raibert, *Legged Robots That Balance*. MIT Press, 1986.

[7] H. K. P. Kokotvic and J. O'Reilly, *Singular Perturbation Methods in Control : Analysis and Design*. SIAM, 1999.