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Improvement of Violinist Robot using a Passive Damper Device

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Abstract The aim of this study was to determine how the violinist robot could produce a good quality of violin sounds. We began our study with the basic physics of producing sound with a violin. We found three parameters that influenced the quality of the sound produced by the violin; the bowing force, the bowing velocity and the sounding point. In particular, the bowing force was found to be the most important parameter in producing good sounds. Furthermore, to produce such sounds, a same amount of the bowing force must be applied on the contact point between a bow and a string. However, it is hard to keep a same amount of the bowing force on the contact point due to inherent characteristics of a bow. Thus, we primarily focused on the bowing force by considering bowing a string as a spring-mass system. Then, we devised a passive damper device to offset variables in the spring-mass system that may result in changing the bowing force on the contact point. We then validated our methodology with the violinist robot, a human-like torso robot.

Keywords Physics of violin · Violinist robot · Entertainment robot · Bowing · Passive damper device

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1 Introduction

Up to now, industrial robots are mainly covered in the field of Robotics. Although it has been proven that industrial robots increase product quality and improve productivity in the factory [1], robots cannot provide human beings with interactions that seem to occur as expressions of emotions. To make up for such shortcoming, a new genre of the robots has been recently introduced, which is called entertainment robots. The entertainment robot is a one of the type, which is a human intimate type robot or is built for fun and amusement [2].

Entertainment robots can be seen in many areas of our life and culture. The human styled robots called 'Hubo' [3],'Asimo' [4], and 'HRP' [5]. Furthermore, Sony's Qrio and Aibo [6], Aldebaran's Nao [7], and ROBOTIS's DARwin-OP [8] are designed to perform some tasks capable of entertaining people by interacting with them through communication or motion. The violin playing robot that we have built, which will be discussed in this paper, is also a type of entertainment robot.

The violin playing robot is classified as a musical performance robot that is operated by automatic mechanism. Several attempts to build an anthropomorphic musical robot have been made for decades, and different outstanding performing robots have been built with advanced technologies. Recently, the Waseda Saxophonist Robot has been developed at Waseda Unversity [9], as a follow-up model of Flutist Robot [10]. Waseda Saxophonist Robot is the human-like robot that is able to play a saxophone with expressing emotions. Also, the superb violin-playing robot, which is equipped with highly advanced control technology, exhibited at the press conference has been built by Toyota [11]. In addition, another violin playing robot producing expressive sounds by considering sensibility has been developed at Ryukoku University [12].

Even though the violin has been the most studied of all the classical instruments, it is still a difficult instrument, as it has one of the most difficult physical interfaces of any musical instrument. Compared with a piano, played with similar left and right hand techniques, a violin is played with different demanding techniques required of the left and right hand. For this reason, when a beginner tries to play a violin, he or she typically has difficulty in regularly placing his or her left fingers on a particular point of the fingerboard and bowing on the specific string. These difficulties might result in producing a musical note at the desired pitch, but might also result in an undesirable sound, such as a screech or raucous noise. To overcome these difficulties, the violinist has to practice playing the violin frequently until they are producing quality sounds. Moreover, perceiving the principles of the basic physics of producing a violin's sound should be conducted at the same time as practicing playing the violin.

In this sense, the violinist robot we have designed is in a similar situation as a novice human being. Accordingly, we have focused on studying the principles of the violin and how to produce a good violin's sound, with the violinist robot in the first stage of developing the accomplished violinist robot.

The sound quality of the violin is primarily influenced by three parameters; the bowing force on the string, the bowing velocity, and the sounding point (it is also called the bow-bridge distance from the bridge to the bow) [13]. In particular, the bowing force was found to be the most important parameter in producing the violin's sounds. Furthermore, to produce a good quality sound, a same amount of the bowing force must be applied on the contact point between a bow and a string. However, it is hard to keep a same amount of the bowing force on the contact point due to inherent characteristics of a bow. Thus, we primarily focus on the bowing force by considering bowing a string as a spring-mass system. Then, we devise a passive damper device to offset variables in the spring-mass system that may result in changing the bowing force on the contact point. During this process, we confirm the close relationships between the sound quality of the violin and the bowing force.

The rest of the paper is organized as follows: Section 2 introduces basic physics of the violin to understand the mechanism of the violin sound generation, and describes application methods for the violinist robot to produce the violin's sound. Section 3 presents a description of the violinist robot we have designed, and Section 4 shows the summary of results of the experiments having the robot plays the violin. Finally, Section 5 summarizes our conclusions and future scope of work to improve the capabilities of the violinist robot.

2 The Physics of the Violin

2.1 Bowed String of the Violin

The ultimate aim of developing the violinist robot is to mimic an accomplished violinist expressing the range of expression in standard repertoire. To become a professional violinist, the robot must first be able to control a violin's pitch, timbre, and loudness; Pitch represents the perceived fundamental frequency of a sound. It is often referred to as "the height of a note". Timbre is the particular quality or acoustic of a sound produced by an instrument or a voice. It is sometimes referred to as " sound color" or "tone color". Lastly, loudness is defined as the perceived strength of a piece of audio. In particular, timbre is the largest factor that affects the sound quality, and it is, to a great extent, connected with the bowing velocity, the bowing force, and the bowing distance. In this sense, this section introduces the methods we approached to obtain a good violin's sound produced by the violinist robot.

There are three techniques used to produce sound on a violin: plucking, bowing, and striking [14]; Plucking is pulling the strings with the fingers. Bowing is pulling the strings with a bow. Lastly, striking is hitting the strings with fingers. The most common technique, and consequently the one we focus on in this paper, is bowing on strings. When bowing a violin, the parameters control the string vibrations: (1) V, the velocity of a bow relative to the violin, (2) F, the force to the bow from the violin (bowing force or "bow pressure"), and, (3) p, the sounding point that is the position where the bow touches the strings (bow-bridge distance). These three primary bowing parameters are defined in Fig. 1a.

Of the three parameters, the most important factor used to determine the sound quality of the violin is the bowing force [16]. In Schelleng's study, the author verified that the bowing force is primarily important as the catalytic agent that makes possible a correct reaction between bowing velocity and sounding point. Furthermore, he verified that there are the upper limit to the bowing force, called the "maximum bowing force", and the lower limit, called "minimum bowing force", depicted in Fig. 1b. If F is increased past the maximum bow force, the musical note is lost, and the bow will produce noise called "raucous". Conversely, if F is too low, the bow will produce what is known as "surface sound". Once these limits have been defined, the range of normal force can be analyzed from the following equations:

$$F_{\max} = \frac{2ZV}{p(u_s - u_d)} \tag{1}$$

$$F_{\min} = \frac{Z^2 V}{2p^2 R(u_s - u_d)} \tag{2}$$

where u_s and u_d are respectively the coefficients of sticking friction and sliding friction. The other notation follows [16]: V is the bow velocity, Z is the characteristic wave resistance of the string, R

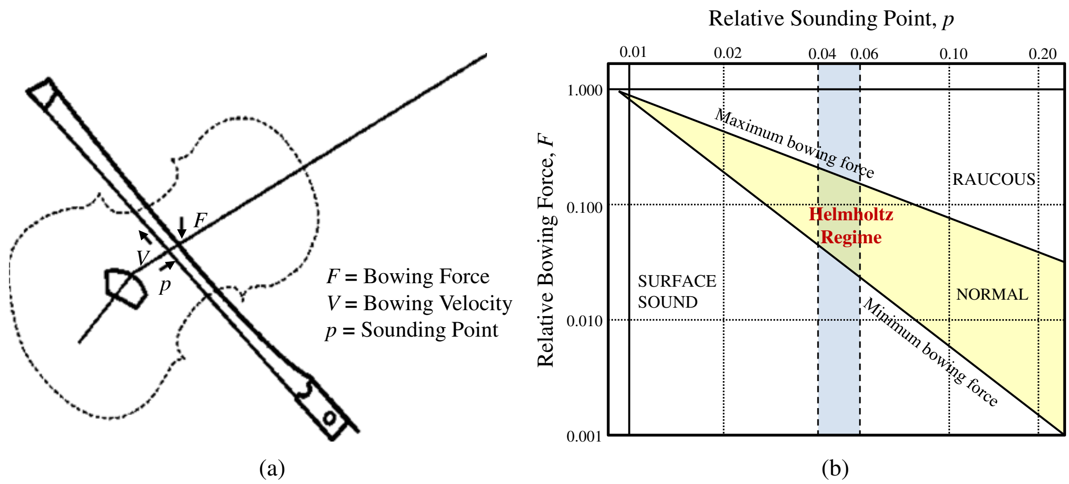


Fig. 1 **a** Definition of the bowing parameters V, F, and p, from [15]. **b** Principal relation between maximum and minimum force and bow-bridge distance for a given bow velocity, from [14] and [16]

indicates the equivalent of the rate of energy loss into the violin body, and p specifies the sounding point.

Equations 1, 2, and Fig. 1b illustrate a close relationship between the bowing force and the sounding point. For a given string, the sound pressure is proportional to V/p. The same volume is therefore maintained when the change in bowing velocity is proportional to the change in the distance of the bow from the bridge. We then obtained Eq. 3 by diving Eq. 2 by Eq. 1,

$$\frac{F_{\max}}{F_{\min}} = \frac{2pR}{Z}. \tag{3}$$

Equation 3 reveals that the shorter the bow-bridge distance, the narrower is the allowed range in bowing force. In other words, the closer the bow is to the bridge, the steadier is bowing force needed to preserve acceptable tone, as illustrated in Fig. 1b.

For all these reasons, it is quite difficult for beginners to determine the proper bowing force affecting mostly the quality of violin's sound. Hence, we will introduce the method to determine the proper force necessary to produce good sounds in the following sections.

2.2 Spring-Mass System

Bowing is the most fundamental and predominant technic to produce a violin sound. The best way to master bowing is that one bows a string at the same bowing speed as slow as possible while keeping producing a good quality of sound. Some of the professional violinists even practice this method in order to produce a good quality sound. If we take a look at violinists who can produce a good sound, we can simply recognize that they gradually vary the bowing force according to the variation of a contact point between the bow and the string. When the contact point approaches to a part of the frog of the bow, they apply less force to the bow. Conversely, when the contract point approaches to a part of tip of the bow, they apply more force to the bow.

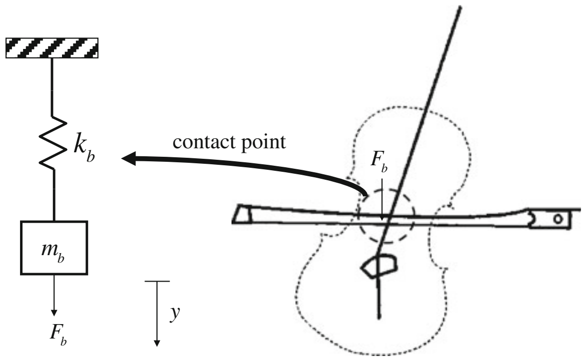


Fig. 2 Spring-mass system

If we assume that bowing a string is a spring-mass system, we can draw its system as shown in Fig. 2, and describe it as follows.

$$\sum F_b = m_b \frac{d^2 y}{dt^2} + k_b y \tag{4}$$

where m_b means a mass of bow measured on the contact point and k_b is a spring coefficient that corresponds to tension of bow hair in this system.

Because the bow stick is not stiff and bow hair is dangling from the tip and frog of the bow, tensions of bow hair are different according to the bow position. Tensions of the bow hair connected at the ends of the bow are high and their middle of the bow is low, depicted in Fig. 3b. Clearly increases in tensions cause the increase of k_b. In addition, because the weight of the part of the frog is much heavier than that of the tip, this also results in the increase of m_b, depicted in Fig. 3c. As a result, if we assume that acceleration of y is constant in Eq. 4, the bowing force F_b would be forced to increase as the contact point between the bow and the string approaches to the part of the frog depicted in Fig. 3d. Note that from the contact point of view denoted with the dotted line in Fig. 2, while bowing either upward or downward, the values of bowing force applied to the string must be same no matter where the point approaches to the frog or it approaches to the tip. Thus, as bowing with the bow hair of the part of the frog, the bowing force applied to the string would transgress "maximum bowing force" depicted in Fig. 1b. These inherent characteristics of the bow compel violinists to pay particular attention to the contact point and to vary the bowing force according to it.

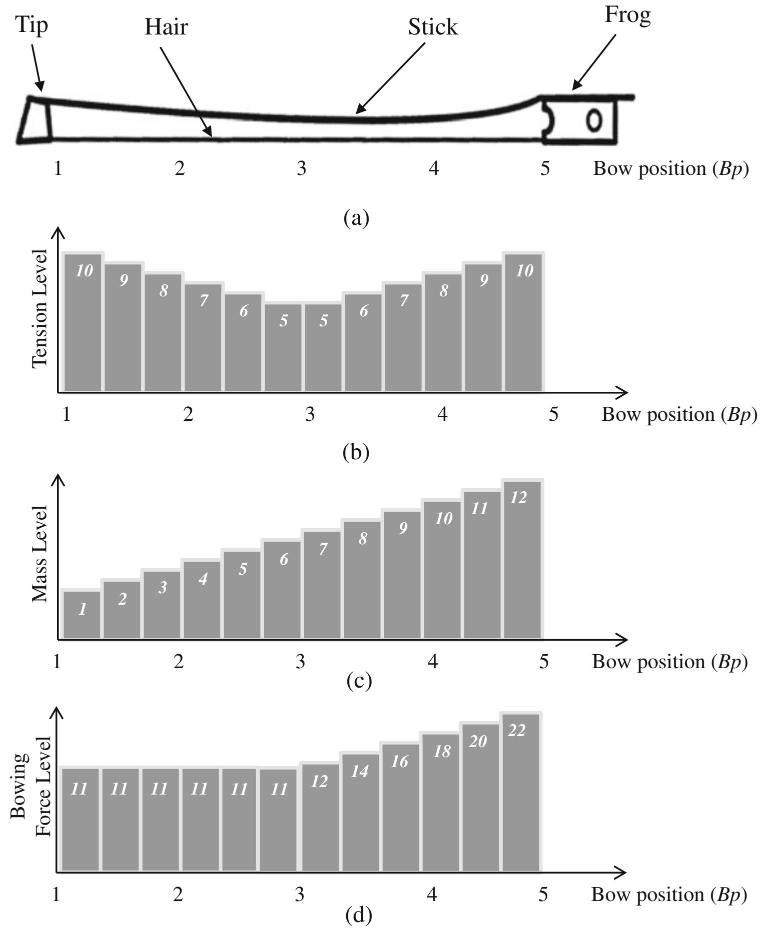


Fig. 3 **a** The components of a typical bow, denoted with the five bow positions and the tension levels. **b** Variations of the bow hair's tension according to the bow positions. **c** Variations of the bow's mass according to the bow positions. **d** Variation of the bowing force would applied on the string according to the bow positions

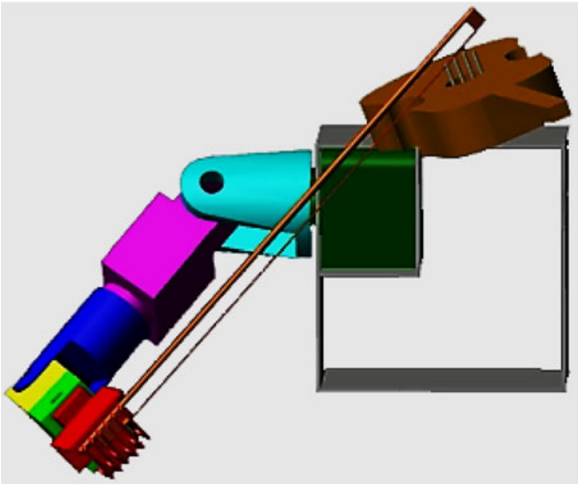
As mentioned above, maintaining the same bowing force at the contact point between the bow and the bow hair is of paramount importance when it comes to producing a good violin sound. However, because the values of m_b and k_b in the Eq. 4 are continually changed due to the inherent characteristics of the bow, it is almost impossible to retain the same force without considering an alternative. Therefore, we will introduce a passive damper system later that will offset a bowing force if it is applied too much on the string.

3 Violinist Robot

3.1 Introduction to Violinist Robot

The violinist robot we designed is a human-like torso robot of 0.5 m in height and 6 kg in weight (Fig. 4b). The robot body consists of 18 joints, so there are a total of 18 degrees of freedom (DOF). In particular, the right-hand arm is given a great deal of weight in the playing violin, as shown in Table 1. Accordingly, the robot's right arm can be implemented by 6 DOFs. On the other hand, 6 DOFs for the left arm is used only to hold the violin. As a result, it is not necessary for the left arm to be equipped with motors. There remains 6 DOFs for fingers, designed for the robot to adjust its fingers to push the appropriate note.

The proposed robot is composed of several primary modules: two personal computers (Intel Core2 Duo CPU 2.40 GHz each) and six microprocessors (DSP Texas 320F2811) are incorporated in the operation of this system. One of the computers, called the "control PC", is in charge of storing the motion data, including path information generated by RecurDyn [18], and transmitting control input to the robot. The other computer, called the "measurement PC", is



(a)

(b)

Fig. 4 **a** A model of the violinist robot simulated in SolidWorks. **b** The external appearance of the developed violin playing robot named "Violinist Robot"

used to evaluate recorded sound from a microphone (MIC). This MIC is attached to the violin's body.

3.2 Passive Damper Device

To generate the paths that the violinist robot's right arm would track to play the violin, we employed motion analyzer commercial software, RecurDyn. First we modeled the violinist robot in Solidworks [19] as shown in Fig. 4a and then, the modeled information was sent to RecurDyn. Using the software we generated a number of straight paths and stored them in the control PC. Each path is for the violinist robot to bow one string either upward or downward for about 300 mm in length.

Table 1 The specification of the robot's right arm

DOF	6DOF
Actuator	DC servo + incremental encoder
Arm length	244 mm + 295 mm + 196 mm
Repeatability	0.3 mm
Speed	0.60 m/s
Payload/Weight	2 kg / 6 kg
Communication	CAN 3.0
Power	24Vdc

However, if the robot's right arm holding the bow tracks a straight path upward to bow a violin, denoted with a solid line in Fig. 5, the bowing force F_b will not be kept at the same value and be changed in proportion to the variations of m_b and k_b as stated in Section 2.2 (see Fig. 3c) due to the m_b and k_b that are continually changed with respect to a bow position.

On the other hand, if the robot's arm tracks a curved path like a dashed line in Fig. 5, this

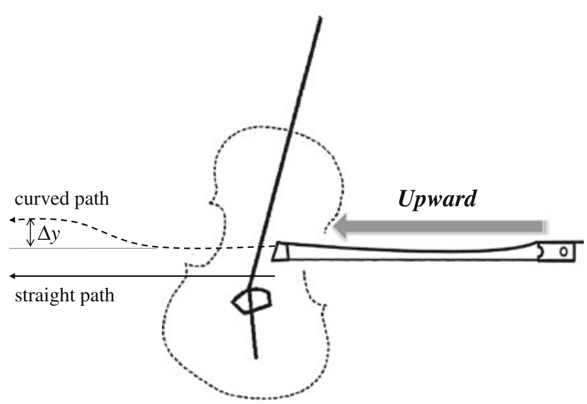


Fig. 5 A *solid straight line* cannot compensate the variations of m_b and k_b causing the different bowing force. On the other hand, a *dashed curved line* can generate Δy, displacement of y, and finally would compensate those variations

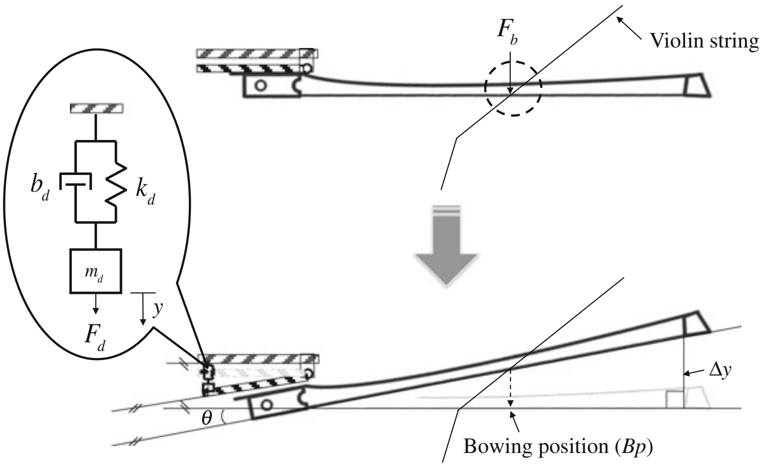


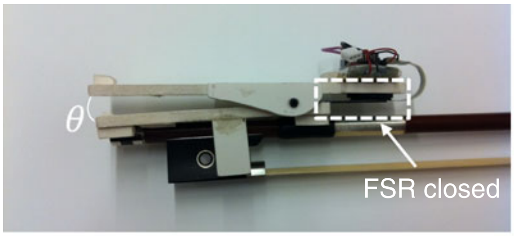
Fig. 6 A passive damper device

alteration can generate the displacement of y with respect to a bow position, and it can finally compensate the increase of m_b and k_b. i.e, as the contact point approaches to the part of the frog (around Bp 3 to 5, see Fig. 3), the value of y is gradually decreased in Eq. 4, and it finally results in the same value on the left side of the equation. (Note that decreasing values of y is made possible by defining a direction of y downward as shown in Fig. 2.) Thus, the bowing force can be maintained at the same value.

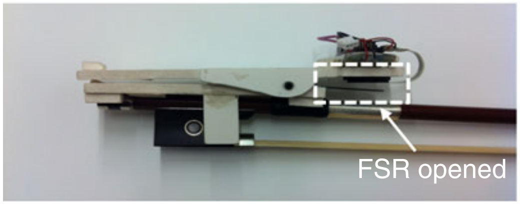
For this reason, we have devised a passive damper device like tongs so that it can generate Δy. In other words, this device was designed to allow the bow, which is supposed to track a straight path, to track a curved path by lifting a tip of the bow according to a bowing force applied on the string. This devised damper device is then modeled as follows,

$$F_d = m_d \frac{d^2 y}{dt^2} + b_d \frac{dy}{dt} + k_d y \tag{5}$$

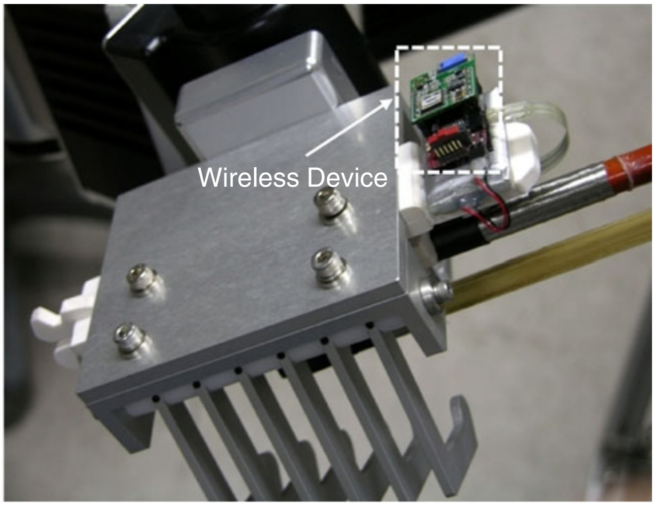
where F_d indicates the downward force that is generated by a bowing force F_b applied on the string, and the right side of the equation including constants of m_d, b_d, and k_d corresponds to the



(a) When Δy is generated



(b) When Δy is not generated



(c) Robot hand with the device

Fig. 7 A built passive damper device attached to the robot tension of the damper device, which can be modulated by fastening both sides of the device with a rubber band.

If a bow is attached to one side of the device, as illustrated in Fig. 6, and the other side is attached to the palm of robot's hand, Δy can be generated when the downward force F_d becomes stronger than the tension of this passive damper device. Since the one side of the device rotates on an axis, Δy depends on the angle θ between two sides of tongs, and is related to the bow posion Bp as follows.

$$\Delta y = Bp\tan\theta \qquad (6)$$

In order to measure the bow force on the string while playing the violin, we designed an electronic device with a force sensing resistor (FSR) and attached it to the passive damper device, as depicted in Fig. 7. FSRs are base on conductive ink technology. They are very sensitive, and their resistance is changed by several orders of magnitude as force is applied. Further, this sensor provides a range of output values, but usually requires an analog-to-digital converter to convert their values into a binary numbers, which a computer can understand. Then, these converted data are directly transmitted to the measurement PC through a wireless device.

Figure 7a shows when Δy is generated. In this case, as some amount of force are applied to the FSR, the output value becomes higher, which means this device offsets a bowing force applied too much on the string. Figure 7b shows when Δy is not generated. In this case, as no force is applied to the FSR, the output value becomes lower. Figure 7c shows the device with a wireless communication device attached on the robot's palm.

4 Experimental Results

To improve upon the quality violinist robot sound, we developed the passive damper device allowing the bow, which is supposed to track a straight path, to track a curved path by lifting a tip of the bow according to a bowing force applied on the string. Since this device is designed to vary its tension, we broke down it into three levels: *Level* 1 (relatively weaker tension), *Level* 2 (relatively medium tension), *Level* 3 (relatively stronger tension). These three different settings were selected according to the results of a preliminary parametric study. During these experiments, we had the robot track the given straight paths orthogonal to the D string, which has a fundamental frequency 294 Hz, upward for 3 sec. The snapshots of 8 sequences of this motion are depicted in Fig. 8. Then, the sounds were recorded on the measurement PC and analyzed.

This first experiment was performed with *Level* 3 (relatively stronger tension). This case

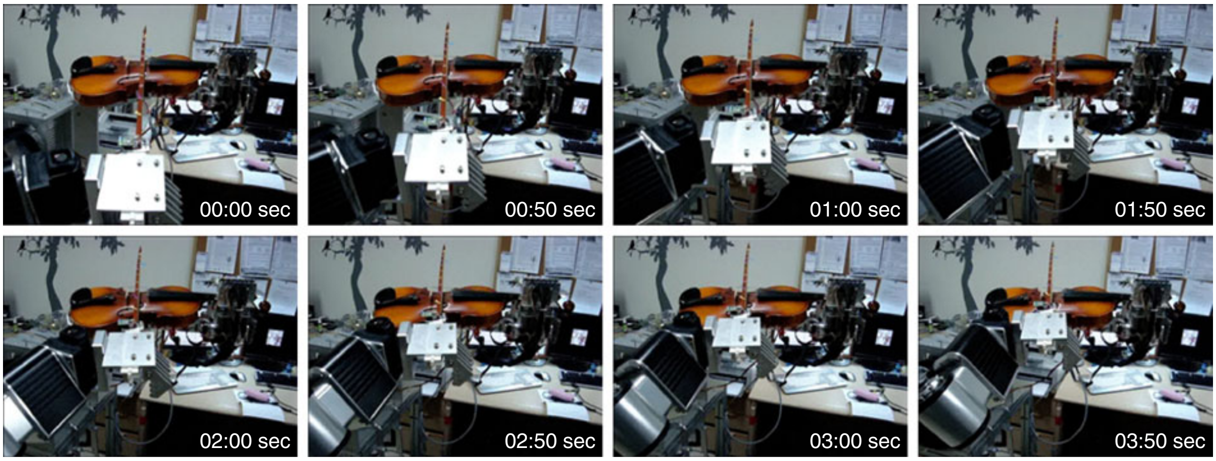


Fig. 8 The snapshots of eight sequences of bowing upward motion

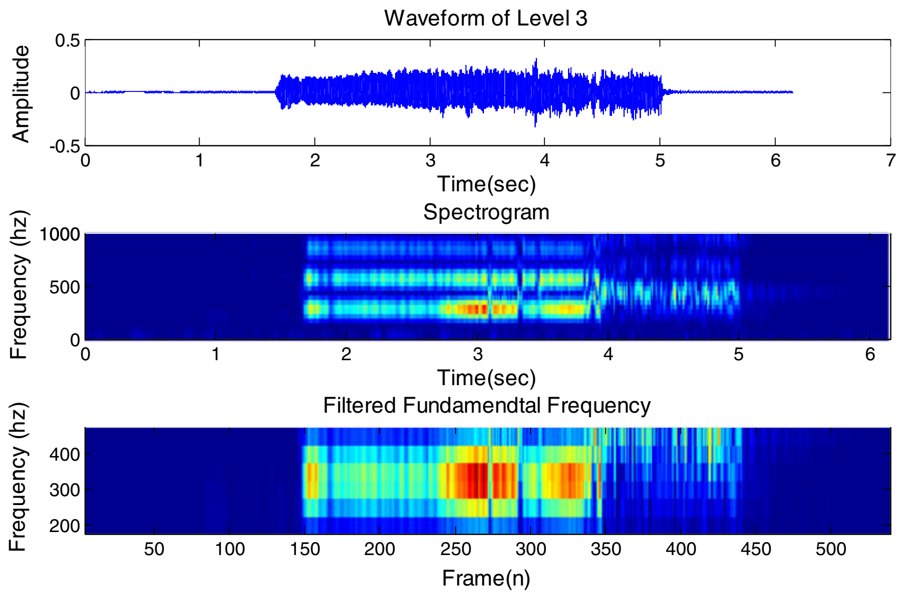


Fig. 9 Sound data while the violinist robot was bowing the D string using the passive damper device with *Level* 3: almost no benefit from the use of the damper device

was intentionally designed to rarely generate Δy, which means there would be almost no benefit from the used of the passive damper device. The results of the first experiment are depicted in Fig. 9. In this figure, the first graph shows the sound strength, while the second and third graphs show the sound spectrogram. In the sound spectrogram, the strength of each frequency is represented by a color. The horizontal axes of both graphs represent time. With the naked eye, as the robot bowed upward, we could see that there were no smooth waves and the uneven variation of the amplitude in Fig. 9. These undesirable results come from too much bowing force applied on the string when the robot used the bow position (Bp) from 4 to 5 to bow.

This second experiment was performed with *Level* 2 (relatively medium tension). In this case,

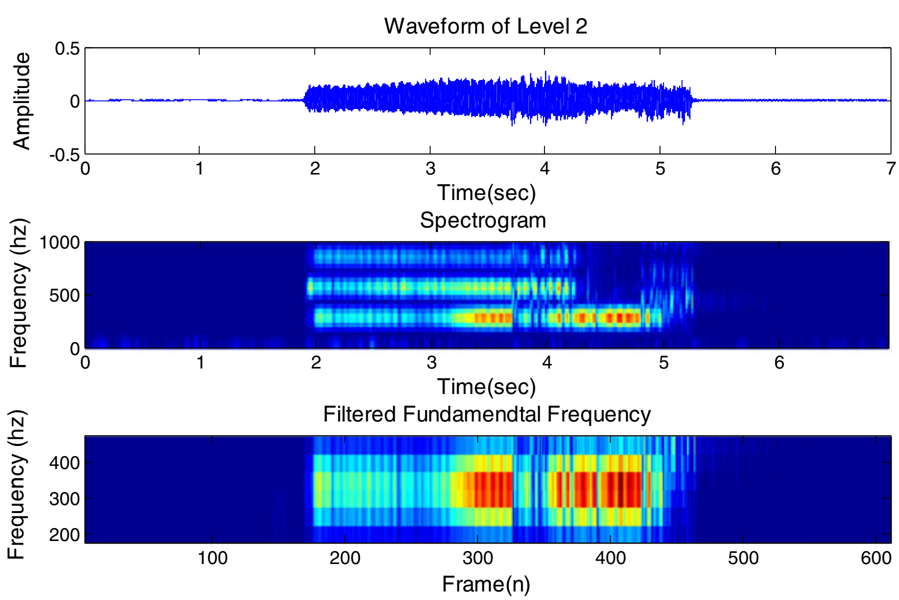


Fig. 10 Sound data while the violinist robot was bowing the D string using the passive damper device with *Level* 2

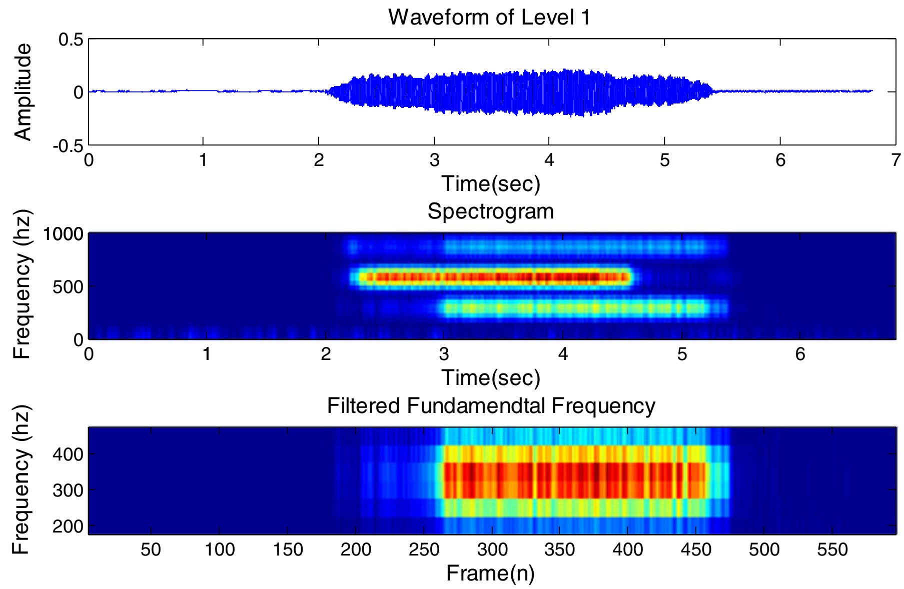


Fig. 11 Sound data while the violinist robot was bowing the D string using the passive damper device with *Level* 1: fully benefit from the use of the damper device

it was intended that Δy would be somewhat generated. The results of the second experiment are depicted in Fig. 10. As shown in this figure, there is a little improvement on smooth waves and the uneven variation of the amplitude, compared to the previous experiment, although it seems that there is still too much bowing force applied on the string when the robot used the *Bp* from 4 to 5 to bow.

This third experiment was performed with *Level* 1 (relatively weaker tension). In this case, we intended that Δy would be suitably generated to offest too much force applied on the string. The results of the third experiment are depicted in Fig. 11. As shown in this figure, there is a distinguishable improvement on smooth waves and the uneven variation of the amplitude, compared to the previous two experiments. Especially, this showed a well-kept sound past the *Bp* 4. Furthermore, pitch of sound, timbre, and volume are relatively clear and constant, as the third figure shows.

Figure 12 shows a comparison of the measured values with the FSR attached to the damper device. This comparison also shows how much forces are compensated on the string by each *Level*. Note that an output format of the FSR is a voltage ranging from 0 to 3.3 volt, so the nearer to zero the value is, the weaker force is compensated and applied to the FSR. As you can see in this figure, as the *Level* decreases from 3 to 1, there are bigger offsets produced, and this finally results in a better quality of violin sounds.

To show a quantitative analysis on a quality of violin sounds with the passive damper device, we refered to the sound quality evaluation function previously introduced in [10] and slightly modified it. The authors in [10] considered the relation among the pitch, the loudness, and the harmonic structure content of flute sound. Similarly, the authors in [17] also analyzed the pitch and loudness based on the harmonic structure of violin sound for their sound evaluation. In this paper, we

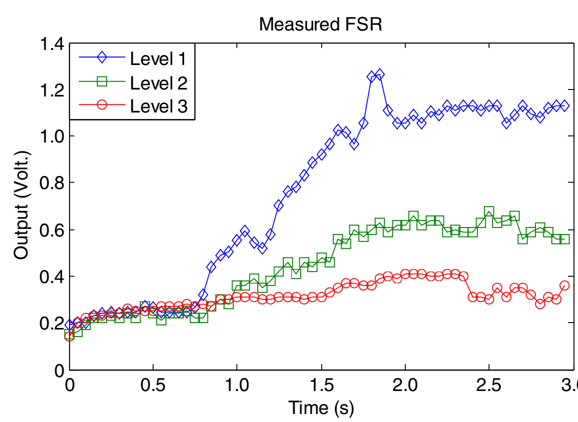


Fig. 12 Output of the force sensing resistor (FSR) according to three different tensions of the passive damper device

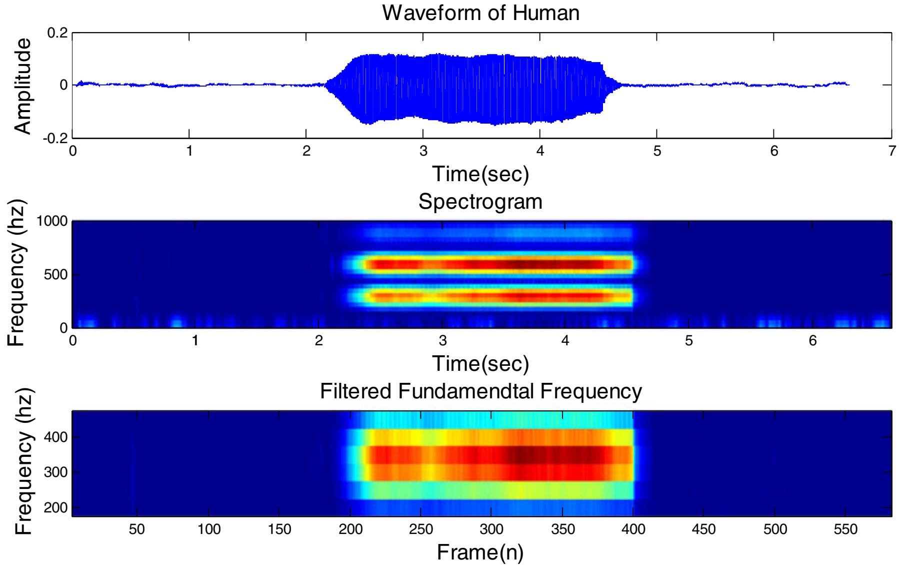


Fig. 13 Sound data while the skilled human was bowing the D string

investgated the change of harmonic in the range of 200 to 450 Hz for the simplicity of the evaluation. Therefore, we summed up the variations of amplitude in waveforms shown in the third row of Figs. 9, 10, and 11 with the following evaluation function.

$$Q = \frac{1}{\gamma} \sum\nolimits_{n=1}^{T_n} \mathrm{X}\left[n\right] - \mathrm{X}\left[n-1\right] \tag{7}$$

where X[.] is the sum of amplitudes in each waveform frame n, T_n is the total number of frame, γ is a positive constant, and Q is the sequence of the sound evaluation function, indicating a score of the recorded sound.

From this analysis, we are able to analyze the quality of the recorded sound. For example, if the value of Q is near zero, then there is less change of harmonic in the recorded sound, and the pitch, timbre and volume of the sound are kept in a decent level to produce good sound. Conversely, if the value of Q is far to zero, then it means that there are more change of harmonic in the recorded sound up and down, and also means pitch, timbre and volume are not kept in the decent level. Furthermore, in this case, we may listen to raucous or surface sound. In short, the nearer to zero the value of the Q is, the better is the quality of the sound.

Additionally, we conducted an experiment in a skilled human to verify the sound evaluation function. In this experiment, the skilled human bowed upward for 3 sec, and sound was recorded with a microphone. The results of this experiment are depicted in Fig. 13, and the sound evaluation function provided a score as 1.1412, which are close to zero. Therefore, this result validates that the good sound illustrates a small difference in the amplitude of each waveform frame, as we expected. Next, we analyzed further on sound data previously produced by the violinist robot to evaluate its performances with the sound evaluation function. As a result, sound evaluation function scored 8.672, 7.0317, and 2.9433, respectively, and the results of these quantitative analysis are depicted in Fig. 14.

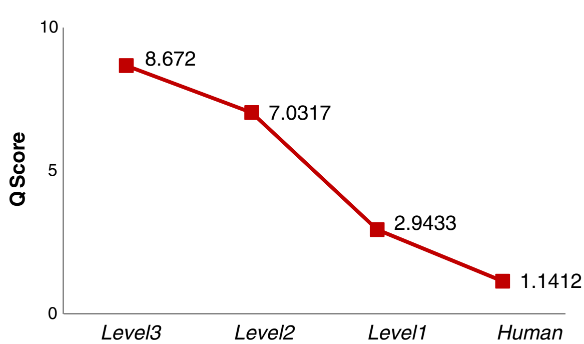


Fig. 14 Q scores showing the quality of the sounds. Note that the nearer to zero the value of the score is, the better is the sound quality of the violin

As shown in Fig. 14, the stronger the tension of the passive damper system was, the worse the sound quality was. When the violinist robot bowed the D string with the *Level* 3, the scores showed the largest value among the three levels. Moreover, when the violinist robot bowed the D string with the *Level* 2 and *Level* 1, all scores exhibited much smaller values than those of the *Level* 3. Consequently, it can be said that the weaker the tension of the passive damper system was, the better the sound quality was. Furthermore, this numerical result proves that the passive damper device could contribute to the improvement of the overall qualities of the sound.

5 Conclusions

In the first stage of the development of the violinist robot having an ability to produce good violin sounds, we observed the close relationship between the bowing force and the sound quality of the violin. On top of that, keeping the same amount of bowing force at the contact point between the bow and the bow hair was very important in terms of producing a good quality of violin sound. It was however not easy without considering an alternative due to the inherent characteristics of the bow such as different tensions of bow hair according to the bowing position and different weight of the bow at the point. Thus, we devised the passive damper device with the purpose of maintaining the same bowing force. This device was designed to be attached to the palm of robot's hand, and a bow was attached to one side of the device. Using this device, the robot could maintain the same bowing force by generating a displacement of path. As a result, we confirmed whether the violinist robot could reproduce a distinguishable sound when we used the passive damper device.

In this paper, we only varied a bowing force with a bowing velocity and the sounding point remained constant to observe the relationship between the bowing force and the sound quality of the violin. However, a bowing velocity and a sounding point may both contribute to sound quality. Hence, in future studies, we will vary both the bowing velocity and the sounding point to determine their relationship as well as the sound quality.

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