Drum Stroke Variation using Variable Stiffness Actuators

Yongtae G. Kim[1], Manolo Garabini[2], Jaeheung Park[3], and Antonio Bicchi[2]

***Abstract*— One interesting field of robotics technology is related to the entertainment industry. Performing a musical piece using a robot is a difficult task because music presents many features like melody, rhythm, tone, harmony and so on. Addressing these tasks with a robot is not trivial to implement. Most of approaches which related to this specific field lacks of quality to perform in front of human audience. Implementation of human-like motions can not be properly achieved with a conventional robot actuator. Consequently, we exploit a new type of actuator which simplifies the drawbacks of a conventional one. We used Variable Stiffness Actuator(VSA) instead of using conventional actuator. We can control position, force, and stiffness, simultaneously by using VSA. The most important novel feature is its controllable stiffness. When the stiffness of the actuator is changed, the characteristics of the actuator's response also changes. We implemented the specific stroke which is called "double stroke" using one of variable stiffness actuator. Although the double stroke is known as a special stroke which could be performed by human only, double stroke is successfully implemented by stiffness variation.**

I. INTRODUCTION

Pursuing pleasure and happiness is a strong instinct of humanity. As technology has evolved, demands of new entertainment getting increased. Many mass media have been showing this applications in literatures, and movies. Then, people found out that the robot can be used in entertainment industry.

Therefore, some researchers tried to investigate real entertainment robots. The objective of these kind of research is 'make the robot similar to human'. Tatsuzo et al. developed a small humanoid platform for motion entertainment [1]. Tarek et al. tried to play many musical instruments using robotic system. They tried 12 musical instruments including drum, guitar, violin, and cello [2]. Roger et al. developed a robotic bagpipe player [3]. Kazuyoshi et al. developed an algorithm that a humanoid robot can following musical beat [4]. Gil and Scott developed an interactive robotic percussionist [5]. Jorge et al. developed a flutist robot, WF-4RIV [6]. Some researchers tried to adjust an entertainment robot to the education field [7]. Moreover, robot can perform some theatric motions [8]. Guy and Gil modeled a musical improvisation using gestures replacing of sequence of note [9].

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[1]Yongtae Giovanni Kim is with the Department of Transdisciplinary Studies, Seoul National University, Republic of Korea, and he is now working as a visiting researcher in Centro di Ricerca "E. Piaggio", Universita di Pisa, Largo L. 'Lazzrino, 1, 56100 Pisa, Italy

[2]Manolo Garabini and Antonio Bicchi are with the Department of Advanced Robotics, Istituto Italiano di Tecnologia, via Morego, 30, 16163 Genova, Italy and with Centro di Ricerca "E. Piaggio", Universita di Pisa, Largo L. 'Lazzarino, 1, 56100 Pisa, Italy

[3]Jaeheung Park is with the Department of Transdisciplinary Studies, Seoul National University, Republic of Korea

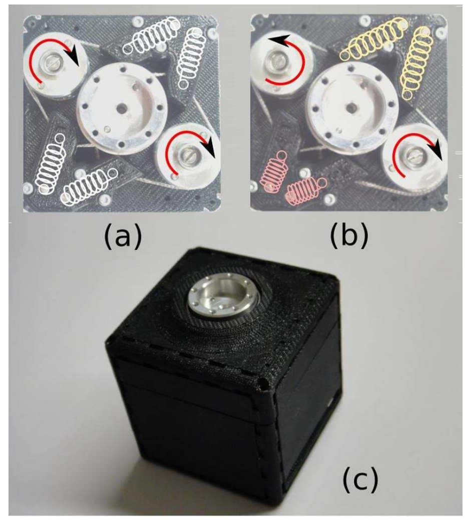


Fig. 1. qbmove v0.1. (a) Low stiffness setting, (b) Stiffness change from low to high stiffness, and (c) Exterior of qbmove.

Some researchers tried to investigate co-play with a human because it looks very friendly to mankind. Ye et al. developed co-play algorithm to play a vibraphone [10] and Takuma et al. developed two-level synchronization algorithm for co-play [11]. Moreover, Youngmoo et al. developed a humanoid for musical interaction [12]. Takeshi et al. investigated human-robot ensemble with a humanoid thereminist [13], and developed an algorithm for gesture recognition and beat tracking [14].

For drumming investigation, the motion of human drummer should be analyzed. Some researchers conducted analysis of human drum motions. Sofia compared four drummers striking mechanisms [15]. Anders modeled percussional instruments including drums, physically [16]. Andreas analyzed interaction between drummer, drum stick, and drum instruments [17].

There are also some previous works about robot drummer. Aram et al. experimented drum rolling motion using a simple mechanical device [18]. Sarah et al. investigated some drumming tasks using humanoid robot [19]. Christoper et al. investigate the synchronization of robotic drumming with a human performer [20]. Atsushi et al. tried to connect drum motion and some martial art motions [21]. More review article for robot research which related to musical instruments can be found in [22].

We believe that some limitations of existing robots in performing human-like tasks can be relieved by natural motions. It can be implemented with compliant elements, and it allows control their stiffness while performing tasks. However, most of entertainment robots are developed by conventional actuators, and they have limitations on performance. Several years ago, a new actuator, which called Variable Stiffness Actuator(VSA) is developed, and it allows an intrinsic safety in actuators [23]. Michael et al, mentioned a safe playing robot can be implemented by new hardware like VSA [24]. Moreover, VSA can enhance the performance using its elasticity [25]. More exhibits and exploits about soft actuation and natural motion can be found in [26].

According to references, the VSA can be a good candidate for implementing an entertainment robot. In drumming motions, one of the core responses is the stroke. The single stroke is normally used in drum play, but drummer requires particular strokes to perform special sounds in sometime. The double stroke is one of the particular strokes. We implemented double stroke using stiffness variation. VSA-Cube(also called as qbmove, shown in Figure 1)[27] is used for implementing this task. In this paper, the classification and analysis of drum stroke motions, the capability of variable stiffness actuators, and the way of finding the rolling stiffness which is based on double stroke are introduced. Also, the theoretical evaluation of drum rolling stiffness, and experimental validations are provided.

II. Drum Stroke

There are many variables to strike percussional instruments. The shape of instrument, striking material, striking speed, contacting time, and contact point vary the generated sound of instruments. So, understanding mechanism of drum stroke should be firstly done.

A. Single Stroke and Double Stroke

A human drummer usually uses single stroke to play a music, because almost every notes in a music are composed of single strokes. The definition of single stroke is “A stroke performs a single percussive note.”. However, some notes request special strokes, and one of the special strokes is the double stroke. In a music, drum notes can be written as “R(Right-hand)” and “L(Left-hand)”. For example, “RLRL” means right-left-right-left handed stroke and it can be performed by single strokes. However, there are some notes like “RR”, “LL”, and the Single Paradiddle(RLRRLRLL). If the frequency of these notes are too fast to be performed by single strokes, the only way is the double stroke.

The double stroke means “make double sound within single swing”. The key factor of double stroke is bouncing of drum stick. When the drum stick strokes the drum membrane, the drum stick immediately bounce from the membrane. In single stroke situation, the bounce would not occurred because the drummer tightly hold the drum stick. If the drummer smoothly releasing his/her grip, the drum stick can bounce and the bounced strokes are naturally performed.

B. Drum Roll

The definition of drum roll is “a sustained sound on a drum”. The drum roll is a quite difficult task, because the rolling motion requires very fast and precise motion. So, some special techniques are required to perform the drum roll. The key point of special technique is the way of grip and controlling stiffness. By controlling stiffness, the drummer can choose the time interval between first and bounced stroke. When the time interval is synchronized, the number of strokes becomes doubled and synchronized. The following Figure shows the relation between stiffness and the number of strokes.

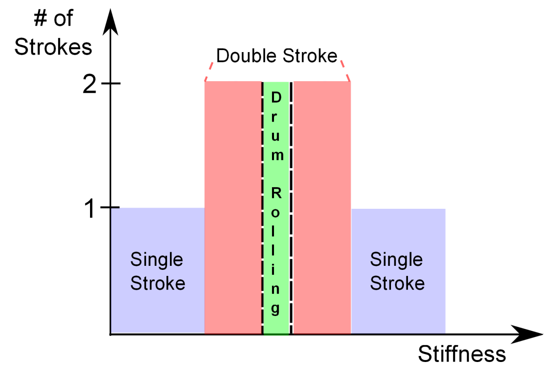


Fig. 2. Relationship of Stiffness-Number of Strokes. Double stroke and drum rolling can be performed in specific stiffness region.

As shown in Figure 2, there are three main regions by stiffness spectrum. In the Figure 2, some repeating strokes are given with a certain period. In high-stiffness region, only single stroke can be performed. In mid-stiffness region, drum stick starts bounce and the time interval of bounced stroke is increased by lowered stiffness. When the stiffness reachs at the specific region which is called “Drum Rolling” region, the time intervals synchronized (In two handed drum, 1/4 of the stroke period), then the drum rolling is performed. In low-stiffness region, only single stroke can be performed because the bounced time interval is so long that the drum stick follows the ’swing-back’ command before the drum stick strike again.

The double stroke mechanism can be modeled by the following formulas. The drum stick is modeled as a bouncing ball with mass m [28].

1) Drum stick mechanism without contact.

$$m\ddot{z} + R_{out}\dot{z} + K_{hand}(z - z_{ss}) = 0, \quad (1)$$

where z is the height of the tip of drum stick. K_{hand} and R_{out} are the stiffness of wrist and damping of wrist, respectively. $z_{ss} = z_{h0} - mg/K_{hand}$ is a function of the rest position of wrist(z_{h0}) and gravity(g).

2) Drum stick mechanism with contact.

$$m\ddot{z} + R_{in}\dot{z} + K_{hand}(z - z_{ss}) + K_{coll}z = 0, \quad (2)$$

where R_{in} is the damping of drum membrane, and K_{coll} is the stiffness of drum membrane.

Fig. 3. Drum stick mechanism without contact.

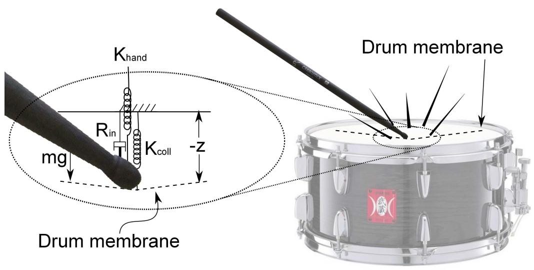


Fig. 4. Drum stick mechanism with contact.

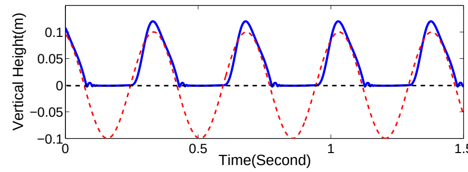
In bouncing mechanism, the coefficient of restitution (COR) is an important variable for bouncing dynamics. The coefficient of restitution can be obtained by comparison of velocity between before and after collision. In drum stroke case, the coefficient of restitution(β) can be calculated by following formula [28].

$$\beta \approx exp \frac{-R_{in}\pi}{\sqrt{4mK_{coll} - {R_{in}}^2}} \tag{3}$$

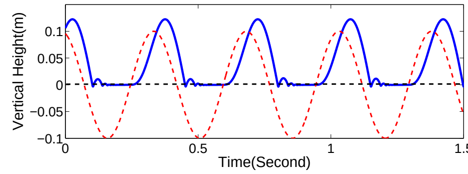
C. Simulation

Using the formulas mentioned in above subsection, the stroke responses of each stiffness can be simulated. We gave same sinusoidal inputs consisted with stroke and swing-back phase. which amplitude is 0.1m and frequency is 18rad/sec, respectively. The variables are $m = 0.05$kg, $R_{out} = 1$, $R_{in} = 10$, $K_{coll} = 20000$N/m. The stiffness of the hands are assumed as a translational stiffness. And we used one stick(The blue line) for confirming the rebound stroke. The red dashed line and the black dashed line represent the input signal and drum membrane, respectively.

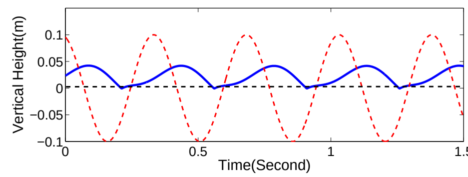
We simulated with four different stiffness(Figure 5). At first, we carried out a simulation in very stiff(almost rigid) setting. As shown in Figure 5.(a), there are almost no bounces, because the rigid wrist preventing the bounce motion. The stiff joint strongly follow the command that the stick staying in membrane. Figure 5.(b) represents the response of high stiffness(not rigid) joint. As shown in Figure 5.(b), there are little bounces because of elasticity of the joint. However, the bounces are not enough to generate synchronized drum roll. Figure 5.(c) represents the response of low stiffness joint. As shown in Figure 5.(c), there are no bounces, because the time intervals of bounce are too long to generate bounced strokes. Figure 5.(d) represents the response of rolling stiffness joint for drum rolling. As shown



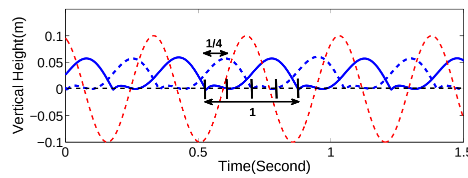
(a) Rigid



(b) High Stiffness



(c) Low Stiffness



(d) Drum Rolling

Fig. 5. Drum stick Trajectory of Joint. The red dashed line represents the input signal of drum stick, the blue line represents the response of drum stick, and the blue dashed line represents the response of secondary drumstick, respectively. (a) Rigid $K_{hand} = 200$N/m, (b) High stiffness $K_{hand} = 50$N/m (c) Low stiffness $K_{hand} = 5$N/m (d) Drum rolling $K_{hand} = 9.3$N/m. The delays are caused by lowered stiffness.

in Figure 5.(d), there are synchronized bounced strokes that makes drum rolling. The time interval between first and next stroke becomes exactly 1/4, then it allows to stroke drum rolling when the drummer uses two sticks (Blue dashed line in Figure 5.(d)).

III. Variable Stiffness Actuators

We used variable stiffness actuators(VSA) for implementing drum strokes. Actually, a conventional actuator can follow the drum motion including precise and fast motion. However, the conventional actuator is not proper for playing drum because its high stiffness has possibility to tear the drum membrane. Also, using low stiffness is not a proper solution for robot drumming because low control bandwidth is not proper for playing percussional instruments.

Variable Stiffness Actuator is a kind of 'human-like design'. The human muscular skeleton model is consisted with muscular-antagonistic mechanism. Flexion and extension motion are generated by contractions of muscles. In VSA, each motor contract each spring for making flexion and extension motion. It means the mechanism is exactly same with human muscular-antagonistic mechanism. Therefore, VSA is more suitable for implementing human-like motion.

Moreover, VSA has capability to do some task which cannot performed by a conventional actuators. As we mentioned in Section II, the robot drummer can play various strokes without hardware change. Also, the shape of sound waveform can be modified by little stiffness change.

IV. Finding Rolling Stiffness for Double Stroke

Not every drum has the same stiffness and damping. Hence the double stroke requires different stiffness for each drum instrument. The most important variable is the time interval between first and bounced stroke. Using model in Section II, and simplifying the model as a simple ballistic dynamics model, the time interval can be calculated by following procedure.

$$mg + K_{hand}\Delta z = ma \tag{4}$$

$$v_{b0} = exp(\frac{-R_{in}\pi}{\sqrt{4mK_{coll} + R_{in}^2}})v_0 \tag{5}$$

$$t_{int} = 2\frac{exp(\frac{-R_{in}\pi}{\sqrt{4mK_{coll}+R_{in}^2}})v_0 m}{mg + K_{hand}\Delta z} \tag{6}$$

The variables are following. a is the vertical acceleration of drum stick after the contact, Δz is the vertical deflection of drum membrane at the contact, v_{b0} is the vertical bounced velocity of drum stick after the contact, and v_0 is the vertical velocity of drum stick before the contact.

Because the direction of bouncing motion is opposite to equilibrium position, the acceleration of drum stick is calculated by Equation 4. The bounced velocity(v_{b0}) can be calculated by coefficient of restitution(5). Using (4) and (5), the time interval(t_{int}) is easily calculated(6).

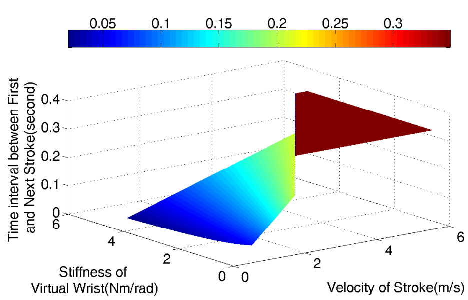


Fig. 6. The relationship among Stiffness of Wrist Joint, Velocity of Stroke, and Time Interval with 0.3m drum stick. The period of stroke was set to 0.35s. When the time interval reaches the swing-back phase of the command(In this Figure, 60% of period of stroke), the double strokes are missing and the time interval immediately becomes the period of stroke. The color of graph represent the value of z-axis. In this Figure, the drum rolling stiffness area is center of the blue area($\approx$0.0875).

Figure 6 shows the relationship between stiffness of wrist joint, velocity of stroke, and time interval. This Figure is obtained by Equation 6, and we used the same variables in Section II.C. As shown in Figure 6, the time interval is proportional to velocity of stroke, and inversely proportional to wrist stiffness.

As shown in Equation 6, the time interval is the function of velocity and stiffness in impact situation ($t_{int} = f(v_0, K_{hand})$). Using following equation, length of drum stick(r), and assuming two-handed drumming situation, the rolling stiffness($K_{hand,roll}$) can be found as :

$$K_{hand,roll} = \frac{8exp(\frac{-R_{in}\pi}{\sqrt{4mK_{coll}+R_{in}^2}})v_0 m - mgT}{\Delta z T} r^2 \tag{7}$$

V. Experimental Setting

We used two variable stiffness actuators for implementing double stroke. The variable stiffness actuators are 'qbmove v0.1 maker pro' which is developed by 'qbrobotics', Italy [26]. This VSA is developed for implementation of natural motion, and it provides open source hardware and software. The specifications of qbmove v0.1 are following.

TABLE I
Specifications of qbmove v0.1

Quantity	Unit	Value
Nominal Torque	Nm	1.3
Nominal Speed	rad/s	7
Maximum Stiffness	Nm/rad	8
Minimum Stiffness	Nm/rad	0.6
Rotation Range	degree	±180

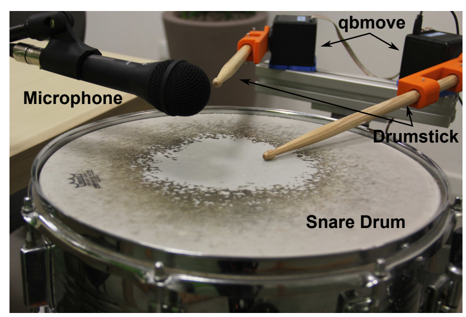


Fig. 7. Experimental Setting.

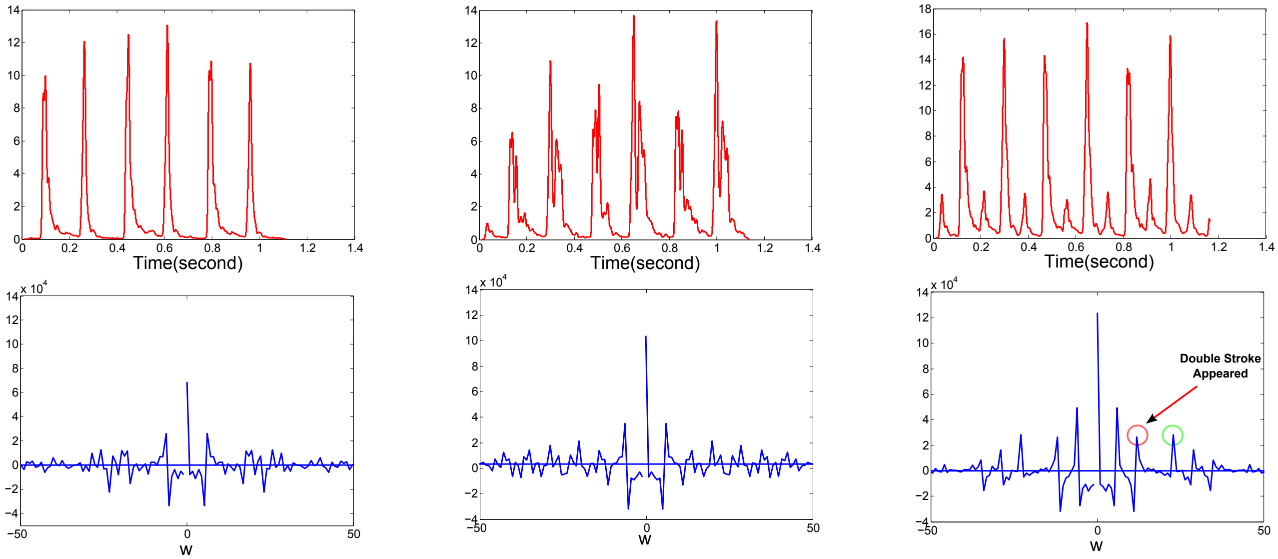
The qbmove is connected to personal computer, and it runs by MATLAB. We used typical snare drum for double stroke. The sounds are collected by a microphone. The experimental setting of this paper is shown in Figure 7.

VI. Experimental Results

The experiments were carried out with the experimental setting mentioned in Section V. We experimented three different stiffness settings which are soft, stiff, and rolling stiffness, respectively. We collected audio signals by 'Goldwave v5.58'. Each samples of experiments are sliced in six strokes for analyze.

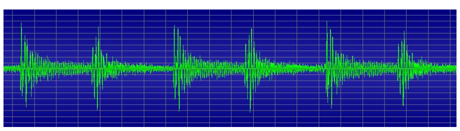
Figure 8 shows the stroke waveforms of each stiffness setting. Because the raw signals contain noise, we did signal processing as follows. First, we get the absolute amplitude of the audio signal. Then, the signals were interpolated. The interpolated signals were transformed by applying FFT for frequency analysis.

The processed signals are shown in Figure 9. The result shows that there are exact double stroke in rolling stiffness

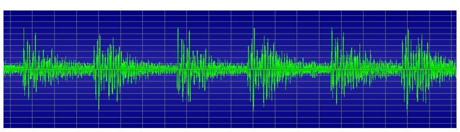


(a) (b) (c)

Fig. 9. Interpolated signals and their Fourier transforms : (a) Low stiffness, (b) High stiffness, (c) Drum rolling stiffness. Double stroke can be found in frquency domain analysis.



(a)



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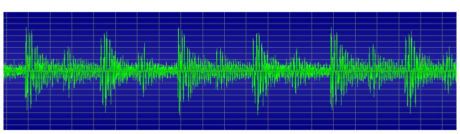


(c)

Fig. 8. Stroke Waveforms whose frequency of stroke are 18 rad/sec. (a) Low stiffness setting, (b) High stiffness setting, and (c) Rolling stiffness, respectively.

setting. Also, the Fourier analysis shows that there is an impulse at twice value of domain frequency(red circle). The impulse at the green circle is also appeared because of reiteration by using two drum sticks for drum rolling. We also experimented with other rolling frequencies. Using the equation of Section IV, the rolling stiffness can be calculated. As shown in Figure 10 and Table II, double strokes are successfully implemented in different rolling frequencies.

VII. Conclusion and Future Works

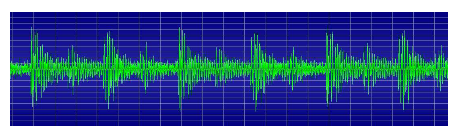
Drum strokes using elastic joints are successfully implemented. The mechanisms of drum stroke variation by stiffness change are also introduced. Either conventional stiff joint or low stiffness or high stiffness joint are not proper for performing various drum strokes. However, Variable stiffness actuator can perform both single and double stroke without change of hardware.

The bounce of drum stick is performed in specific stiffness region. Especially, a certain small area is for drum rolling, and we showed how to find the stiffness for drum roll. The

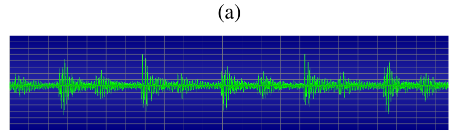
TABLE II

Rolling stiffness for each frequency. The Calculated Stiffness is obtained by Equation 7 with following assumed variables : $m = 0.05kg$, $R_{in} = 10$, $K_{coll} = 20000N/m$, $v_0 = f * 0.1rad/sec$, $r = 0.3m$, $\Delta z = 0.02m$, and the values f are chosen as 15 and 18 rad/sec. The Experimented Stiffness are obtained by real experiment.

Stroke Frequency	Calculated Stiffness	Experimented Stiffness
15rad/sec	1.74Nm/rad	≈ 2.05Nm/rad
18rad/sec	3.48Nm/rad	≈ 3.20Nm/rad



(a)



(b)

Fig. 10. Rolling Stroke Waveforms. (a) Frequency : 18 rad/sec and (b) Frequency : 15 rad/sec, respectively. Drum rollings are successfully performed in each frequency.

most important variable is the time interval, and the time interval is proportional to the velocity of stroke and inversely proportional to wrist stiffness.

In this paper, we only mentioned fixed constant stiffness for double stroke. Bounced drum stick strikes again because of repulsive force and gravity. While drum stick bouncing, the drummer can modifying frequency of bouncing interval by controlling stiffness. Changing stiffness in double stroke situation requires precise control because the drumming task is a quite fast application, and VSA requires stiffness variation time. We want to implement this issue in a near future. Moreover, we think the variable stiffness can improve the performance of single strokes. So we also want to implement optimal controller which improve the richness of sound.

Variable stiffness actuators might be more capable than conventional actuators. because the mechanism of VSA is similar to human muscular-antagonistic mechanism. We expect VSA can be used in various robot applications which require human-like motion.

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