Concrete-Wall-Climbing Testing Robot

S. Tokuomi, K. Mori, and Y. Tsuruzono

***Abstract*—**A concrete-wall-climbing testing robot, has been developed. This robot adheres and climbs concrete walls using two sets of suction cups, as well as being able to rotate by the use of the alternating motion of the suction cups. The maximum climbing speed is about 60 cm/min. Each suction cup has a pressure sensor, which monitors the adhesion of each suction cup. The impact acoustic method is used in testing concrete walls. This robot has an impact acoustic device and four microphones for the acquisition of the impact sound. The effectiveness of the impact acoustic system was tested by applying it to an inspection of specimens with artificial circular void defects. A circular void defect with a diameter of 200 mm at a depth of 50 mm was able to be detected. The weight and the dimensions of the robot are about 17 kg and 1.0 m by 1.3 m, respectively. The upper limit of testing is about 10 m above the ground due to the length of the power cable.

***Keywords*—**Concrete Wall, Nondestructive Testing, Climbing Robot, Impact Acoustic Method

I. INTRODUCTION

A lot of concrete structures are deteriorating to dangerous levels throughout Japan. These concrete structures need to be inspected regularly to be sure that they are safe enough to be used. The inspection method of these concrete structures is typically the impact acoustic method. In the impact acoustic method the worker taps the surface of the concrete with a hammer. So it is usually necessary to set up scaffolding to access vertical structures for inspection. However, setting up of high scaffolding is not economical in both time and money. Moreover setting up scaffolding is difficult on very high concrete walls. Therefore, there is an urgent need for an economical solution to this problem of testing.

Some methods of testing at high places have already been attempted. Aerial vehicles are one such method that have been attracting attention [1]. Video cameras are being mounted to remote controlled helicopters and inspecting concrete structures visually. However, the impact acoustic system is too heavy to be mounted on them. Wall climbing robots have also been developed [2], [3] but only use a video camera.

So we developed a concrete-wall-climbing testing robot with an impact acoustic device designed specifically for concrete walls as shown in Fig. 1. This testing machine adheres to the concrete wall by two sets of suction cups, and climbs the concrete wall by the alternating motion of the two sets of suction cups. The impact acoustic method is used in this testing robot. The effectiveness of the impact acoustic device was investigated using concrete walls with artificial defects.

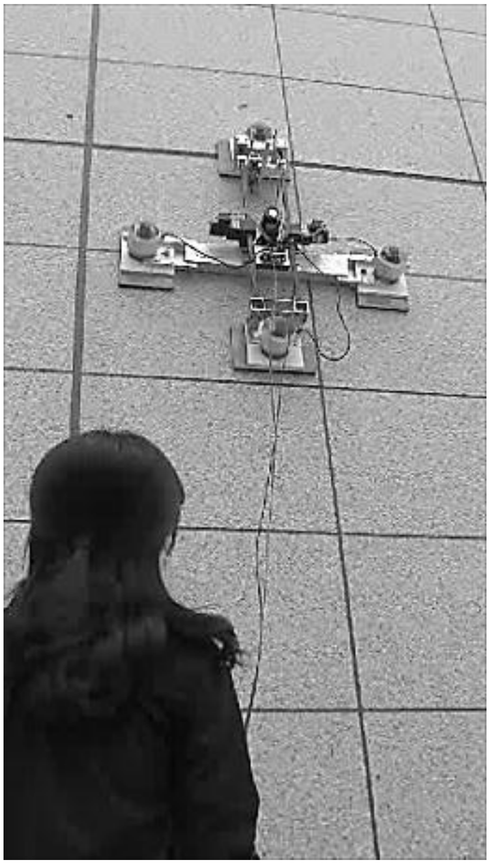

Fig. 1 Concrete-wall-climbing testing robot

II. CONCRETE-WALL-CLIMBING TESTING ROBOT

A. Architecture of the climbing testing robot

Fig. 2 shows the architecture of the climbing testing robot we have developed. This robot has four suction cups, and strongly adheres to concrete walls. Two suction cups A and C or two suction cups B and D are connected to each other. The two sets of suction cups move in relation to each other to create rotational motions by one rotary actuator and linear translations by two linear actuators. The power is supplied through electrical cables from the ground. Each suction cup has a pressure sensor. The width and the height of the robot is 1.0 m by 1.3 m, respectively. The weight is 17 kg.

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B. Suction cup

In academic literature, multiple kinds of propulsion and adhesion mechanisms and systems for climbing robots can be found. Methods such as suction cups [2], [3], molecular adhesion [4], magnetic adhesion [5], and claws [6] are common and well-known. However, these technologies are not suitable for inspecting vertical concrete structures because they lack the adhesion force required. The magnetic adhesion method specifically isn't able to obtain enough adhesion force because concrete is not a magnetic substance.

Therefore, we adopted the suction cup method. The cross section of the suction cup is shown in Fig.3. The body of the suction cup is made of lightweight wood and is in contact with the concrete wall via a ring-shaped rubber sheet. A pressure sensor is mounted on each suction cup which monitors the adhesion. If the adhesion pressure is compromised the suctions cups can then be re-adjusted manually.

C. The impact acoustic device

Fig. 4 shows a detailed drawing of the impact acoustic device. A hammer with a weight of 162 grams as shown in Fig. 5 is attached to a spring. Compression of the spring is created by a hook and chain mechanism powered by a geared motor. The compression is released causing the hammer to impact the concrete wall. The maximum impact speed is about two meters per second. The interval between impacts is about one second. The impulse of the impact is comparatively the same as that generated by a human operator's hammering.

D. The acoustic acquisition system

Four microphones are installed for the acoustic acquisition system as shown in Fig. 6. The four microphones are set at the same distance from the impact point by four arms of vibration damping material. The impact signals are averaged to provide a more accurate signal with less outside interference. The vibration damping material reduces the noise of the impact acoustic device.

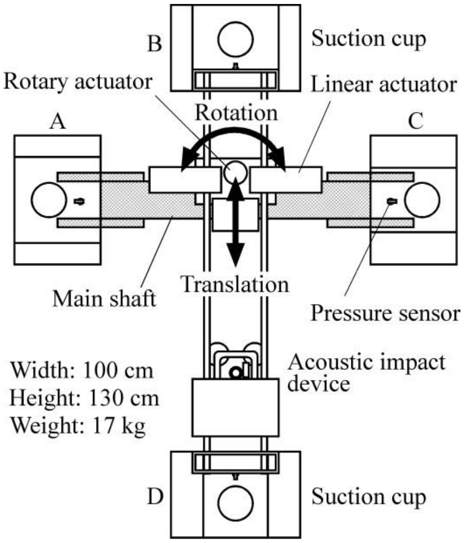

Fig. 2 Structure of testing robot

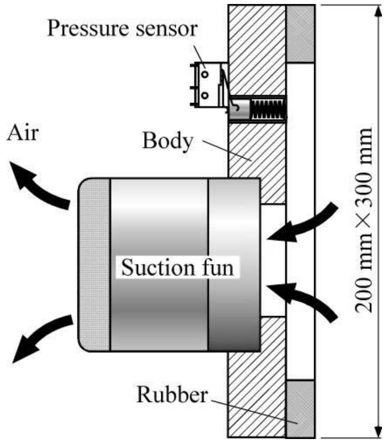

Fig. 3 Cross section of suction cup

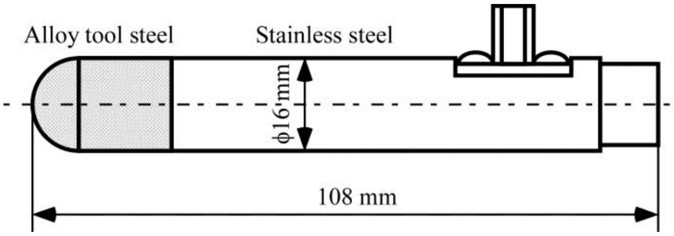

Fig. 5 Hammer of the impact acoustic device

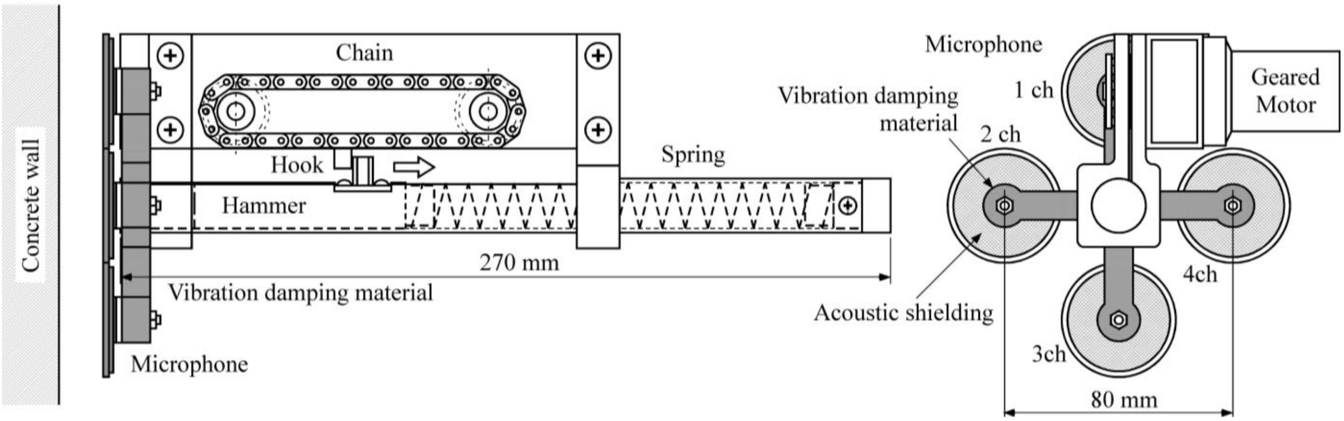

Fig. 4 Impact acoustic device and sound acquisition system

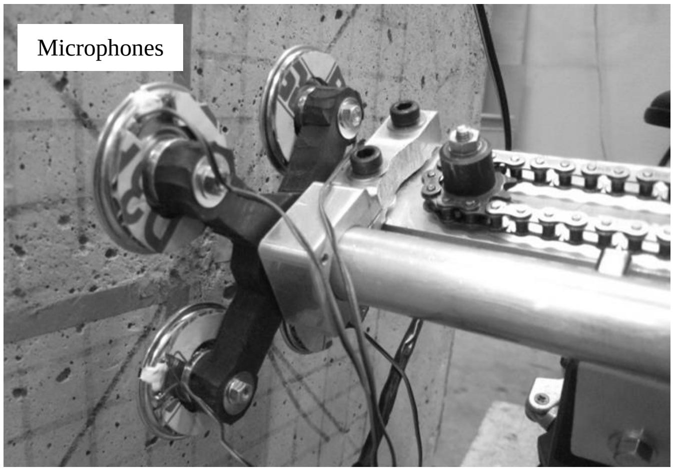

Fig. 6 The acoustic acquisition system consists of four microphones supported by vibration damping material

E. The acoustic acquisition system

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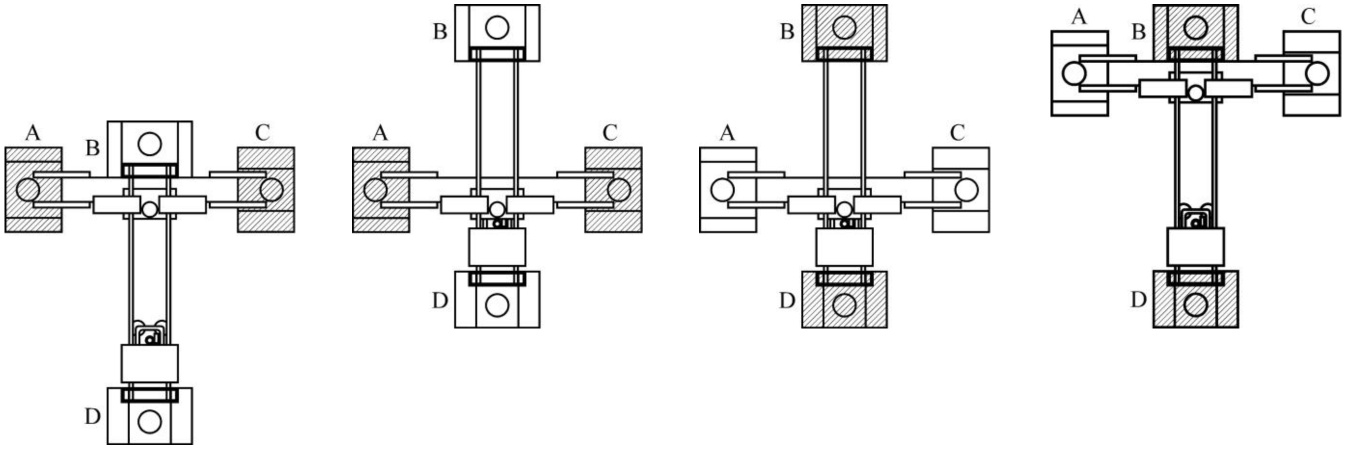
F. Climbing mechanism

Fig. 7 shows the configuration of the robot when ascending. Fig. 7 (a) shows the configuration of the robot when the suction cups A and C are in operation to support the main shaft of the robot. In the next stage in Fig. 3 (b), the suction cups B and D are lifted up. Then in Fig. 3 (c), the suction cups B and D are in operation, and the suction cups A and C are out of operation. Finally in Fig. 3 (d), the main shaft of the robot is lifted up by the two linear actuators. Repeating these operations, the climbing testing robot is able to climb up walls. The inverse operation allows the robot to descend.

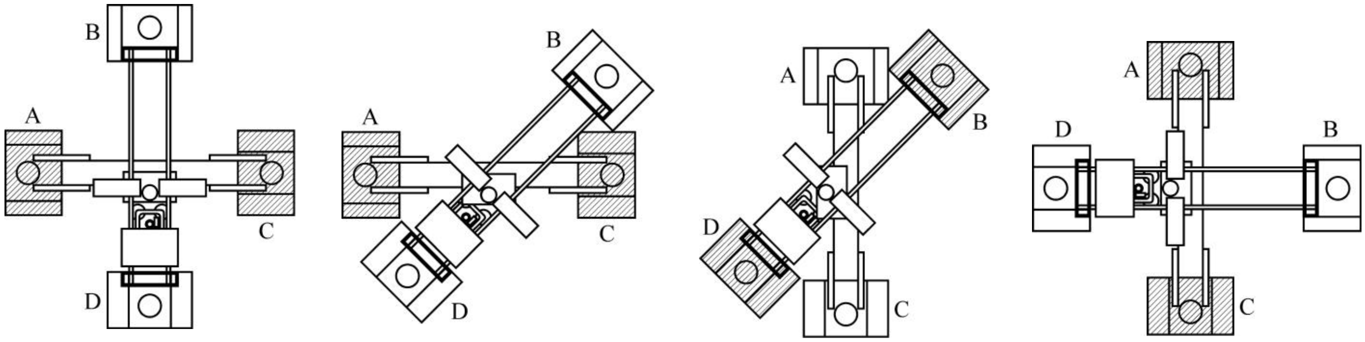
Fig. 8 shows the configuration of the robot when rotating. Fig. 8 (a) shows when the suction cups A and C are in operation to support the main shaft of the machine. In the next stage, Fig. 8 (b), shows the arm with suction cups B and D rotated. Fig. 8 (c) shows the suction cups B and D in operation and the main shaft with suction cups A and C rotated. Finally Fig. 8 (d), shows the main shaft of the robot at 90 degrees rotation.

Combining the climbing and rotational motion, the robot is able to move freely anywhere on the wall. The height limit of the robot is only restricted by the length of the power cable and the control cable which is about 10 meters. The climbing speed is determined by the speed of the linear actuators, which is 60 centimeters per minute.



(a) Suction cups A & C ON (b) Suction cups B & D UP (c) Suction cups B & D ON (d) Suction cups A & C UP

Fig. 7 Motion of climbing



(a) Suction cups A & C ON (b) Suction cups B & D TURN (c) Suction cups A & C TURN (d) Suction cups B & D TURN

Fig. 8 Motion of rotation

III. EXPERIMENT

The performance of the acoustic impact device was investigated using concrete specimens. The concrete specimens and the experiment method are illustrated in Fig.9. Two types of concrete specimens were used. One type was a concrete wall without defect. The others were concrete walls with a defect. The defects were disk shaped voids with a diameter of 200 mm. The defects were at a depth of 25 mm, 50 mm, and 100 mm.

C. Reference Sound Signal

In practical testing, the soundness of structures is evaluated by comparing the measured signal with that of a reference signal known to be free of detects. Fig. 10 shows this reference signal from an acoustic impact test on a specimen without any defect. As can be seen, the signal level is low. Through head phones this signal is an audible low dull sound.

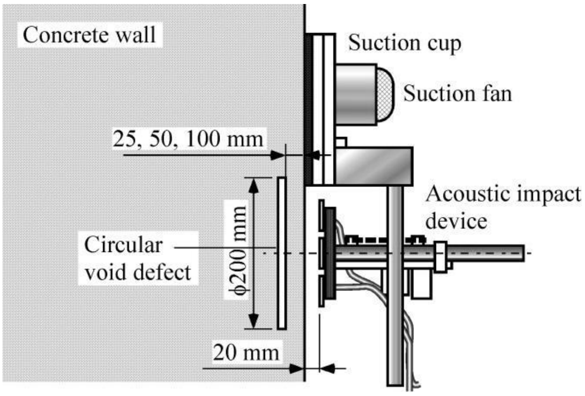


Fig. 9 Acoustic impact test by using concrete specimens

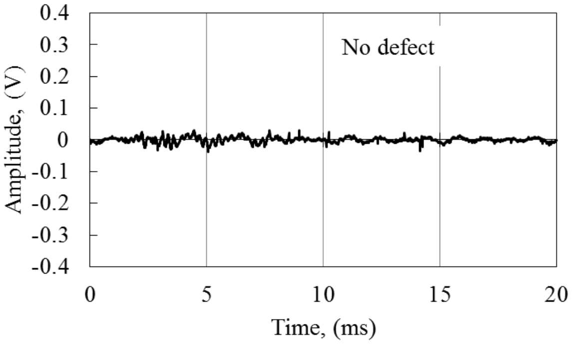


Fig. 10 The sound signal of acoustic impact test on a specimen without any defect

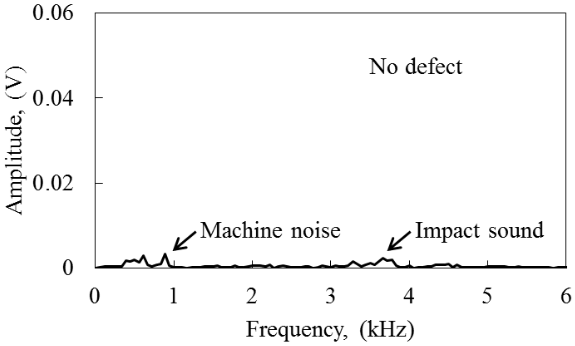


Fig. 11 The frequency spectrum of Fig. 10 (specimen without defect)

Fig. 11 shows the frequency spectrum of Fig. 10 (specimen without any defect). Peaks due to the mechanical noise and peaks due to the impact can be seen. Defects might be suspected if signal patterns differ from this.

D. Acoustic impact results on a specimen with a circular void defect

Fig. 12 shows the signal from an acoustic impact test on a specimen with a 200 mm diameter circular void defect at 25 mm depth (see Fig. 9). The tapping point on the surface was right above the center of the circular void. A clear attenuating waveform can be seen in Fig. 12. This oscillation comes from the flexural vibration of the area of concrete between the surface and the circular void defect [7].

Fig. 13 is the frequency spectrum of Fig. 12 (25 mm depth defect). As we can see, there is a sharp peak at 2.6 kHz. Through headphones this signal is a light clear metallic sound. The unique sounds that each signal produces also make it easier for operators to identify defects.

However, in the case of specimens with a circular void defect at 50 mm and 100 mm depth, the audible sounds are so similar to that of the reference specimen that the use of headphones becomes impractical. That being said defects could also be detected visually by observing their frequency spectrums.

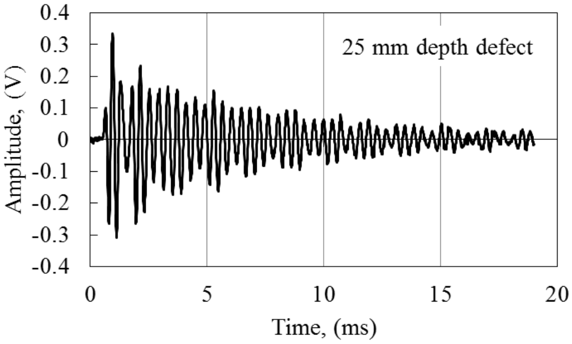


Fig. 12 The sound signal of acoustic impact test on a specimen with a circular void defect at 25 mm depth

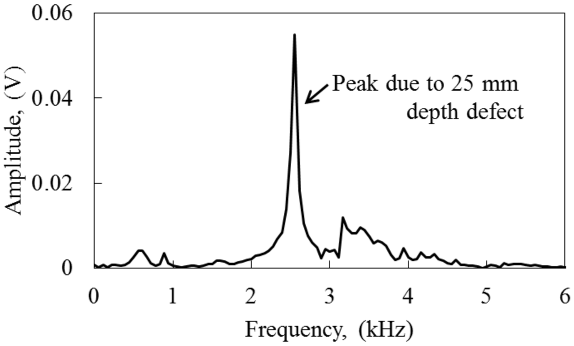


Fig. 13 The frequency spectrum of Fig. 12 (25 mm depth)

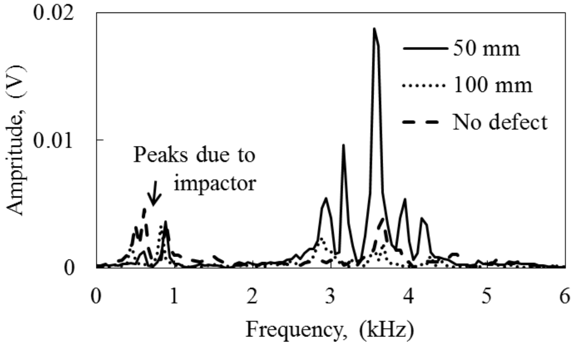


Fig. 14 The frequency spectrum of 50 mm and 100 mm voids

Fig. 14 shows the frequency spectrums of the acoustic impact tests on specimens with a circular void defect at 50 mm depth and 100 mm depth. In the case of the 50 mm depth defect, there are some characteristic peaks around 3.0 kHz to 4.0 kHz. In the case of the 100 mm depth defect, a small peak can be seen at about 3.0 kHz. We have concluded that in the case of a circular void defect with a diameter of 200 mm the detectable depth is limited to 100 mm.

IV. CONCLUSION

A concrete-wall-climbing testing robot has been developed. The robot is able to adhere and climb vertical concrete walls. It has an acoustic impact device so that it is able to detect defects. The performance is as follows;

1) The robot is able to climb up and down vertical concrete walls at a speed of 60 cm per minutes as well as rotate. The height limit of climbing is about 10 meters and is determined by the length of the cables.
2) The adhesion of the suction cups is ensured by pressure sensors which can detect a loss of pressure so that the robot's position can be adjusted.
3) The impact acoustic device mounted on the concrete-wall-climbing testing robot was able to detect a defect with a diameter of 200 mm and at a depth of 100 mm or less.

REFERENCES

[1] Advanced Highway Maintenance and Construction Program, University of California at Davis, "CALTRANS Bridge Inspection Aerial Robot," Report No. CA08-0182, 2008, pp. 1-26.

[2] T. Abe, "Wall Climbing Robot for Inspection of Concrete Structure," Journal of the Robotics Society of Japan, Vol. 10, No. 5, pp. 34-37, 1992.

[3] L. Briones, P. Bustamante, M. A. Serna, "Wall-climbing robot for inspection in nuclear power plants," Proceedings - IEEE International Conference on Robotics and Automation, Issue pt 2, 1994, pp. 1409-1414.

[4] D. Schmidt, C. Hillenbrand, K. Berns, "Omnidirectional locomotion and traction control of the wheel-driven, wall-climbing robot, CROMSCI," Robotica, Vol. 29, Issue 7, pp. 991-1003, 2011.

[5] O. Unver, A. Uneri, A. Aydemir, M. Sitti, "Geckobot: A gecko inspired climbing robot using elastomer adhesives," Proceedings - IEEE International Conference on Robotics and Automation , Vol. 2006, No. 1642050, pp. 2329-2335, 2006.

[6] W. Fischer, F. Tâche, and R. Siegwart, "Inspection system for very thin and fragile surfaces, based on a pair of wall climbing robots with magnetic wheels ," IEEE International Conference on Intelligent Robots and Systems, Vol. 2007, No. 4399060, pp. 1216-1221, 2007.

[7] K. F. Graff, "Wave Motion in Elastic Solids," Dever Publications. Inc., New York, pp. 229-258, 1991.