빠른 바람의 세기 추적을 위한 프로펠러를 사용한 전자 관악기 취구의 선형 모델링

준회원 곽 재 형*, 정회원 이 강 성**°

Mouthpiece Modeling of the Electronic Wind Instrument Using a Propeller and Linear Analysis for Fast Tracking Wind Velocity

Jae-Hyung Kwak* *Associate Member*, Gang-Seong Lee**° *Regular Member*

요 약

본 논문에서는 프로펠러를 사용한 전자관악기를 위한 취구의 모델링 방법을 제안한다. 이 방법은 프로펠러의 각속도에 의한 바람의 세기를 계산을 빠르게 하도록 풍속계의 방식을 이용한 것이다. 풍속계의 경우에, 바람의 세기가 프로펠러의 각속도에 비례한다는 속성을 이용하여 바람의 세기를 계산한다. 하지만, 프로펠러의 각속도로부터 기대하는 바람의 세기가 계산되기까지 과도시간이 있기 때문에, 바람의 세기와 프로펠러의 각속도는 일대일대응이 아니다. 이 문제를 개선하기 위하여, 풍속계를 선형 시스템으로 해석하여, 그 시스템의 임펄스 응답과 프로펠러의 각속도를 디컨벌루션하여 바람의 세기를 추정한다. 실험으로 제안된 시스템의 타당성을 입증하기 위하여, 모터와 프로펠러, 엔코더로 구성된 취구 모델을 디자인하였다. 이 방법으로 바람의 세기를 추정한 결과는 이 시스템이 기존의 풍속계의 방법 보다 8배 빠른 시스템을 보여주었다.

Key Words : Modeling, Mouthpiece, Electronic, Wind Instrument, Propeller

ABSTRACT

In this paper, we propose a new mouthpiece model for the electronic wind instrument using a propeller and linear analysis for fast tracking wind velocity blown. This method is a modification of the velocity anemometer for fast tracking wind velocity by the propeller's angular velocity (speed of revolution). In the case of velocity anemometer, wind velocity is calculated using the property that wind velocity is in proportion to the propeller's angular velocity. However, wind velocity and angular velocity of the propeller are not in one-one correspondence because wind velocity takes some transitional time for the expected wind velocity to be calculated from angular velocity. To resolve this problem, we propose a method for finding the impulse response of the system which can be considered as a linear system, and for estimating the wind velocity by deconvolving the propeller's angular velocity with the impulse response. To experiment and to prove the validity of the proposed system, we designed a mouthpiece model which consists of a motor, a propeller and an encoder. The result of estimated wind velocity in this method showed that this system is about eightfold faster than the method by the conventional velocity anemometer.

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* 광운대학교 정보디스플레이학과(wogud86@kw.ac.kr), ** 광운대학교 정보디스플레이학과(gslee@kw.ac.kr), (°: 교신저자)

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Ⅰ. Introduction

A significant number of electric/electronic instruments have been developed alongside the development of electronic industries, such as electronic keyboard instruments modeling the piano and electric percussions and string instruments using pick-up microphones and electric amplifiers like an electric guitar.

For electronic wind instruments, the mouthpiece is a sensitive but difficult device to develop, which is one reason that electronic wind instruments have not been sufficiently improved.

Recently, a microphone or an atmospheric pressure sensor has been used for the mouthpiece of electronic wind or brass instruments: a model called EZ-trumpet from YAMAHA, which uses a microphone. This mouthpiece uses the sound amplitude from the voice to decide the amplitude of the instrument output rather than using the vibration of lips. EWI4000s of AKAI uses an atmospheric pressure sensor the mouthpiece of which is an applied device from the pressure anemometer. Wind velocity is measured from the pressure of the sensor around which has a small hole to keep the pressure. The player tends to feel uncomfortable because the small hole only allows the air to leak little by little.

In this paper, we propose a new mouthpiece model for electronic wind instrument, which is a modification of the velocity anemometer. With the velocity anemometer, wind velocity is calculated using the property that wind velocity is in proportion to the propeller's angular velocity. It is not easy to calculate wind velocity without any time-delay because there is a transitional time between the onset of the wind blowing and the response of it to the propeller's angular velocity. To resolve this problem, we assume that the mouthpiece model is a linear system. The input to the system is wind velocity and the output is the propeller's angular velocity. We also propose a method to analyze the linear system and to estimate wind velocity. Through the experiment, the proposed mouthpiece model and the analysis method were verified to be effective.

Ⅱ. System analysis

The proposed method in this paper is to analyze the relationship between wind velocity and the propeller's angular velocity. In the case of the velocity anemometer, wind velocity is calculated using the propeller's angular velocity. However, the transitional time is necessary for the input wind to drive the propeller because of the propeller's inertia, which is the reason why velocity anemometers cannot measure instantaneous wind velocity in the transitional time. To resolve this problem, we made a model for the mouthpiece with wind velocity as input and the propeller's angular velocity as output.

Figure 1 shows the mouthpiece model. Air blown into the tube reaches the propeller which then spins. Figure 2 shows the system diagram of Figure 1, where *G(s)* represents the linear system. The input of *G(s)* is wind velocity and the output of *G(s)* is the propeller's angular velocity. The characteristics of the system *G(s)* is determined by analyzing the input and the output.

The system *G(s)* is analyzed by using the model-fitting method that determines the system function and the parameters by using the response of unit-step input. Equation (1) is the function used in this method[1],[2].

$$G(s) = \frac{ke^{-t_0 s}}{\tau s + 1} \tag{1}$$

In Equation (1), k is a steady-state value, t_0 is a delay time and τ is a time constant. Figure 3 illustrates the unit step response of *G(s)*, where *y(t)*

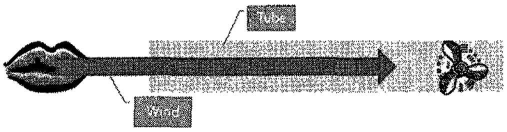

Fig. 1. Mouthpiece model showing wind blowing

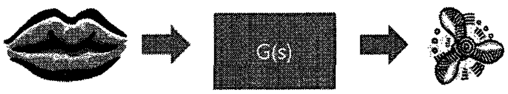

Fig. 2. Model of the mouthpiece using a linear system

is an expression of the inverse Laplace transform of *G(s)*. ΔCss is the value in the steady-state of *y(t)* determined by *k*. If there is no steady-state error, the value of ΔCss becomes 1. Values of t_0 and τ are determined by the linear Equations (2) and (3). The system function *G(s)* is determined by the values of *k*, t_0 and τ.

$$y(t_0+\frac{\tau}{3})=0.28\triangle Css \tag{2}$$

$$y(t_0+\tau)=0.63\triangle Css \tag{3}$$

As shown in Figure 4, wind velocity can be calculated by inputting the propeller's angular velocity into the inverse system $G^{-1}(s)$.

Wind velocity becomes the output of deconvolution of the propeller's angular velocity with the impulse response of $G^{-1}(s)$. The deconvolution equation is shown in Equation (4), where *x* is an input, h is an impulse response and *y* is an output[3],[4]. If the system has a delay time, the initial value *h[0]* of the impulse response becomes zero, and deconvolution cannot be calculated because the denominator of Equation (4) becomes zero. Now we should assume *G(s)* to be the system without a delay time (t_0 = 0), even though it is inevitable.

$$x[n]=\frac{y[n]-\sum_{k=0}^{n-1}x[k]h[n-k]}{h[0]} \tag{4}$$
$$(\because n\geq 1,\ h[0]\neq 0)$$

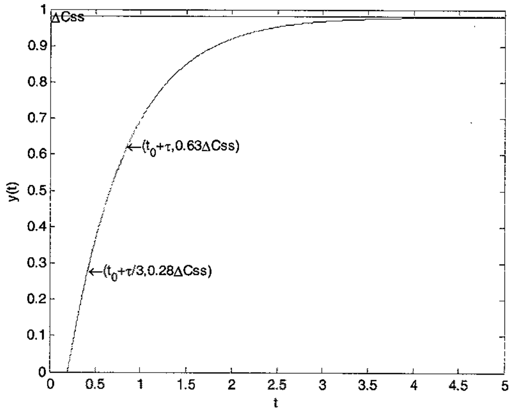

Fig. 3. Unit step response of *G(s)*

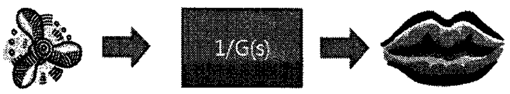

Fig. 4. The wind velocity estimation by G^{-1}(s)

Ⅲ. Experimental model design

When more precise values of input and output are provided, a more accurate system can be obtained. It is difficult for humans to control air-blow pressure and to maintain wind velocity. A propeller spun by motor can be the replacement of human lips for blowing wind. The motor is controlled by the duty-cycle of PWM (pulse-width modulation), as shown in Figure 5. The motor is placed with a propeller on the right side, and the encoder is placed with a propeller measuring wind velocity on the left side.

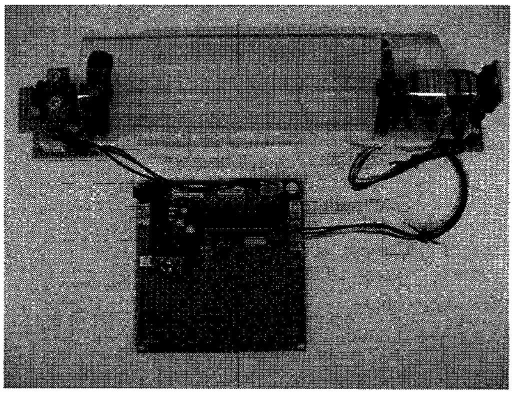

Fig. 5. Experimental model

3.1 Setting input value

The input of the system is the duty-cycle of PWM, which controls the motor speed. The transition time of the motor (the time interval from the stop to the steady-state of the motor) is assumed to be zero because the time is short enough to ignore, compared to the transition time of the encoder's propeller. When the motor is in steady-state, the motor's torque becomes zero. With Equation (5), the operating voltage of motor (V_o) is in proportion to angular velocity (ω)[5]. Equation (6) expresses the kinetic energy of the rotation of the motor, which is converted into the kinetic energy of the fluid of Equation (7) using Equation (8)[6]. In Equations (6)-(8), it is shown that the angular velocity of motor (ω) is in proportion to fluid velocity (V_{fv}), and the operating voltage of motor is in proportion to fluid velocity. The operating voltage of motor is controlled by Equation (9). Finally, fluid velocity which is the system input is in proportion to the duty-cycle of PWM. With this fact, the duty-cycle can be replaced into the system input instead of fluid velocity.

$$\tau = \frac{K_r}{R} V_o - \frac{K_r K_b}{R}\omega \tag{5}$$

τ : Torque of motor
ω : Angular velocity of motor
R : Motor internal resistance
K_r, K_b : Proportionality constant
V_o : Operating voltage of motor

$$KE_r = \frac{1}{2} I\omega^2 \tag{6}$$

KE_r : Kinetic energy of rotation
I : Moment of inertia

$$KE_f = \dot{m}\frac{V_{fv}^2}{2} \tag{7}$$

KE_f : Kinetic energy of the fluid
I : Moment of inertia
$\dot{m}$: Mass of fluid
V_{fv} : Fluid velocity

$$KE_f = \eta KE_r \tag{8}$$

η : Energy efficiency

$$V_o = V_s \times D \tag{9}$$

D : duty-cycle
V_s : Supply voltage

3.2 Output unit

Output of the system is the propeller's angular velocity. The encoder measures angular velocity by counting 50 per turn around. The count value is read every 1 ms to recalculate angular velocity. Some quantization noises are observed because the resolution of the encoder is not very significant. To ease the noise, a triangular moving average is applied. The length of the triangular moving average is set to 150.

Ⅳ. Measuring the propeller's angular velocity

Two types of experiments were carried out to measure the propeller's angular velocity. The first one was several different duty-cycles fed into the system to measure the propeller's angular velocity. The second one was different time intervals applied with a fixed value for duty-cycles to measure the propeller's angular velocity.

Figure 6 shows the result of the propeller's angular velocity when duty-cycles are at 70%, 80%, 90% and 100% and the time interval was for 3 seconds. Figures overleaf show the changes of increasing and decreasing slopes and the steady-state durations of depending on the duty-cycles.

Figure 7 shows the result of the propeller's angular velocity with the time intervals of 0.5s, 1s, 3s and 5s and 90% of the duty-cycle to drive the motor. The velocity starts to decrease right after the input power is off. The decreasing slope falls steeper with a longer driving time until it reaches the steady-state.

The value of the propeller's angular velocity in steady-state is proportional to the duty-cycle. This property is the principal of the velocity anemometer. Figure 8 shows the measured propeller's angular velocity when the motor is driven by the duty-cycles of 70%, 80%, 90% and 100% with 5

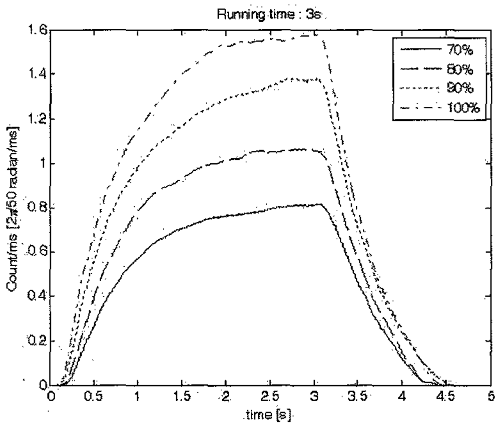

Fig. 6. Propeller's angular velocities on duty-cycles

seconds of duration. The result of this experiment shows the relation between the duty-cycle and its corresponding propeller's angular velocity in steady-state. The values of duty-cycle and the steady-state angular velocity are shown in Table 1. Because the duty-cycle is proportional to the propeller's angular velocity, the relationship can be expressed using the first order equation like Equation (10). Figure 9 shows the calculated plot of Equation (10) and the experimental measured data.

$$count/ms = 0.028 \times DutyCycle - 1.1859 \quad (10)$$

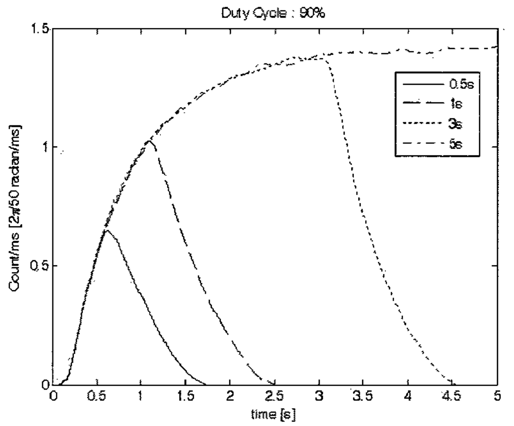

Fig. 7. Propeller's angular velocities on the duration of PWM input

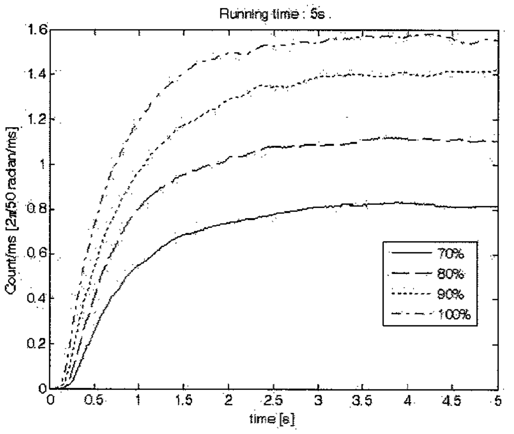

Fig. 8. Propeller's angular velocities in steady-state on duty-cycles.

Table 1. Duty-cycles and angular velocities in steady-state

duty-cycle	Angular velocity [count/ms]
70%	0.8127
80%	1.1057
90%	1.3788
100%	1.5544

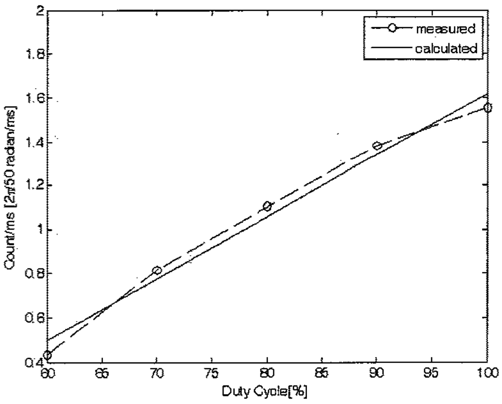

Fig. 9. Comparing measured data by encoder and calculated data by equation (10).

V. Experimental model system analysis

We can solve Equation (1) in Section II using the data from Figure 8, setting t_0 0.1961s and τ 0.6463s. We suppose t_0 is zero because the system assumes the absence of any delay time in Section II. Also if the system assumes no steady-state error, k becomes 1. As the result, the system $G(s)$ can be re-written as Equation (11). The solid line in Figure 10 is the

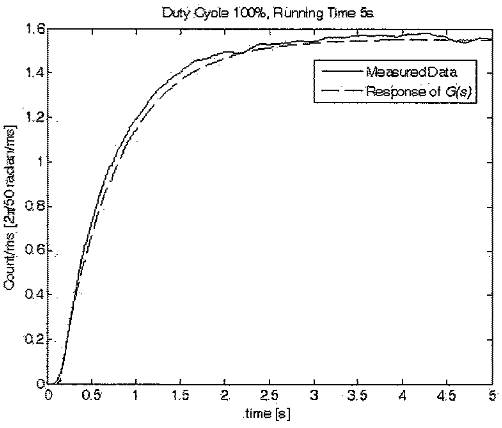

Fig. 10. Comparing measured data by encodering with 100% duty-cycle and unit-step response of G(s) multiplied by 1.5544

angular velocity when the duty-cycle is 100% with 5 seconds of duration, and the dashed line is the calculated system output when the input is a unit-step function multiplied by 1.5544, which explicates that the system *G(s)* satisfactorily resembles the actual system.

$$G(s) = \frac{1}{0.6463s+1} \qquad (11)$$

Ⅵ. Input value estimation

Wind velocity which is the system input is obtained by the deconvolution of the propeller's angular velocity with the impulse response of the system. To remove the measuring noise, a triangular moving average with the length of 50 is applied.

The reason for noise can be found in *G(s)*. The deconvolving output *y(t)* with the impulse response has the same connotation that the output *Y(s)* is multiplied by the inverse of the system G-1(s) in laplace transform. G-1(s) is expressed in Equation (12), where *s* has differential characteristics which increase noise, causing the deconvolution to be sensitive to noise.

$$G^{-1}(s) = \tau s + 1 \qquad (12)$$

Figure 11 shows the deconvolution result filtered by a moving average when the duty-cycle is at 70%, 80%, 90%, and 100% and the duration is 3 seconds. The input duty-cycles are well estimated from the outputs using the deconvolution. We see some noise in steady-state that might be caused by the swirl of fluid, which always happens when a tube-axial fan is used (See Figure 12)[6].

When the motor is stopped, the estimated input falls below zero, which means the propeller's angular velocity drastically decreases. This phenomenon is a non-linear characteristic within this experimental model.

Figure 13 shows the result of estimating the wind velocity with time intervals of 0.5s, 1s, 3s and 5s and 90% of duty-cycle. Measured durations are 0.475s, 0.979s and 2.977s and they are very close to the input durations.

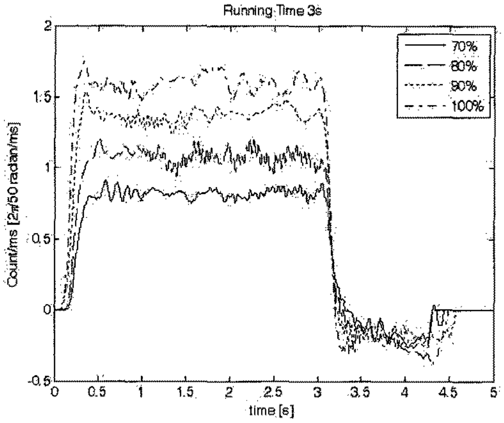

Fig. 11. Result of deconvolution of the propeller's angular velocity with the impulse response of the system on duty-cycle

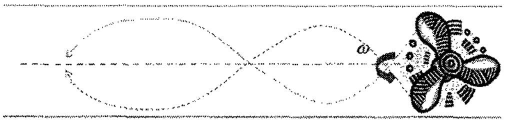

Fig. 12. Swirl of tube-axial fan

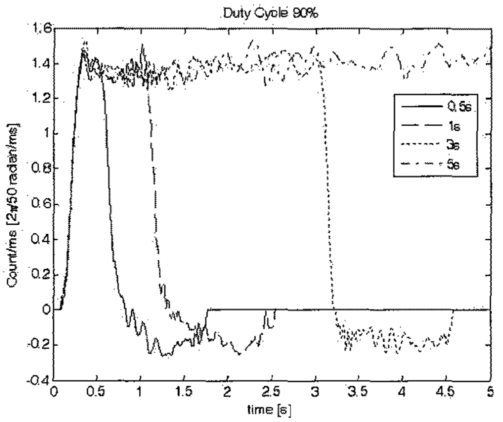

Fig. 13. Result of deconvolution of the propeller's angular velocity with the impulse response of the system on the duration of PWM input

For a more accurate analysis, another experiment was carried out with 90% of duty-cycle and 3s of duration time. The input, output and the result of deconvolution are shown in Figure 14. When the duty-cycle was 90%, the steady-state value of output became 1.3788 count/ms. The result of deconvolution is vibrated between 1.250 count/ms and 1.532 count/ms, which is about at a 15% range

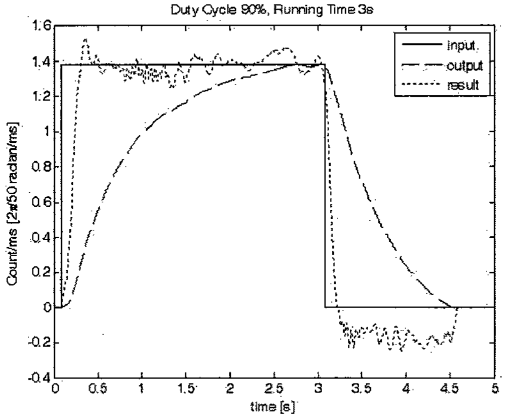

Fig. 14. input (duty-cycle), output (angular velocity), and the result of deconvolution(estimated input) of output with impulse response of system

of the steady-state value. If we define the settling time to an elapsed time to reach at 85% of the steady-state value, the settling time of output becomes 2.235s and the settling time of the result of deconvolution became 0.210s. Provided that velocity anemometers were used, the output angular velocity would be considered for wind velocity. It means the result of deconvolution is about eightfold faster than velocity anemometers to estimate wind velocity.

Ⅶ. Conclusions

In this paper, we proposed a new mouthpiece model for the electronic wind instrument using a propeller and a linear analysis for fast tracking wind velocity blown. To prove the effectiveness of the system, we set up an experimental model, estimated wind velocity with the system and evaluated the performance. The experimental result tells that this proposed method detects input wind velocity eightfold faster than the method using velocity anemometers.

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곽 재 형 (Jae-Hyung Kwak) 준회원

2009년 2월 단국대학교 전자공학과
2009년 3월~현재 광운대학교 정보디스플레이학과 석사과정
<관심분야> 전자공학, 신호처리, 음악공학

이 강 성 (Gang-Seong Lee) 정회원

1986년 2월 광운대학교 전자계산기공학
1988년 2월 광운대학교 전자계산기공학 석사
1993년 2월 광운대학교 전자계산기공학 박사
2009년 2월 서울대학교 음대 작곡과 석사
1991년 3월~현재 광운대학교 교수
<관심분야> 음성인식, 신호처리, 컴퓨터음악, 음악공학