Distributed force sensor based on acoustic characteristics of elastic tube

Kentaro Nakamura*, Shota Odajima and Marie Tabaru

Laboratory for Future Interdisciplinary Research of Science and Technology, Institute of Innovative Research, Tokyo Institute of Technology, R2–26, 4259 Nagatsuta, Midori-ku, Yokohama, 226–8503 Japan

(Received 27 April 2016, Accepted for publication 17 September 2016)

Abstract: The measurement of distributed force is highly demanded in various fields such as robotics. A flexible and nonmetal sensor configuration is often required in these applications. In this report, a distributed sensing method using an elastic tube, a small loud speaker and a microphone has been proposed, where the position of deformation along the tube can be determined from the acoustic characteristics of the tube. The basic properties of the distributed sensor were studied for a 1.2-m-long resin elastic tube of 10 mm inner diameter. The distribution of deformation was estimated from the power spectrum measured at one end of the tube with white-noise excitation. The position of deformation was successfully detected from the Fourier transform of the power spectrum. It was also proved that two separate deformed parts were able to be discriminated.

Keywords: Distributed sensor, Force sensor, Elastic tube, Acoustic characteristics

PACS number: 43.35.–c, 43.35.+d, 07.07.Df [doi:10.1250/ast.38.80]

1. INTRODUCTION

Multipoint or fully distributed sensing of pressure or load is highly required for tactile sensors in robotics [1], pressure distribution evaluation in a bed/chair, and various other fields. An array of electrical sensors, such as load cells and strain gauges has been commonly employed for evaluating the pressure distribution [2–6]. However, with increasing number of sensors, the measurement setup becomes a huge system with a thick bundle of signal wires. The sensor array is basically a discrete-point system and is not able to respond to the force/strain applied between the sensor elements. Cable-type sensors based on conductive rubber or piezoelectric materials have been developed [7,8] but these sensors have no spatial resolution. On the other hand, fiber optic sensor based on Brillouin scattering have been intensively developed for distributed stress measurement to monitor the structural health of civil engineering structures [9]. The detection of the resonance of acoustic cavity [10] and microwave transmission line were tried to detect tactile force or position.

In this study, using sound waves traveling inside an elastic tube, both the position and intensity of deformation can be evaluated from the change in the acoustic response of the tube. As a practical setup, the power spectrum of a rubber tube is measured from one end of the tube using a small loudspeaker and a microphone. Position information is obtained through Fourier transform of the power spectrum. The position of deformation in the elastic tube was successfully detected over a length of 1.2 m using audible-range signals lower than 10 kHz. When two independent deformations were applied at different positions simultaneously, these two responses were separately identified by the proposed method. From the width of the peak in the power spectrum, the spatial resolution was estimated to be 50 mm. In this method, excluding the loudspeaker and the microphone installed at one end of the tube, the sensor consists of nonmetal soft material. The detection circuit and signal processing are simple and inexpensive, but the information about the radial deformation applied to the tube can be collected quickly. In this paper, several basic characteristics of the proposed sensor are presented.

2. SENSOR CONFIGURATION

Figure 1 shows the configuration of the sensor system proposed in this paper. A small loudspeaker (dynamic earphone) and an electret condenser microphone unit are installed at one end of a rubber tube of 12 mm outer diameter, 10 mm inner diameter and 1,200 mm length, as shown in Fig. 2. The earphone and microphone used in the experiments are both commercially available cheap

*e-mail: knakamur@sonic.pi.titech.ac.jp
devices, and the high frequency limits are less than 10 kHz. The microphone is set at the end of the tube, while the earphone is coupled to the tube through a small hole made at a position 10 mm from the end. The other end of the tube is open. The tube is deformed with a rigid bar of 12 mm diameter on a table. The position of the deformation is denoted as $x_L$. The cross section of the tube is reduced to 50% of the original cross section owing to the loading with the bar.

White noise generated with a personal computer was used as the driving source for the earphone, where the standard PC audio output was utilized. The microphone output was recorded with a USB-connected digital oscilloscope through an amplifier with a gain of 20 dB at a sampling rate of 50 kS/s. A 1,024-point fast Fourier transform (FFT) with a Hanning window was applied to the signal. This FFT was practically processed as one of the functions of the digital oscilloscope. First, before the main experiments, the electrical input signal to the earphone was directly observed as shown in Fig. 3. A linear scale was applied to the frequency in this figure. In the results shown hereafter, the linear axis will be used. The average of eight measurements is applied to all the results in this paper. It is confirmed here that the source electrical signal used in this experiment is flat up to 10 kHz. Next, the output sound from the earphone is observed with the microphone located 20 mm from the earphone in a free-field without a tube. As shown in Fig. 4, the response is not flat and expresses the frequency characteristics of the earphone and microphone. The peak found in the lower frequency region might originate from the earphone, and the peak in the kHz region might be due to the microphone. It is thought that these frequency characteristics may induce errors in the measurement results.

### 3. METHOD TO DETERMINE POSITION

Fourier transform of the frequency data gives the responses as a function of the position. The procedure explained here is summarized in Fig. 5. In this section, we explain the principle behind the determination of the deformation in the tube as a function of the position.

Let us assume the case in which a deformation caused by loading reflects some of the transmitted sound waves. The sound pressure $P(f)$ observed at the input end of the
The power spectrum is written as

$$|P|^2 = P^* (f) \cdot P(f) = P_0^2 \left\{ 1 + r^2 + 2 r \cos \left( 2 \pi \frac{x_L}{c} f \right) \right\}. $$  \hspace{1cm} (2)$$

Being based on this theory, the power spectrum for one deformation position may become a periodic signal whose pitch is proportional to the distance to the position of the deformation \(x_L\). In practice, we also observe the reflections from the open and excited ends of the tube. If the reflection coefficient \(r\) is sufficiently small, we may observe a sinusoidal change in the power spectrum instead of the pulselike change originating from multiple reflections. Fourier transform of the result of Eq. (2) provides a peak at the position of deformation \(x_L\) with a level proportional to that of the reflection coefficient \(r\). If there are many reflection points, peaks are observed at the corresponding reflections. The spatial resolution, or the minimum readable scale in distance, \(\Delta x\), is equal to the half-wavelength at the highest frequency and is expressed using the maximum frequency \(f_m\) as

$$\Delta x = \frac{c}{2 f_m}. $$  \hspace{1cm} (3)$$

As we used the frequency up to 10 kHz in the case of the experiments in this study, the spatial resolution is estimated to be 17 mm with the sound speed of 340 m/s.

4. MEASUREMENT RESULTS

4.1. Detection of Position

The results without deformation are shown in Fig. 6. The upper figure shows the power spectrum, while the lower figure shows the position response as a result of FFT processing applied to the upper figure. An apparent peak found at the distance of 1,200 mm represents the reflection from the open end of the tube. The width (−3 dB) of the peak at the open end is approximately 50 mm, which is almost three times the theoretical spatial resolution discussed in the previous section.

A high peak is observed at around 100 mm, although no deformation is applied at this position. This may be attributed to the frequency characteristics of the earphone and microphone or the positions of these devices. To avoid the ghost responses at short distances, a sound source and a sensor with a better power spectrum are required. Possible equalization of the frequency characteristics is to be considered.

The power spectrum and the results converted by FFT are presented in Fig. 7 when a deformation was given to
the tube at the distance of 500 mm. It can be confirmed that the period of the fine ripples in the power spectrum became longer, and this may imply that the reflection point moved to a nearer place. In the FFT results, a clear peak is detected at around 500 mm. Another peak corresponding to the open end at 1,200 mm is also observed.

Next, Fig. 8 shows the results for the case in which two independent deformations were applied at 700 mm and 900 mm respectively. Two peaks at these individual deformations, as well as one corresponding to the open end, are observed. The signal strength for the response of the remote location is lower than that beside the sound source. This is due to the reduced signal energy traveling beyond the first deformation and the attenuation with distance.

In Fig. 9, the results are summarized, where the distance to the deformation is varied from 100 mm to 1,100 mm in steps of 100 mm. The response due to the deformation is overlapped with the peak originating from the aforementioned intrinsic nature of the system. If the deformation is applied at positions with distances longer than 200 mm, peaks are clearly observed in accordance with the distance. The position of the peak is plotted as a function of the distance to the deformation as shown in Fig. 10. The maximum distance error observed was 27 mm and the average error was 11 mm. The results agree closely with the positions calculated using the free-space sound speed of 340 m/s. This means that the fundamental mode traveling inside the tube is dominant in this experiment, and that the elastic property of the tube negligibly affects it.

**Fig. 8** Power spectrum of the tube with two deformations at \(x_L=700\) mm and 900 mm (top). Position responses obtained from the frequency characteristics through Fourier transform (bottom).

**Fig. 9** Position responses for different locations of the deformation from 100 to 1,100 mm.
the results. It has been reported that the propagation speed is affected by the elastic characteristics of the tube when the vibration and resonance of the tube are effective [11].

The signal levels at the response peaks are plotted against distance in Fig. 11, where the signal strength decreases with distance. The curve drawn in the figure is an exponential function fitted to the data, and the rate was 0.06 dB/cm. The attenuation coefficient in this curve is higher than that of the absorption of air in free space (0.0026 dB/cm at 10 kHz [12]) and is thought to be sufficiently affected by the loss originating from the friction on the inner surface of the tube.

4.2. Consideration of the Measurement Performance

Let us consider several possible problems that might arise when the maximum frequency is increased for a higher spatial resolution. First, attenuation should restrict higher frequency operation. In the case of Fig. 11, a considerable attenuation exists, when the maximum frequency is 10 kHz. Further theoretical and experimental studies are required to clarify the relationship between distance and frequency.

Second, higher modes might be excited in addition to the fundamental mode if a higher frequency is used. To avoid the reduction in spatial resolution owing to mode dispersion, we should carefully select the frequency and the diameter of the tube for single-mode operation. Considering the single-mode condition for a tube with an inner diameter of 10 mm, the cutoff frequency was estimated to be approximately 20 kHz, and thus, the single-mode operation was maintained throughout the experiments in this paper. To maintain the single-mode condition with rising frequency, the tube diameter should be reduced. However, the use of a higher frequency will result in a
higher propagation loss. The spatial resolution and measurement range are not compatible.

In our experiments, the 1,200-mm-long tube was freely placed on a table without fixing it, and the radius of curvature was 300 to 400 mm. The position along the tube was successfully detected in this curled tube.

4.3. Estimation of Applied Deformation

A method of estimating the degree of deformation applied to the tube will be discussed in this section. Here, we assume that the intensity of the responses to the deformation \( h \) is related to the reflection coefficient. The reflection coefficient for sound pressure is written as

\[
r = \frac{Z_2 - Z_1}{Z_2 + Z_1} = \frac{S_2 - S_1}{S_2 + S_1}.
\]

As illustrated in Fig. 12, \( Z_1 \) is the acoustic impedance for the cross section of the tube without deformation, and \( Z_2 \) is the acoustic impedance at the position of deformation. The acoustic impedance is proportional to the cross sections, and thus, we assumed that the reflection coefficient can be written with the cross sections \( S_1 \) and \( S_2 \), which represent the cross sections without and with deformation, respectively. The cross section \( S_2 \) that admits the passage of the acoustic waves is expressed as Eq. (5) using the inner radius \( R \) and the deformation \( h \), as explained in Fig. 12.

\[
S_2 = 2R^2 \sin^{-1} \left( 1 - \frac{h}{2R} \right) + 2 \left( R - \frac{h}{2R} \right) \sqrt{R \left( R - \frac{h}{4} \right)}
\]

To prove this assumption, the relationship between the degree of deformation applied to the tube and the acoustic responses was measured. The deformation was given at a point 300 mm from the microphone, while the deformation \( h \) was varied from 2 to 8 mm in steps of 1 mm by clamping with a caliper. The change in response corresponding to the applied deformation is summarized in Fig. 13. The vertical axis represents the signal strength after the FFT, while the horizontal axis shows the distance measured from the microphone location \( x_L \). Higher peaks are observed proportionally to the deformation in the tube.

Responses to the compressive deformation and the reflection coefficient calculated with Eqs. (4) and (5) are shown in Fig. 14. A good correlation between the experimental peak levels and the change in calculated reflection coefficient are observed. In the case of the deformation of 2 mm, the experimental result deviated from the reflection coefficient. This can be attributed to a low signal-to-noise ratio caused by a small reflection coefficient of 0.05. By excluding such a small deformation, the peak signal level can be estimated from the change in the cross section of the tube.

5. CONCLUSIONS

We discussed the method of evaluating the position and degree of deformation in an elastic tube using the acoustic responses observed from one end of the tube. In practice, the position information was successfully analyzed using a simple Fourier transformation of the frequency characteristics of the acoustic responses. Audible sound up to 10 kHz was used in the experiments, and we succeeded in detecting the deformation applied to a 1,200-mm-long tube. Two independent deformations applied to the tube simultaneously could be measured with a good separation.
The spatial resolution was estimated to be around 50 mm. The relationship between the deformation and the signal level was studied using a simple model. The region of deformation in the axial direction varied in accordance with the deformation in the radial direction of the tube. The effect of the degree of deformation on the spatial resolution should be studied. In this experiment, most of the results were expressed not as ‘force’ but as the acoustic response. Appropriate transformation will be made on the results in the future by studying the relationship between the applied force and the acoustic responses. This should be deeply related to the elastic characteristics of tubes.

If a large deformation is applied, the signal intensity for the deformations given at longer distances might be changed because the acoustic energy transmitted beyond the large deformation is reduced. A method to compensate this effect must be developed in the future.

ACKNOWLEDGEMENT

This study was partially supported by The Eno Science Foundation, The Takano Science Foundation and Grants-in-Aid for Scientific Research 15K20991.

REFERENCES

[1] D. Silvera-Tawil, D. Rye and M. Velonaki, “Artificial skin and tactile sensing for socially interactive robots: A review,” Robotics Auton. Syst., 63, part 3, 230–243 (2015).
[2] T. V. Papakostas, J. Lima and M. Lowe, “A large area force sensor for smart skin applications,” Sensors, 2002. Proc. IEEE, vol. 2, pp. 1620–1624 (2002).
[3] D. J. Beeve, A. S. Hsieh, D. D. Denton and R. G. Radwin, “A silicon force sensor for robotics and medicine,” Sens. Actuators A: Phys., 50, 55–65 (1995).
[4] B. Choi, H. R. Choi and S. Kang, “Development of tactile sensor for detecting contact force and slip,” 2005 IEEE/RSJ Int. Conf. Intelligent Robots and Systems, pp. 2638–2643 (2005).
[5] D. Yamada, T. Maeno and Y. Yamada, “Artificial finger skin having ridges and distributed tactile sensors used for grasp force control,” IEEE/RSJ Int. Conf. Intelligent Robots and Systems, Vol. 2, pp. 686–691 (2001).
[6] J. G. da Silva, A. A. de Carvalho and D. D. da Silva, “A strain gauge tactile sensor for finger-mounted applications,” IEEE Trans. Instrum. Meas., 51, 18–22 (2002).
[7] R. Lazzarini, R. Magni and P. Dario, “A tactile array sensor layered in an artificial skin,” Proc. 1995 IEEE/RSJ Int. Conf. Intelligent Robots and Systems, Vol. 3, pp. 114–119 (1995).
[8] G. H. Büscher, R. Köiva, C. Schürmann, R. Haschke and H. J. Ritter, “Flexible and stretchable fabric-based tactile sensor,” Robotics Auton. Syst., 63, part 3, 244–252 (2015).
[9] K. Hotate, “Fiber distributed Brillouin sensing with optical correlation domain techniques,” Opt. Fiber Technol., 19, 700–719 [http://dx.doi.org/10.1016/j.yofte.2013.08.008] (2013).
[10] N. Terada, H. Shinoda and S. Ando, “Tensor cell tactile sensor utilizing multimode acoustic resonance,” Trans. Soc. Instrum. Control Eng., 33, 234–240 [http://doi.org/10.9746/sicetr1965.33.234] (1997) (in Japanese).
[11] H. Hasegawa, T. Kamakura and Y. Kumamoto, “Propagation of sound waves in a multi-layered viscoelastic tube,” J. Acoust. Soc. Jpn. (E), 15, 269–276 (1994).
[12] J. Saneyoshi, K. Kikuchi and O. Nomoto, Cho-onpa Gijyutsu Binran (Handbook for Ultrasonic Technologies), New Edition (Nikkan-Kogyo-Shinbun, Tokyo, 1984), p. 1192.