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Development of a Recorder-playing Robot Using Unsteady Flow Rate Control Technique

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Abstract: The purpose of this study is to develop a robot that plays an alto recorder and sounds like a human playing an alto recorder. In recent years, the development of robots that entertain people by playing a variety of musical instruments has been observed. Many of these robots have specific features, for example, 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 an alto-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 by an unsteady flow rate generator, are applied to control the blown air for the robot.

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

1. 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, some robots can play a musical instrument[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 been developing a robot that plays a recorder[3)], but naturally expressing the special musical effects of tonguing and vibrato remains a problem.

Therefore, the purpose of this study is to develop a robot playing an alto recorder that produces natural vibrato sounds, that is, vibrato sounds matching those produced by a human player. This study employs unsteady flow rate measurements and control techniques to control the air blown through an alto recorder. First, not only the static but also the dynamic characteristics of a flow sensor used for measuring the blown air are calibrated by an unsteady flow generator to judge whether the performance of the flow sensor is adequate for measuring the blown air. Second, the flow sensor measures the blown air flow rates of actual human musicians (members of the Fukuoka Institute of Technology Wind Symphony) expressing vibrato with a n alto recorder. Third, a measured blown air flow rate model is applied to the air flow rate control system of a soprano-recorder-playing robot. The flow rate is controlled by a spool type servo valve (SP valve). The recorder sounds played by a human and those played by the robot are compared using a sound analyzer. Then, a new modeling method using statistical analysis is proposed to build the target profile of air flow rate for the recorder-playing robot from the measured blown air flow rate profile by a human player.

2. DEVELOPED RECORDER-PLAYING ROBOT

We developed the recorder-playing robot shown in Fig. 1. The robot system consists of a computer, a musical keyboard (Edirol Musical Instrument Digital Interface[4)] (MIDI) keyboard controller PC-50), an electronic circuit as a signal receiver and a fingering controller, an SP valve (Festo MPYE-M5-B-SA), an alto recorder (Aulos 309A), and a fingering part consisting of solenoid plungers (Maruha DC Solenoid MD-232) (Fig. 2).

The configuration of the recorder-playing robot system is shown in Fig. 3. In the computer, the MIDI sequencer software (Cakewalk SONAR 6 LE) generates MIDI signals for playing (controlling) the recorder. The sequencer software also generates accompaniment music synchronized with the MIDI signals. The MIDI

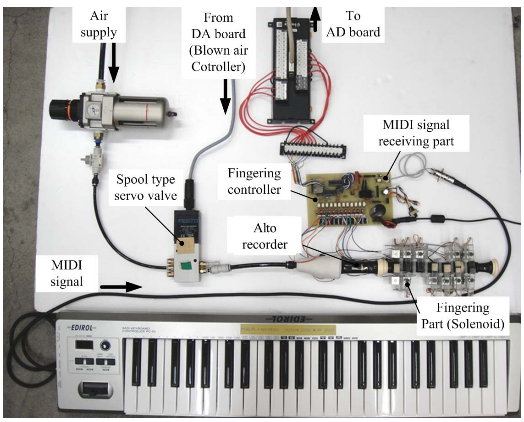

Fig. 1 Developed recorder playing robot.

Fig. 2 Fingering part (solenoid plungers).

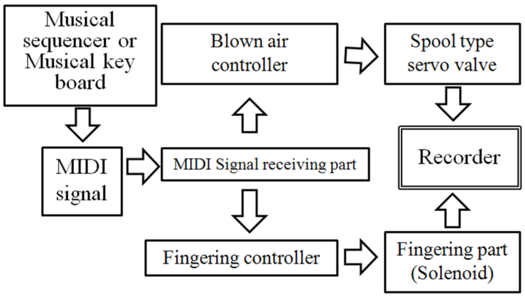

Fig. 3 Configuration of the recorder-playing robot system.

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. The MIDI signal is divided into two signals: one that controls the blown air (i.e., the signal sent to the SP valve), and the other that controls the fingering part (i.e., the solenoid plungers). Eleven solenoid plungers are attached to acrylic hinge plates as the robot fingers.

3. QUICK RESPONSE LAMINAR FLOW SENSOR

3.1 Selection of the flow sensor

Measuring and controlling the blown air for the recorder requires a flow sensor with sufficient resolution and dynamic characteristics. Our research group[5] has been developing the flow sensor, named "quick response laminar flow sensor" (QFS), used in this study. The QFS is composed of a laminar flow element and a differential pressure gauge. The static characteristics of the QFS are expressed in equation (1).

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

The model type 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).

3.2 Dynamic characteristics test of the QFS using an unsteady flow generator

The dynamic characteristics of the QFS up to 20 Hz were tested using an unsteady flow generator (UFG). The UFG, illustrated in Fig. 4, is a device that can generate arbitrary oscillation air flow up to at least 50 Hz[6]. The UFG includes two SP valves and an isothermal chamber. The QFS is set downstream of the UFG. Downstream of the QFS is open atmospheric air. A schematic of the dynamic characteristics test of the QFS and the UFG is shown in Fig. 5. 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).

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

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. 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. Thus, it is considered that the QFS is suitable for the measurement of blown air.

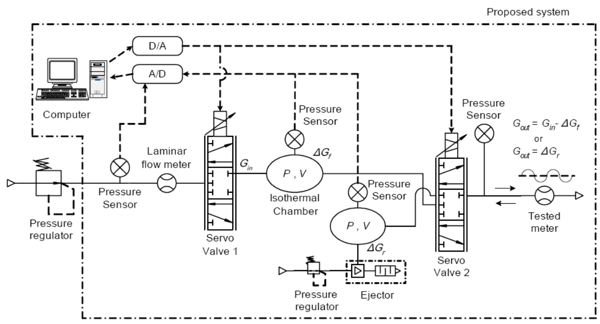

Fig. 4 Schematic of the unsteady flow generator (UFG).

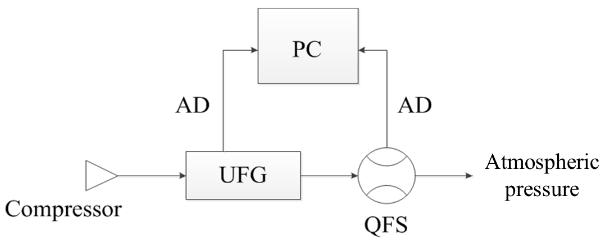

Fig. 5 Schematic of the dynamic characteristics test.

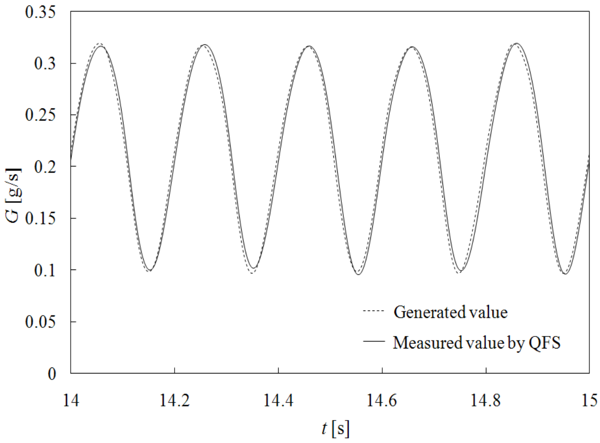

Fig. 6 Experimental results of the dynamic characteristics test (5 Hz).

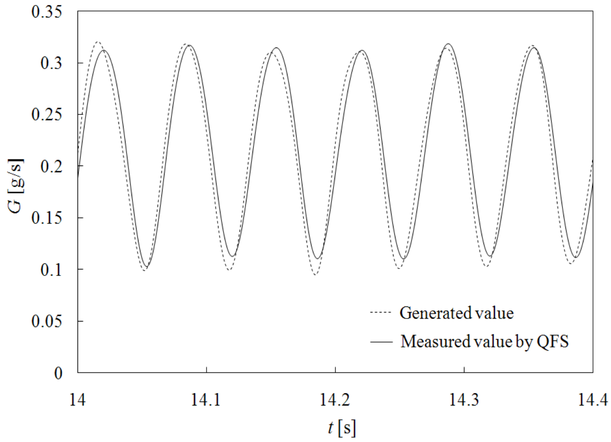

Fig. 7 Experimental results of the dynamic characteristics test (15 Hz).

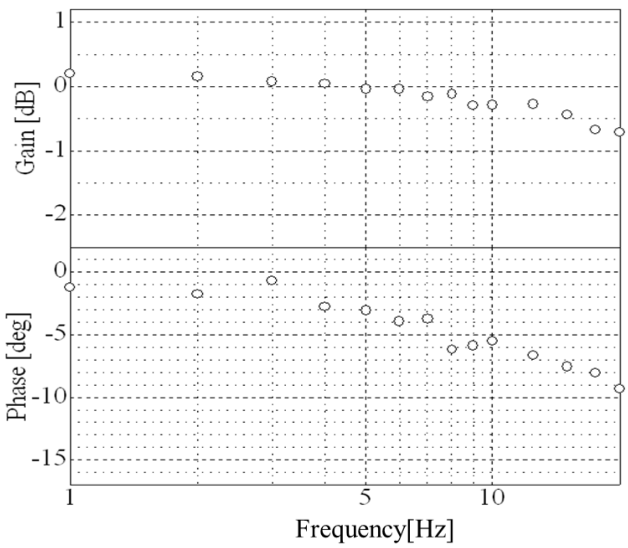

Fig. 8 Bode diagram of the dynamic characteristics of the QFS.

4. IDENTIFICATON 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 an alto 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 optimal sound and measured using the QFS. The musical tuner for discerning the musical tone was a Korg GA-1. The experimental results are shown in Fig. 10.

5. BLOWN AIR FLOW RATE MEASUREMENT FOR HUMAN RECORDER PLAYERS

5.1 Definition of vibrato

Vibrato is a musical sound expressed by a varying periodic tone pitch or intensity of sound around a certain tone when playing a musical instrument or singing. 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

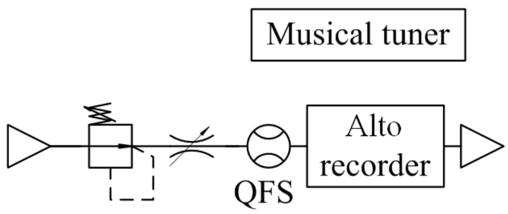

Fig. 9 Schematic of the experimental setup for the optimum flow rates for musical intervals.

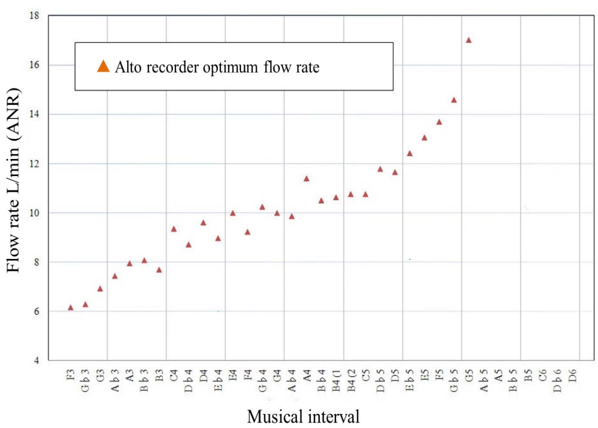

Fig. 10 Experimental results of the optimum flow rates for musical intervals.

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.

5.2 Measurement of vibrato played by human recorder players

Using the experimental setup shown in Fig. 11, "The experimenter stabilized the experimental setup, but the sound characteristics were assumed to not be altered. The sound level and the blown air flow rate were measured when a human player expresses vibrato with an alto recorder. Air from the player's mouth is blown into the recorder through its windway, shown on the far right. The QFS is set between the player's mouth and the windway of the recorder. The blown air flow rate is measured by the QFS and the sound level is recorded by a microphone (Sony ECO-DS30P) and analyzed by a sound analyzer (Sound Engine Free).

Three human recorder musicians participated in the experiments. The three people were wind instrument players of the Fukuoka Institute of Technology Wind Symphony, one of the most famous university symphony orchestras in Japan. The experiments were conducted five times for each player.

The tone played in the experiments was “la” (A4), since A is a commonly used criterion in the tuning of musical instruments. Fig. 12 shows one example of the experimental data measured by the QFS. The cyclic profile indicates the changes of the blown air flow rate which generates the changing intensity of the sound (vibrato). As shown in Fig. 12, the frequency of the blown air flow rate was approximately 5 Hz. Fig. 13 shows the results of the frequency analysis of the sound wave measured by the microphone. Since the tone is “la” (A4), the 1st mode frequency is 440 Hz.

6. APPLICATON TO A RECORDER-PLAYING ROBOT

In this section, the identified flow rate model, described in the preceding section in Fig. 12, is applied to the air flow rate control system of the alto-recorder-playing robot to realize humanlike sounds produced while playing vibrato.

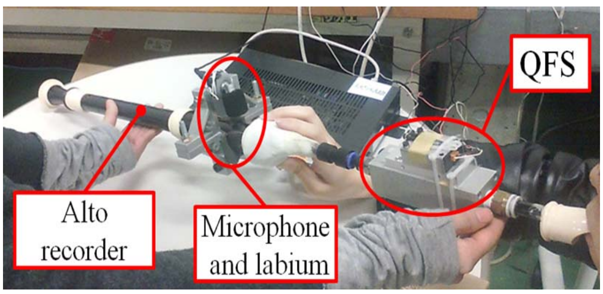

Fig. 11 Photograph of the experimental setting.

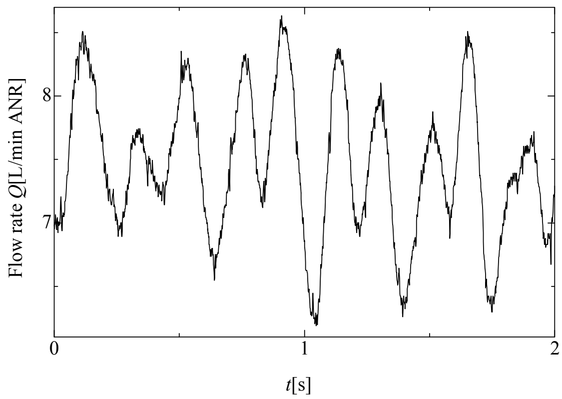

Fig. 12 Experimental data of one human recorder player as measured by the QFS.

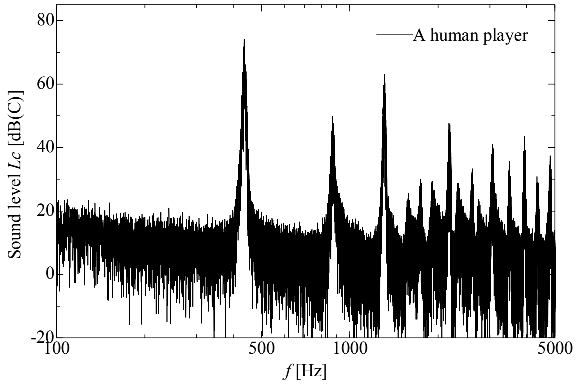

Fig. 13 Experimental result of the sound level

6.1 Proposed blown air controlling method

The schematic of the control part of the blown air of the recorder-playing robot is shown in Fig. 14. In the system shown in Fig. 14 (unlike the system shown in Fig. 1), the QFS between the SP valve and the recorder, and the digital signal processor (DSP: MTT s-BOX) are added. The measured flow rate of the DSP in Fig. 12 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. 15. Since the SP valve has nonlinearity, the relationship between the control

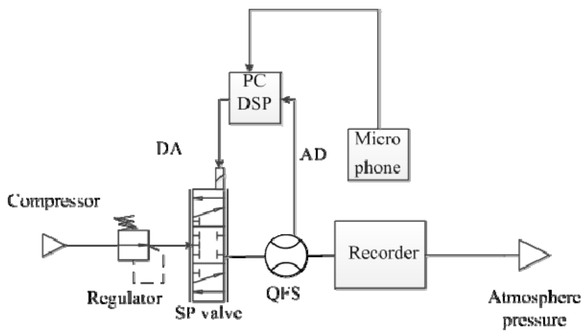

Fig. 14 Schematic of blown air flow control part.

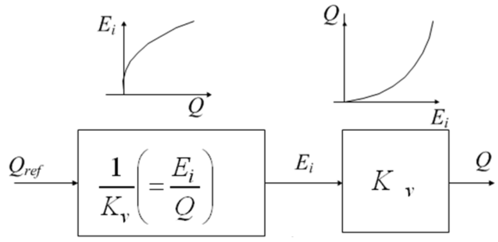

Fig. 15 Schematic of the feed-forward control (nonlinearity compensation of the SP valve).

signal and the sonic conductance (effective cross-sectional area) was 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. 15.

6.2 Experimental results of the robot playing the recorder

In the experiment, the tone was set to “la” (A4), so the MIDI signal corresponding to that tone was sent to the fingering controller. The measured flow rate stated in the preceding section and shown in Fig. 12 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. 16. 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. 17 and 18 show the results of the frequency analysis. Since the tone is “la” (A4), the 1st mode frequency is 440 Hz. The analyzed results obtained by the human player and the robot correspond very well.

The correlation of each experimental result of the measured blown air flow rate by the recorder-playing robot to the target value was evaluated by a correlation coefficient. The correlation coefficient is a measure of the correlation between two variables and gives a value between +1 and −1 inclusive[7]. The calculated results are shown in Table 1. The overall average was 0.964, so we can say that the results correlate very well.

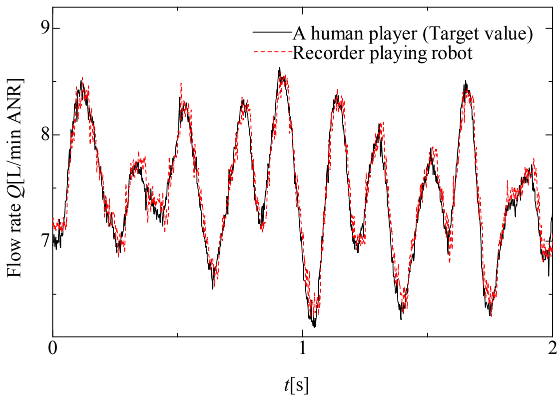

Fig.**16** Measured flow rates obtained by the QFS while vibrato was being expressed.

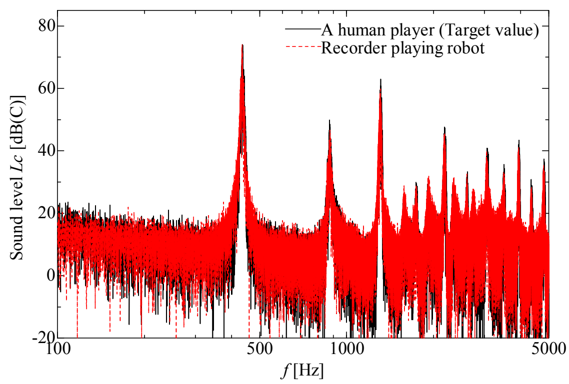

Fig. 17 Experimental results of the sound level.

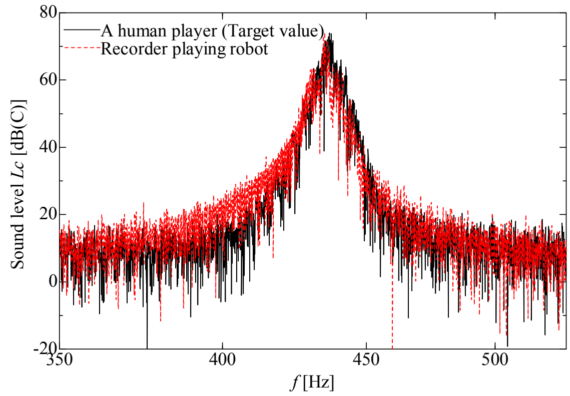

Fig. 18 Experimental results of the sound level (magnified).

Table 1 Comparison of correlation coefficients for blown air rate by the robot and each human player.

	Person		
	A	B	C
1st	0.956	0.966	0.972
2nd	0.935	0.968	0.988
3rd	0.942	0.971	0.975
4th	0.946	0.975	0.970
5th	0.953	0.972	0.970
Average	0.946	0.970	0.975

Overall average 0.964
Standard deviation 0.0155

7. CONCLUSIONS

To realize an alto-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 air blown into the alto recorder. In the present research, 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 adequate to measure the blown air. Second, using the flow sensor, the blown air flow rates were measured when real human players (members of a wind symphony) performed vibrato on an alto recorder. Third, the identified blown air flow rate model was applied to the air flow rate control system of the alto-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 agreed very well.

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