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CONTROL OF BLOWN AIR FOR A SOPRANO-RECORDER-PLAYING ROBOT USING UNSTEADY FLOW RATE MEASUREMENTS AND CONTROL TECHNIQUES

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ABSTRACT

The purpose of this study is to construct a robot playing a soprano recorder that sounds like a human playing a soprano recorder. Recent years have seen the development of robots that entertain people by playing a variety of musical instruments. There have been many reports describing the musical expression of such robots, for example, that of robots with artificial lips for playing wind instruments. However, particularly when performing special musical effects, such as vibrato, tremolo, and tonguing, robots playing wind instruments often produce artificial sounds that differ considerably from those produced by their human counterparts. To build a soprano-recorder-playing robot that produces natural sounds matching those produced by a human player, this study employs unsteady flow rate measurements and control techniques. A spool type servo valve and a quick response laminar flow sensor (QFS), whose dynamic characteristics are calibrated using an unsteady flow rate generator, are applied for controlling the blown air for the developed recorder-playing robot.

KEY WORDS

Pneumatics, Flow Rate Measurement, Unsteady Flow Generator, Quick Response Laminar Flow Sensor, Recorder-playing Robot

NOMENCLATURE

E	:	Control signal of servo valve
f	:	Frequency
G	:	Mass flow rate
G_{out}	:	Mass flow rate from unsteady flow generator
K_v	:	Flow rate gain of servo valve
L_c	:	Sound level
P	:	Pressure
P_a	:	Atmospheric pressure
ΔP	:	Differential pressure
Q	:	Flow rate (L/min ANR)
Q_{ref}	:	Set flow rate value
t	:	Time

INTRODUCTION

Due to the rapid development of robot technology in recent years, the number of applications of robots in fields other than industrial fields has been increasing. Robots for entertaining people or encouraging social interactions have been developed[1]. For example, in recent years robots have entertained people by playing a variety of musical instruments[2]. To enable the musical expression of these robots, researchers have created many devices, including artificial lips for playing wind instruments.

However, robots playing wind instruments often produce artificial sounds that differ considerably from those produced by their human counterparts. This is particularly true for robots performing special musical effects, such as vibrato, tremolo and tonguing.

We have developed a robot that plays a soprano recorder before this research. Nevertheless, naturally expressing the special musical effects of tonguing and vibrato remain a problem.

Therefore, the purpose of this study is to build a robot playing a soprano recorder that produces natural sounds, that is, sounds matching those produced by a human player. This study employs unsteady flow rate measurements and control techniques for controlling the air blown through the soprano recorder. In the present research, the following procedure was conducted. First, not only the static but also the dynamic characteristics of the flow sensor used for measuring the blown air were calibrated using an unsteady flow generator to judge whether the performance of the flow sensor was high enough for measurement of the blown air. Second, using the flow sensor, the blown air flow rates were measured for real human players (members of Fukuoka Institute of Technology Wind Symphony) expressing vibrato with a soprano recorder. Finally, the identified blown air flow rate model was applied to the air flow rate control system of the soprano-recorder-playing robot. The flow rate was controlled by a spool type servo valve (SP valve). The recorder sounds played by a human and the sounds played by the robot were compared using a sound analyzer.

OVERVIEW OF THE DEVELOPED RECORDER-PLAYING ROBOT

We previously developed the recorder-playing robot shown in Fig. 1. The robot system consists of a computer, a musical keyboard (Edirol MIDI keyboard controller PC-50), an electronic circuit as a signal receiver and a fingering controller, an SP valve (Festo MPYE-M5-B-SA), a soprano recorder (Aulos 503B), and a fingering part consisting of solenoid plungers (Yamaha DC Solenoid MD-232) (Fig. 2). The configuration of the recorder-playing robot system is shown in Fig. 3. In the computer, MIDI (Musical Instrument Digital Interface)[3] sequencer software (Cakewalk SONAR 6 LE) generates MIDI signals for playing (controlling) the recorder. The sequencer software also generates accompaniment music in synchronization with the MIDI signals. The MIDI signal is sent to the musical keyboard, which can be used both as a MIDI signal transmitter and a musical interface. Then, the MIDI signal is received by the electronic circuit. In the circuit, the MIDI signal is divided into two signals. One is the signal for controlling the blown air (i.e., the signal sent to the SP valve), and the other is the signal for controlling the fingering part (i.e., the solenoid plungers). Eleven solenoid plungers were attached to acrylic hinge plates as robot fingers. By tuning the sound by trial and error (particularly the relationship between

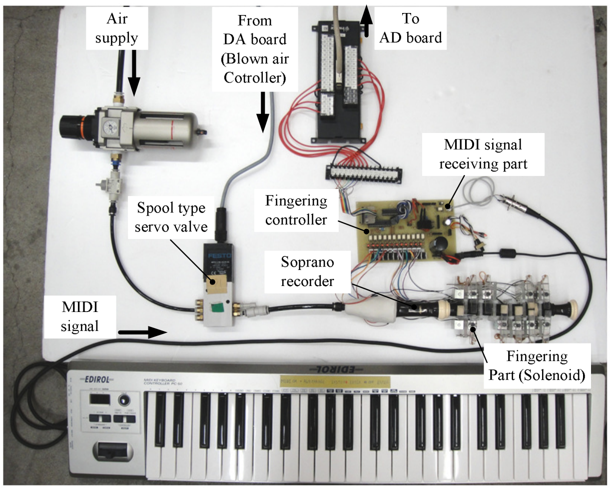

Fig. 1 Developed recorder-playing robot

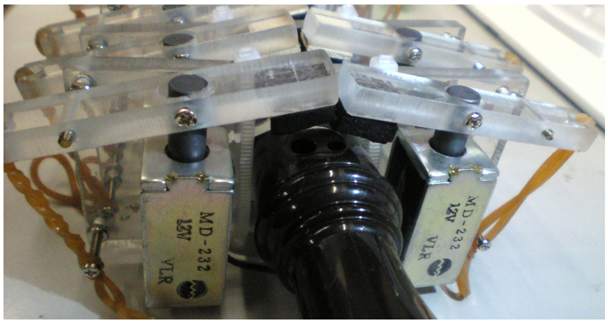

Fig. 2 Fingering part (solenoid plungers)

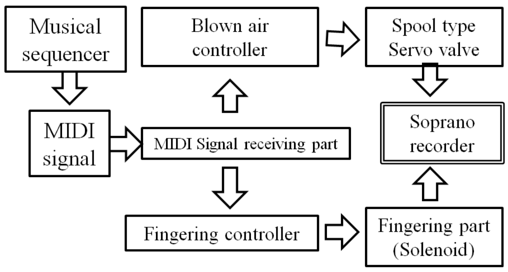

Fig. 3 Configuration of the recorder-playing robot system

the MIDI signal and the controlling signal of the SP valve that controls the blown air flow rate for the recorder), the robot system could play several musical songs well. For example, a demonstration at a school festival was well received. But, expressing the special musical effects of tonguing and vibrato naturally remained a problem.

QUICK RESPONSE LAMINAR FLOW SENSOR

Selection of flow sensor

To measure and control the blown air for a recorder, a flow sensor having sufficient resolution and dynamic characteristics is needed. The type of flow sensor used in this research is a laminar flow type, named "quick response laminar flow sensor" (QFS), which our research group has been developing[4]. The QFS is composed of a laminar flow element and a differential pressure gauge. The static characteristics of the QFS used in this research are expressed in equation (1).

$$Q \quad [\text{L/minANR}] = 0.256\frac{P}{P_a}\Delta P \qquad (1)$$

The model type of the QFS used in this research is QFS-0.3-50-30 (Tokyo Meter Co., Ltd.). Suppose, as an example, the resolution of the differential pressure gauge is 0.1 Pa; then the resolution of the QFS is 25.6 mL/min (ANR).

Dynamic characteristics test of the QFS using an unsteady flow generator

The dynamic characteristics of the flow sensor (QFS) up to 20 Hz were tested using an unsteady flow generator (UFG). The UFG is a device that can generate arbitrary oscillation air flow up to at least 50 Hz[5]. A schematic of the UFG is shown in Fig. 4. The UFG includes two SP valves and an isothermal chamber. A schematic of the dynamic characteristics test of the QFS is shown in Fig. 5. The QFS is set downstream of the UFG. Downstream of the QFS is open to atmosphere. Both the generated flow rate from the UFG (as the standard) and the measured flow rate using the QFS are recorded and compared in a computer equipped with an AD/DA converter. In the experiments, the set value of the generated flow rate from the UFG is defined according to equation (2).

$$G \quad [\text{g/s}] = 0.216 + 0.108\sin(2\pi f t) \qquad (2)$$

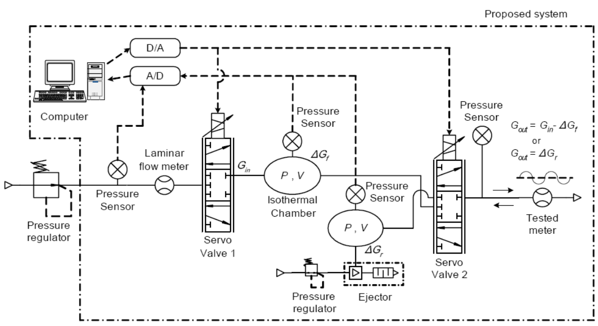

Fig. 4 Schematic of the unsteady flow generator (UFG)

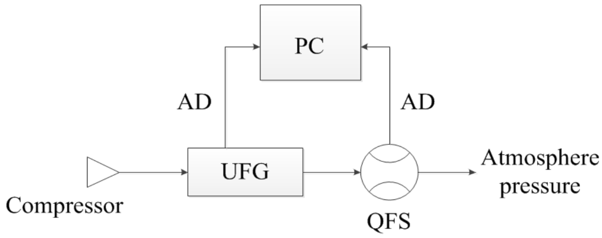

Fig. 5 Schematic of the dynamic characteristics test

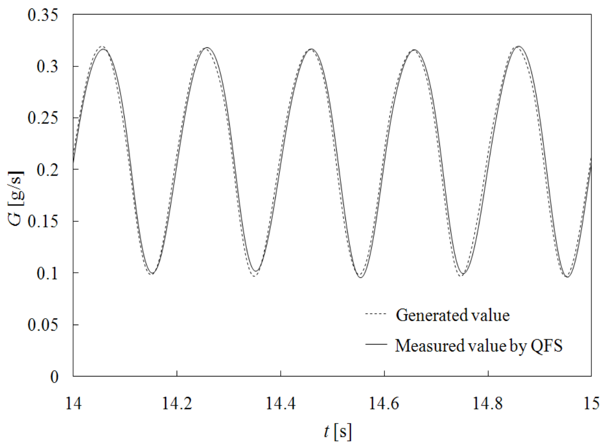

Fig. 6 Experimental results of the dynamic characteristics test (5 Hz)

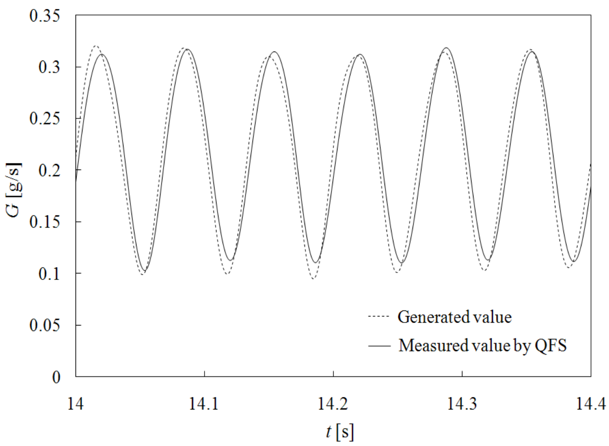

Fig. 7 Experimental results of the dynamic characteristics test (15 Hz)

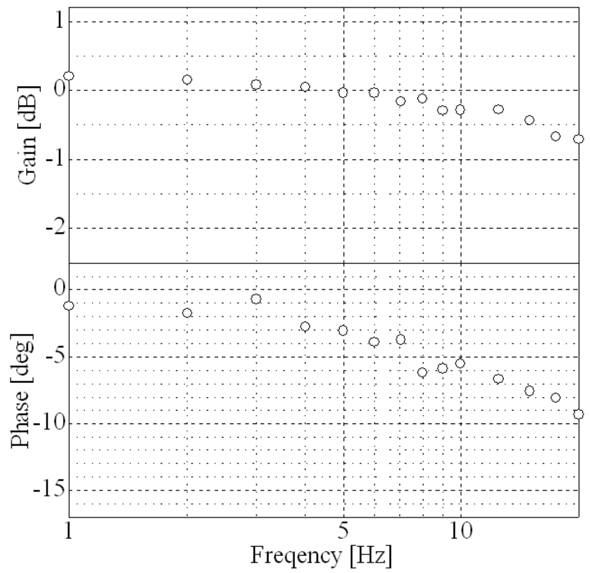

Fig. 8 Bode diagram of the dynamic characteristics of the QFS

The frequency f was varied from 1 Hz to 20 Hz. Examples of the experimental results when f = 5 Hz and 15 Hz are shown in Fig. 6 and Fig. 7, respectively. In Figs. 6 and 7, the broken line indicates the generated flow rate from the UFG and the solid line indicates the values measured by the QFS. The experimental results are summarized in the Bode diagram shown in Fig. 8. In the Bode diagram, the generated flow rate using the UFG is the denominator and the measured flow rate using the QFS is the numerator. The experimental results show that when f = 20 Hz, the gain is -0.8 dB and the phase is -9 deg. The needed frequency range for measuring the blown air into a soprano recorder when vibrato is expressed is several hertz at the highest. So, it is considered that the QFS is suitable for measurement of the blown air.

IDENTIFICATION OF RELATIONSHIP BETWEEN BLOWN AIR FLOW RATE AND MUSICAL INTERVAL USING THE QFS

When playing a recorder, an optimum blown air flow rate exists for each musical interval (tone). If the blown air flow rate is higher than the optimum value, the tone is high, and if the rate is lower, the tone is low, relative to the target tone. To identify the relationship between the optimum value of the blown air flow rate and the musical interval sounded by a soprano recorder, the experimental setup shown in Fig. 9 was used. In the experiment, the tone holes were closed by the solenoid plungers (i.e., fingers) and the blown air flow rate was adjusted using a variable throttle. The flow rate was adjusted to make the sound optimal. The flow rate was measured using the QFS, which was tested for static and dynamic

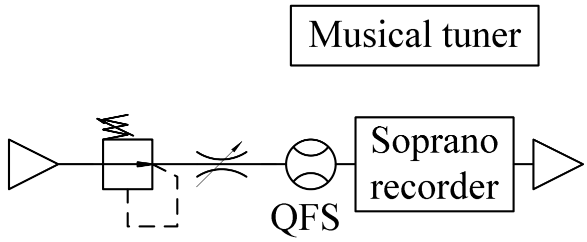

Fig. 9 Schematic of the experimental setup for the optimum flow rates for musical intervals

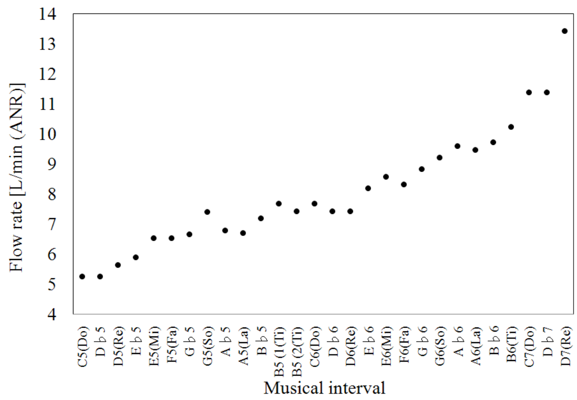

Fig. 10 Experimental results of the optimum flow rates for musical intervals

characteristics as described in the previous section. The musical tuner for discerning the musical tone was a Korg GA-1. The experimental results are shown in Fig. 10.

BLOWN AIR FLOW RATE MEASUREMENT FOR HUMAN RECOREDER PLAYERS

Definition of vibrato

Vibrato is a musical sound expressed by varying periodically tone pitch or intensity of a sound around a certain tone when playing a musical instrument or singing a song. In musical terminology, the vibration of the tone pitch is called "vibrato" and the vibration of the intensity of the sound is called "tremolo", but the discrimination between these two terms is often difficult in practice. For a recorder especially, both the tone pitch and the intensity of the sound change as the blown air flow rate changes.

Measurement of vibrato played by human recorder players

In this section, by using the experimental setup shown in Figs. 11 and 12, the sound level and the blown air flow rate were measured when a human player expresses vibrato with a soprano recorder. Air from the player's mouth is blown into the recorder through its windway, shown on the far left. The QFS is set between the player's mouth and the windway of the recorder. The

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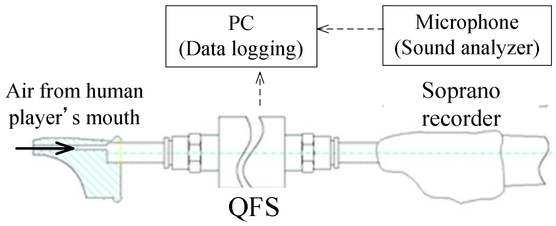

Fig. 11 Schematic of the experimental setup for measuring the sound level and blown air of a human playing a recorder

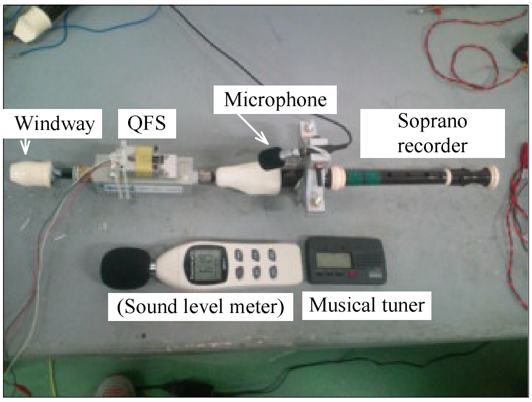

Fig. 12 Photograph of the experimental setup for measuring the sound level and blown air of a human playing a recorder

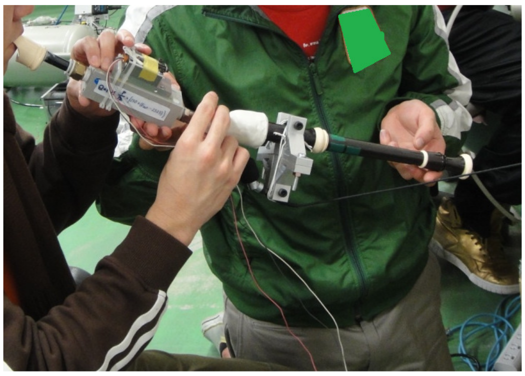

Fig. 13 Photograph of the experimental setting

blown air flow rate is measured by the QFS and the sound level is recorded and analyzed using a microphone (Sony ECO-DS30P) and a sound analyzer (Sound Engine Free).
The experiments were performed by three human recorder players. The three people were flute players of Fukuoka Institute of Technology Wind Symphony, one of the most famous university symphony orchestras in Japan. A photograph of the experimental setting is shown in Fig. 13. The experiments were conducted five times

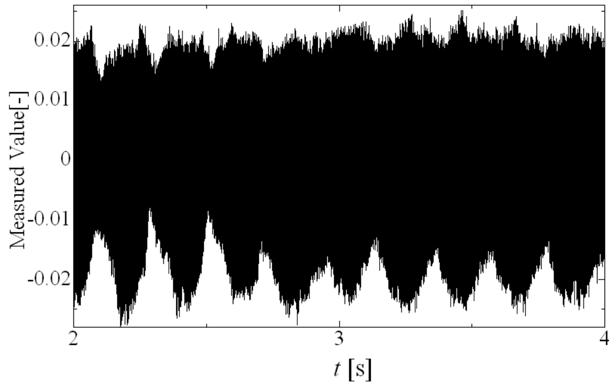

Fig. 14 Experimental data of a human recorder player playing the tone "la" (A5) measured by the microphone

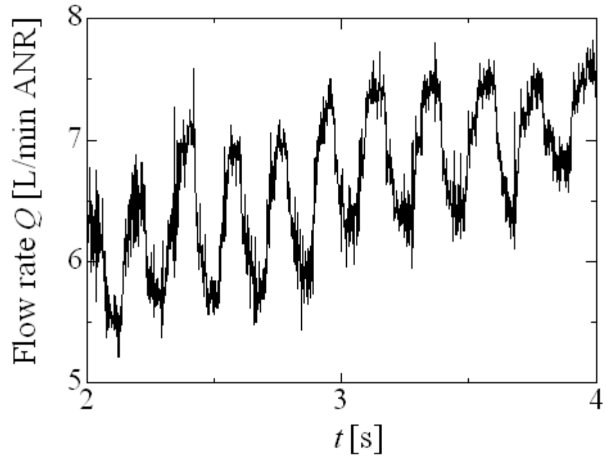

Fig. 15 Experimental data of human recorder players measured by the QFS

for each player. The tone played in the experiments was "la" (A5), since A is commonly used as a criterion in the tuning of musical instruments. One example of the experimental data measured by the microphone is shown in Fig. 14. In Fig. 14, the longitudinal axis indicates the scale of the WAV file, which by itself shows no physical characteristics to measure the sound level and blown air of a human playing a recorder. The cyclic wavy profile indicates the change of intensity of the sound. Fig. 15 shows the experimental data measured by the QFS. As shown in Figs. 14 and 15, the frequency of the blown air was approximately 5 Hz.

APPLICATION TO A RECORDER-PLAYING ROBOT

In this section, the identified flow rate model in the last section is applied to the air flow rate control system of the soprano-recorder-playing robot, shown in Fig. 16, to realize humanlike sounds produced while playing vibrato.

In the robot system shown in Fig. 16, a QFS was added between the SP valve and the recorder, in contrast with the system shown in Fig. 1.

Proposed blown air controlling method

The schematic of the controlling part of the blown air of the recorder-playing robot is shown in Fig. 17. In the digital signal process (DSP: MTT s-BOX), the measured flow rate in Fig. 15 was used as the set value of the flow rate controller. To precisely control the flow rate, feed forward control (nonlinearity compensation of the SP valve) was conducted, as illustrated in Fig. 18. Since the SP valve has nonlinearity as a characteristic, the relationship between the control signal and the sonic conductance (effective cross-sectional area) was

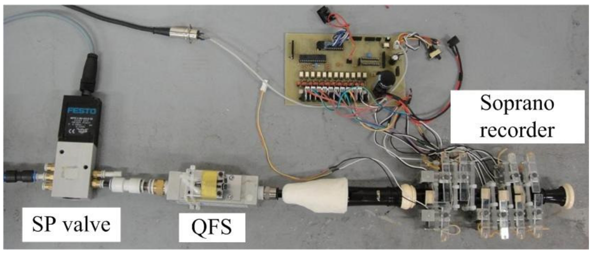

Fig. 16 Recorder-playing robot with the QFS

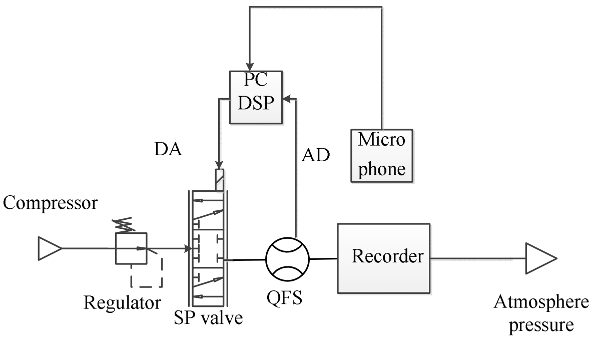

Fig. 17 Schematic of the blown air control part

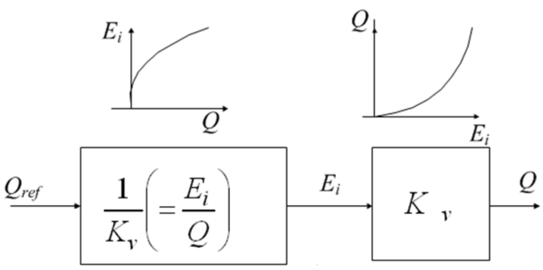

Fig. 18 Schematic of the feed forward control (nonlinearity compensation of SP valve)

preliminarily measured. Then, the inverse function ($1/K_v$) was multiplied by the set value of the flow rate Q_{ref}, as shown in the left block in Fig. 18.

Experimental results of the robot playing the recorder

In the experiment, the tone set was "la" (A5), so the MIDI signal corresponding to that tone was sent to the fingering controller. The measured flow rate stated in the last section (Fig. 15) was used as the set value of the flow rate controller.

The experimental results of the blown flow rates obtained by the QFS are shown in Fig. 19. As shown, the measured value of the flow rate of the human player performing vibrato and that of the recorder-playing robot correspond very well. Figs. 20 and 21 show the results of the frequency analysis. Since the tone is "la" (A5), the 1st mode frequency is 880 Hz. The analyzed results obtained by the human player and the robot correspond very well.

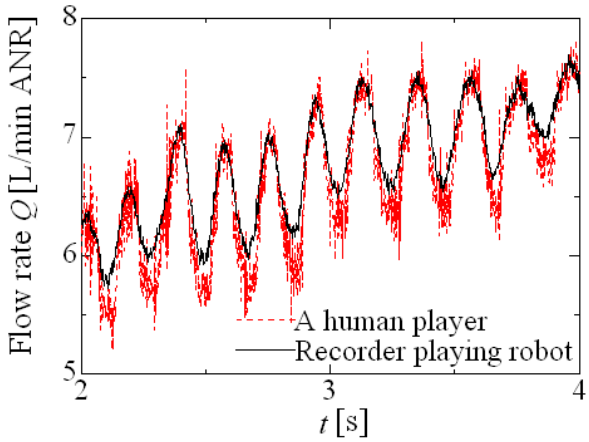

Fig. 19 Measured flow rates obtained by the QFS while vibrato was expressed

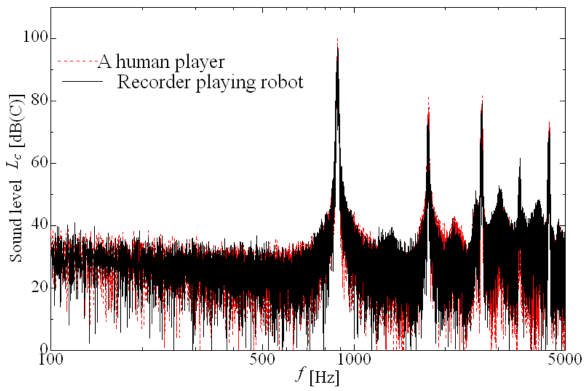

Fig. 20 Experimental results of the sound level

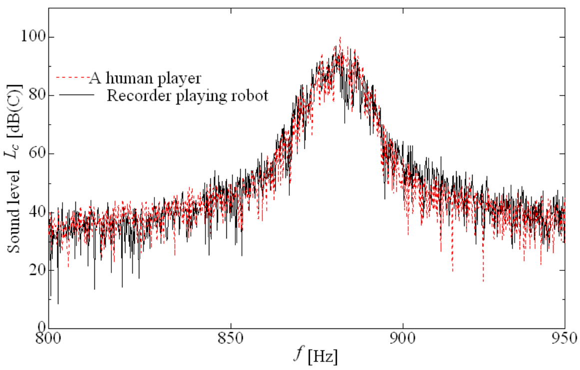

Fig. 21 Experimental results of the sound level (magnified)

CONCLUSIONS

To realize a soprano-recorder-playing robot that produces natural sounds matching those produced by a human player, this study employs unsteady flow rate measurements and control techniques to control the blown air for a soprano recorder. In the present research, the following procedure was conducted. First, not only the static but also the dynamic characteristics of the flow sensor used for measurement of the blown air were calibrated using an unsteady flow generator to judge whether the performance of the flow sensor was high enough to measure the blown air. Second, using the flow sensor, the blown air flow rates were measured when real human players (members of a brass band) performed vibrato with a soprano recorder. Finally, the identified blown air flow rate model was applied to the air flow rate control system of the soprano-recorder-playing robot. The flow rate was controlled by a spool type servo valve. The sounds played by the real human player and those played by the robot were compared using a sound analyzer. The experimental results showed that the results obtained for the human player and for the recorder-playing robot agreed very well.

In future work, the measured flow rate waves for human players should be modeled and applied to the control of the blown air flow rate of the recorder-playing robot when playing a song.

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