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Mechanism Design and Air Pressure Control System Improvements of the Waseda Saxophonist Robot

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***Abstract*— Since 2007, the research on the anthropomorphic saxophonist robot at Waseda University aims in understanding the human motor control from an engineering point of view as well as an approach to enable the interaction with musical partners. As a result of our research, last year we have introduced the Waseda Saxophonist Robot No. 1 (WAS-1), composed of 15-DOFs that reproduced the lips (1-DOF), tonguing (1-DOF), oral cavity, lungs (2-DOF) and fingers (11-DOFs). However, even that the mouth mechanism of WAS-1 was useful in order to adjust the pitch of the saxophone sound, the range of sound pressure was too narrow. Thus, no dynamic effects of the sound can be reproduced (i.e. crescendo and decrescendo). Moreover, the finger mechanism was designed only to play from C3-C#5. On the other hand, a cascade feedback control system has been implemented in the WAS-1; however, a considerable delay in the attack time to reach the desired air pressure was detected. Therefore, in this paper, the Waseda Saxophone Robot No. 2 (WAS-2) which is composed by 22-DOFs is detailed. The lip mechanism of WAS-2 has been designed with 3-DOFs to control the motion of the lower, upper and sideway lips. In addition, a human-like hand (16 DOF-s) has been designed to enable to play all the keys of the instrument. Regarding the improvement of the control system, a feed-forward control system with dead-time compensation has been implemented to assure the accurate control of the air pressure. A set of experiments were carried out to verify the mechanical design improvements and the dynamic response of the air pressure. As a result, the range of sound pressure has been increased and the proposed control system improved the dynamic response of the air pressure control.**

I. INTRODUCTION

THE development of anthropomorphic robots is inspired by the ancient dream of humans replicating themselves. However, human behaviors are difficult to explain and model. Owing to the evolution of computers, electronics, and signal processing, this ancient dream is becoming a reality. In fact, current humanoid robots are able to perform activities such as dancing and playing musical instruments.

However, these mechanical devices are still far from understanding and processing emotional states as humans do. Research on musical performance robots seems like a particularly promising path toward helping to overcome this limitation [1], because music is a universal communication medium, at least within a given cultural context. Furthermore, research into robotic musical performance can shed light on aspects of expression that traditionally have been hidden behind the rubric of "musical intuition" [2]. In 1984, at Waseda University, the WABOT-2 was the first attempt of developing an anthropomorphic musical robot; it was able to play a concert organ. Then, in 1985, the WASUBOT built also by Waseda, could read a musical score and play a repertoire of 16 tunes on a keyboard instrument [3]. The late Prof. Ichiro Kato argued that the artistic activity such as playing a keyboard instrument would require human-like intelligence and dexterity [4]. Nowadays, different kinds of musical performance robots (MPRs) and robotic musicians (RMs) have been developed. MPRs are designed to closely reproduce the required motor skills displayed by humans in order to play musical instruments ([5]-[8]).

Some examples of MPRs are described as follows. Shibuya is developing an anthropomorphic arm which reproduced the movement required to play a violin [6]. In particular, this violin robot is designed to produce expressive sounds by considering kansei (sensitivity). The arm has a total of 7-DOFs actuated by DC motors. From experimental results, the violin robot is able of playing notes with a high level of repetitiveness. Takashima has been developing different music performance robots that are able of playing wind instruments such as [7]: saxophone, trumpet, trombone and shakuhachi (traditional Japanese bamboo flute). In particular, the saxophone playing robot has been developed under the condition that the musical instrument played by robots should not be change or remodeled at all. This robot is composed of an artificial mouth, fingering mechanisms and air supplying system. Due to the complexity of replicating the motion of human fingers, the fingering mechanism is composed by

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twenty-three fingers so that each finger can press each key of the saxophone. Shimojo has worked on a violin-playing robot, which it is composed by a commercial 7-DOFs manipulator and a 2-DOFs fingering mechanism [8]. The end effector of the manipulator has been designed to hold a bow. A force/torque sensor has been attached to the end effector to control the bowing pressure. As a result, the violin-playing robot is able of performing simple musical scores.

In resume, the research on MPRs has been particularly intensified in recent decades. In fact, we may distinguish four different researches approaches [2]: Enabling the Human and Robot interaction, understanding the human motor control, introducing new ways of art/entertainment and introducing new methodologies of music teaching. Even that the above anthropomorphic musical robots have achieved promising results; up to now, only few of them are able to perform as human musicians (in terms of perception and motor dexterity). Moreover, none of the above robots are able of playing different kinds of musical instruments which could be useful to improve our understanding of the nature of human musicians.

For this purpose at Waseda University, since 2007, we have proposed the development of an anthropomorphic saxophone robot. In [7], the requirements for developing a tenor saxophone performance robot were introduced at Hosei University. Such automatic performance saxophone robot is composed by three main components: mouth mechanism (as a pressure controlled oscillating valve), the air supply mechanism (as a source of energy), and fingers (to make the column of air in the instrument shorter or longer). Such automatic performance saxophone robot has been designed under the principle that the instrument played by the robot should not be changed. However, a total of twenty-three fingers have been used to play the saxophone's keys (actuated by solenoids), a modified mouth mechanism has been designed (composed by a flexible artificial lip and a reed pressing force control mechanism were developed) to attach it with the mouthpiece, and no tonguing mechanism has been implemented (normally reproduced by the tongue motion).

From these issues, it could be rather difficult to understand the human motor control mechanism. Instead; based on our experience in developing the WF-4RIV, we proposed the development of an anthropomorphic saxophonist robot as an approach to extend our knowledge on the motor control skills required by players to play woodwind instruments. In addition, we would like to enable the interaction with musical partners to study in more detail the HRI in a musical context. As a matter of fact, we are aiming as a long-term goal two basic issues: enabling the interaction between two human-like robots (by developing two different robots able of performing different wind instruments), and enabling a single human-like robot to play different kind of wind instruments (our ability to enable a single human-like robot to play different kind of wind instruments can be studied in detail).

As a result of our research, in [9], we have presented the Waseda Saxophonist Robot No.1 (WAS-1), which was composed by 15-DOFs required to play an alto saxophone. In particular, the mouth (1-DOF's lower lip), tongue (1-DOF), oral cavity, artificial lungs (1-DOF's air pump and 1-DOF's air flow valve) and fingers (11-DOFs) were developed. Both lips and oral cavity were made of a thermoplastic rubber (named Septon). The tongue was implemented to reproduce the tonguing technique; which is an important source for adding expressiveness to the saxophone performance. Even that the lip mechanism of WAS-1 was useful in order to adjust the pitch of the saxophone sound, the range of sound pressure was too short. Moreover, the finger mechanism was designed only to play from C3 to C#5.

Therefore, in this paper, the mechanical design of the lip and finger mechanisms were improved to increase the range of sound pressure (required to add dynamic effects to the sound such as crescendo and decrescendo) and to enable the saxophone robot to play all the keys of the alto saxophone (A#2 to F#5). From the control system point of view, a cascade feedback control system has been implemented. However, a considerable delay in the attack time to reach the desired air pressure was detected when playing musical scores at fast tempo. Thus, we describe the mechanical improvements on the lip and hand mechanisms on the anthropomorphic saxophone robot and the implementation of a feed-forward air pressure control system with dead-time compensation.

II. WASEDA SAXOPHONIST ROBOT NO. 2

In this year, we have developed the Waseda Saxophonist Robot No. 2 (WAS-2) which it has been designed to increase the range of sound by improving the design of the artificial lips and increase the range of fingering by designing a human-like hand. In particular, the WAS-2 is composed by 22-DOFs that reproduce the physiology and anatomy of the organs involved during the saxophone playing as follows (Figure 1): 3-DOFs (from which 1-DOF is passively controlled) to control the shape of the artificial lips, 16-DOFs for the human-like hand, 1-DOF for the tonguing mechanism and 2-DOFs for the lung system (1-DOF for the air pump and

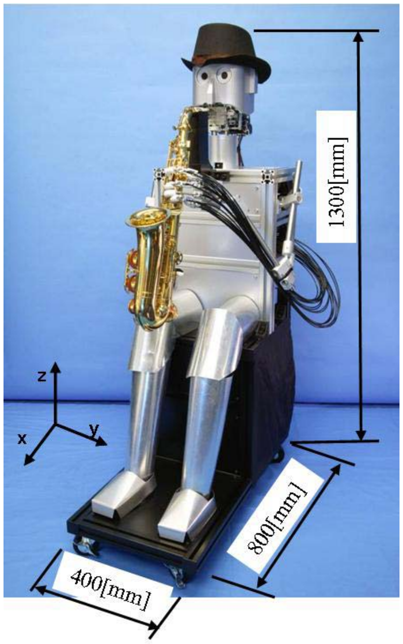

Fig.1 Anthropomorphic Saxophonist Robot WAS-2.

1-DOF for the valve mechanism).

A. Design Improvements of the Mouth and Hand Mechanisms

The artificial lip of the mouth mechanism of the WAS-1 was designed with 1-DOF in order to control the vertical motion of the lower lip [9]. Based on the up/down motion of the lower lip, it became possible to control the pitch of the saxophone sound. However, it is difficult to control the sound pressure by means on 1-DOF. In addition, as we have previously described, in the future the saxophonist robot should be able of stand-up as a human player does. Therefore, it is difficult to hold the instrument with the artificial mouth.

For this purpose, the improved version of the mouth mechanism has been designed to expand the range of sound as well as to reduce the movement of the instrument when the robot holds the instrument with its mouth. The new artificial lip of the WAS-2 is shown in Fig. 2. The lip mechanism consists of 2-DOFs designed to control the up/down motion of both lower and upper lips and a passive 1-DOF (to modify the shape of the side-way lips). Thanks to this mechanism design, the dimensions of the robot's mouth weren't increased and the control of the artificial lip's shape can be improved. The material of the artificial lips is thermoplastic elastometer (Septon), which reproduces the elasticity and stiffness of human lips. In particular, the arrangement configuration of the lip mechanism is as follows:

1. Upper Lip: When the lower lip is slightly displaced, a leak of the air flow coming from the artificial lungs is produced. From this, the range of sound pressure drastically changes. By using the actuation system of the lower lips (the rotation of the motor axis is converted into vertical motion by means of a timing belt and ball screw), it is possible to avoid the leak of air flow (Figure 2a).
2. Lower Lip: Basically, the lower lip apply the required pressure to the reed of the instrument in order to produce its vibration. The actuation system is composed by a timing belt and ball screw so that the rotational movement of the motor axis is converted into vertical motion. From this, it is possible to change the amount of pressure on the reed (Figure 2b).
3. Sideway Lip: In order to avoid the rolling of the artificial lips, a passive 1-DOF coupled to the motion of the upper lip has been implemented to close/open the lips when the instrument is hold by the mouth (Figure 1a). The upper lip is attached to a roller with a limited range of motion. When the range of motion is exceeded (Figure 3), the guide is horizontally moved along the sliding guide. From this, it becomes possible to implement the extension motion of the lips. On the order side, the contraction motion depends on the stiffness properties of the artificial lips.

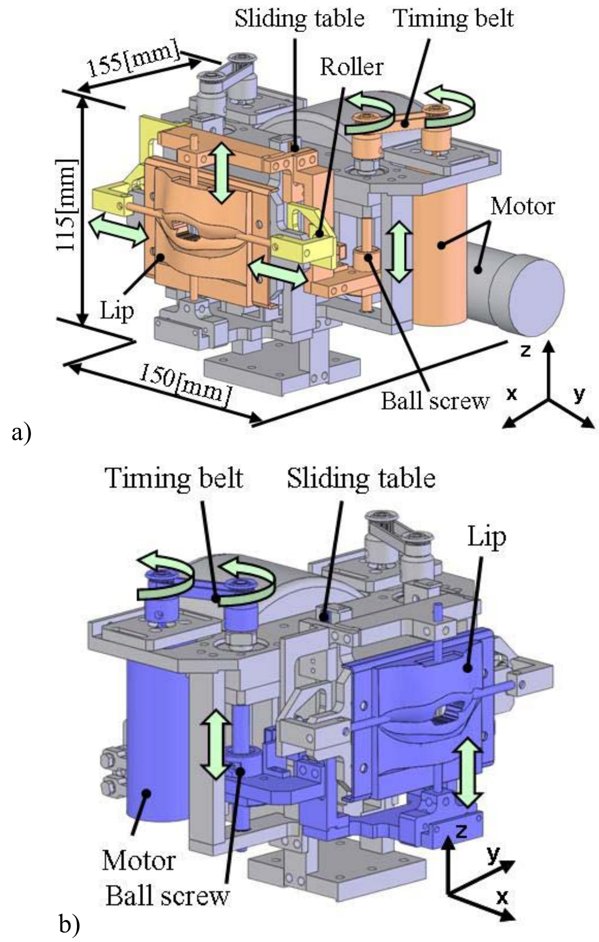

Fig.2 New mouth mechanism designed for the WAS-2, where the motion of a) upper and sideway lips, as well the b) lower lips was implemented.

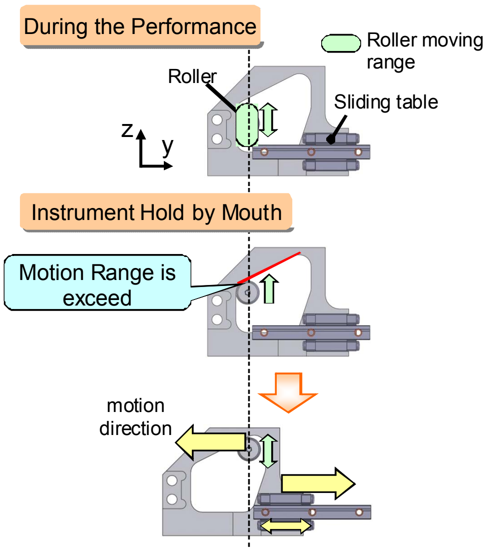

Fig.3 Detail of the mechanism of the passive DOF implemented for the motion of the sideway lip.

In addition to the mechanism design improvement, we have embedded an array of sensors to determine the displacement of the instrument while the saxophone is hold with the robot's mouth. For this purpose, we have embedded an array of sensors to sense the changes in shape of the lips. As a first approach, four photo-interrupters were attached as it shown in Fig. 4. The photo interrupter combines a GaAs IRED with a high-sensitivity phototransistor in a super-mini package with dimension of 2.7 mm x 3.2 mm. The light emitted by the

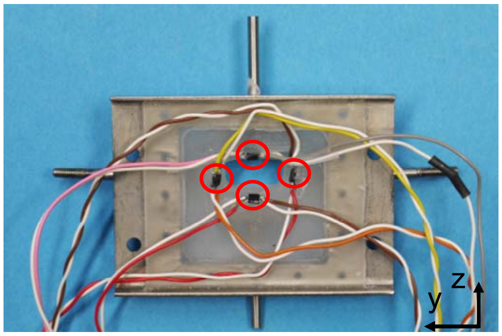

Fig.4 Detail of the embedded sensor system implemented for the artificial lips of WAS-2.

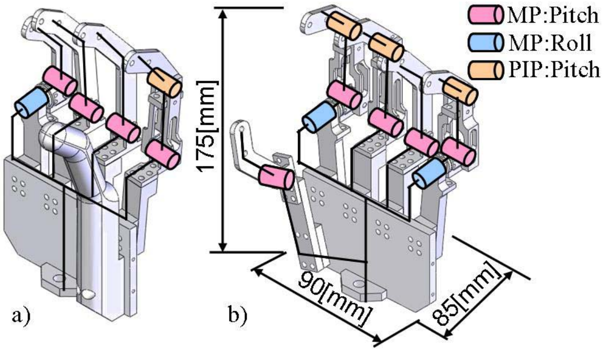

Fig.5 Arrangement of DOFs: a) right hand; b) left hand

Table I. DOFs Configuration of the Human-Like Hand of WAS-2

Finger Name	Left Finger	Right Finger
thumb	1	-
index	3	2
middle	2	1
annular	1	2
little	3	2

photo-interrupter is then reflected by the surface of the mouthpiece of the instrument.

Finally, in order to produce the saxophone sound, it is required to control the motion of each of the fingers to push the correspondent keys. The finger mechanism of the WAS-1 was composed by a link connected directly to the RC motor axis. In particular, eleven motors were used in order to push each of the keys required to play from the C3 to C#5. However, with the alto saxophone is possible to play from A#2 to F#5. For this purpose, a new human-like hand has been designed, which it is composed by 16-DOFs (Figure 5). The configuration arrangement of the finger is resumed in Table 1. In order to reduce the weight on the hand mechanism due to the actuation mechanism, a wire and pulley connected to an RC motor axis was used. All the motors were controlled based on the RS-485 communication protocol.

B. Implementation of an Air Pressure Feed-Forward Control System with Dead-Time Compensation

In our previous research, a cascade feedback control system was implemented to assure the accuracy of the air pressure during a musical performance [9]. Basically, based on the measurements of the pressure sensed at the output of the air pump and the position of the lower lips, the air pressure has been controlled. However, during the attack time the target air pressure is reached around 100ms later during a musical performance. Mainly, this effect is related to the way the musical performance control is implemented. Basically, the signal of the note to be played is sent to the control system through a MIDI message. As soon as message of a note change is received, the air pressure as well as the position of the lower lips is adjusted. Thus, a delay on the control of the air pressure (during the attack time) is observed.

Actually, if we analyze the performance of a human playing the saxophone, the distance between the lungs and the oral cavity there are a few dozens of centimeters. This distance provokes the existence of dead-time. However, musicians when playing a musical performance, in order to avoid any delay on the adjustment of the air pressure located inside the oral cavity, controls the required parameters of the lungs and the mouth beforehand the notes changes.

Inspired on the above principle, a modified version of the feedback error learning has been used. The feedback error learning is a computational theory of supervised motor learning proposed by Kawato [10]; which is inspired by the way the central nervous system. In addition, Kawato extended that the cerebellum, by learning, acquires an internal model of inverse dynamics of the controlled object [11]. From this extension, the feedback error learning can be also used as training signal to acquire the inverse dynamics model of the controlled system based on Neural Networks. On the other hand, the dead-time compensation is used to control devices that take a long time to show any change to a

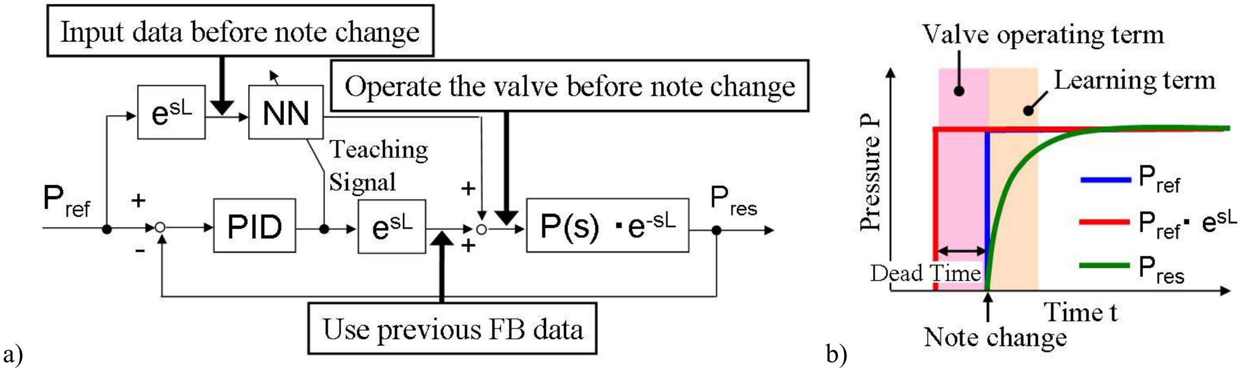

Fig.6 a) Block diagram of the proposed feed-forward control system with dead-time compensation implemented to assure the accuracy of the air pressure control during a performance; b) Principle of operation of the dead-time compensation during the attack time phase.

change in input. A dead-time compensation control uses an element to predict how changes made now by the controller will affect the controlled variable in the future [12].

For our purpose, we have proposed the implementation of a feed-forward error learning control system with dead-time compensation as it is shown in Fig. 6a. The inputs of the ANN are defined as follows (the input is based on the difference with the previous played note): pressure reference, note, and lower/upper lips position. In this case, a total of six hidden units were used (experimentally determined while varying the number of hidden units). As an output, the position of the air valve is controller to assure the accurate control of the required air pressure to blow a sound. In addition, a dead-time factor (referred as e^{sL}) is introduced to compensate the delay during the attack time (Figure 6b).

III. EXPERIMENTS & RESULTS

A. Range of Sound Pressure

In order to verify if the designed new mouth mechanism enables to extend the range of sound pressure; we have compared the previous mechanism with the new one while playing the notes from C3 to C5. The experiment results are shown in Fig. 7. As we may observe, the new mechanism has effectively increased the range of sound pressure (an average increment of 33%). Even though the range of sound pressure was expanded, still there differences with the one measure by an intermediate level saxophonist.

Thanks to this improvement, we could perform experiments with the WAS-2 in order to vary the dynamic properties of the sound such as decrescendo. For this purpose, we performed an additional experiment in order to program the WAS-2 to reproduce the decrescendo effect on the sound. The experimental results are shown in Fig. 8. As we may observe, we could observe a difference on the sound pressure while applying the decrescendo effect in comparison to the plain sound.

In addition, we have performed an experiment to verify the possibility of sensing the movement of the lips while holding the saxophone with the mouth. For this purpose, we have programmed the upper and lower lips to move from up and down (0.5 mm) and vice-versa. The experimental results are shown in Fig. 9. As we may observe a linear response has been obtained without hysteresis effects. From these results, we consider the possibility of using such information to adjust the position of the instrument (by adding an actuation system to the arms) and to measure the vibration of the reed (by means of analyzing the frequency content of the signal from the sensor placed on the lower lip.

B. Air Pressure Feed-Forward Control System with Dead-Time Compensation

In order to determine the effectiveness of the proposed control system implemented on the WAS-2, we have programmed the saxophonist robot to perform the moonlight serenade composed by Glenn Miller. In order to train the ANN, a total of 523 learning steps were done. The experimental results are shown in Fig. 10. As we may observe, we can clearly observe that the proposed feed-forward control system with dead-time compensation presented a more stable dynamic response to the air pressure reference (in particular during the first 5sec of the musical performance). In order to

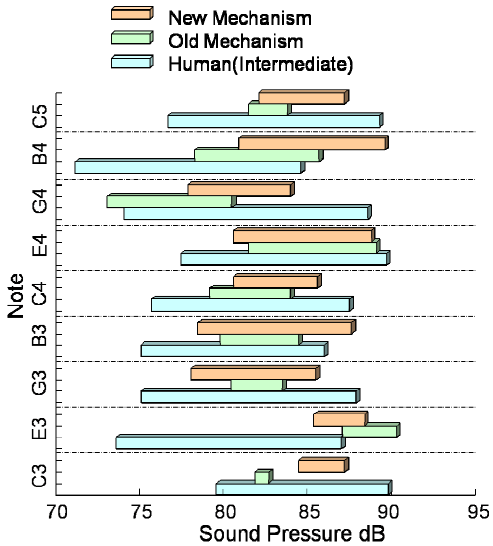

Fig.7 Comparison of the range of air pressure between the previous mouth mechanism of WAS-1 and the new one of WAS-2.

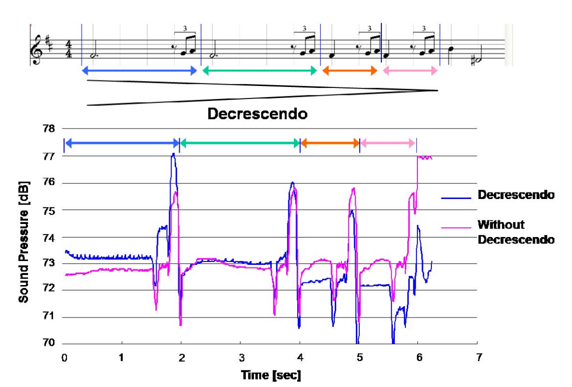

Fig.8 Experimental results to analyze the imitation of the decrescendo with WAS-2.

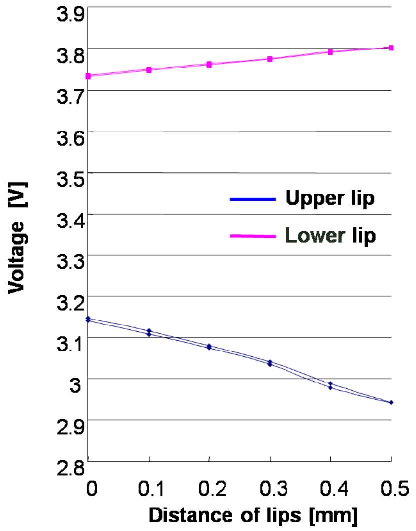

Fig.9 Experimental results while sensing the movement of the upper and lower lips with the proposed embedded sensors.

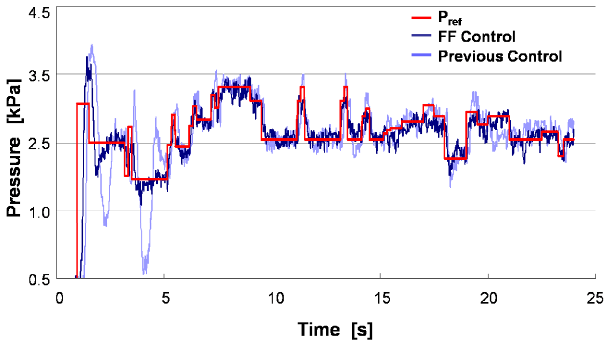

Fig.10 Experimental results with the Feed-Forward Control System with Dead Time Compensation.

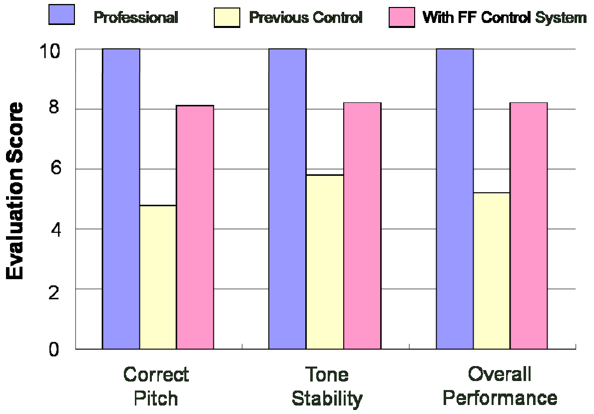

Fig.11 Experimental results of the subjective evaluation of the improvements of the WAS-2.

compare both dynamic responses, we have computed the correlation coefficient respect to the target signal (P_{ref}). The correlation coefficient is a quantity that gives the quality of a least squares fitting to the original data (in this case, the target signal). As a result, we found that the resulted air pressure with the feed-forward control system with dead-time compensation was more similar to the target one (correlation coefficient of 0.636) than the previous control system (correlation coefficient of 0.459). With these results, we can assure the improvements done respect to the previous control system (cascade feedback control).

In addition, we have performed a subjective analysis of the improvements thanks to the implementation of the propose control system. For this purpose, we have recorded the performance of WAS-2 while playing the moonlight serenade with the proposed control system and with the previous one. A total of twelve subjects were asked to compare the above recordings with the performance of a professional saxophonist. The evaluation criterions are: pitch quality, tone stability and overall performance. The maximum score (10) was considered the professional one. The experimental results are shown in Fig. 11. As we may observe, a higher evaluation was given to the performance in all the evaluation parameters with the feed-forward control system.

IV. CONCLUSION & FUTURE WORK

In this paper, we have presented the details of the mechanical improvements on the Waseda Saxophonist Robot No. 2, designed to mechanically reproduce the organs involved during the saxophone playing. In particular, the mouth and hand mechanisms were improved to expand the range of sound pressure as well as the possible notes played by the robot with the fingers. Moreover, an air pressure feed-forward control system with dead-time compensation has been implemented to improve the dynamic response of the air pressure control. From the experimental results, we verified the expansion of the range of sound pressure as well as verified the improvement of the dynamic control of the air pressure during the performance.

Even that we found further improvements on the above issues of the saxophone playing, we still require performing further improvements. In particular, during the performance (especially when playing one octave above from note to note), there is a deviation of the pitch. Therefore, the proposed feed-forward control system will include as well the pitch information (acquired by measuring the vibration of the reed with the embedded sensors attached to the artificial lips).

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