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Design and Experiment of a Small Legged Robot Operated by the Resonant Vibrations of Cantilever Beams

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ABSTRACT A new driving method for small size legged robots was proposed and tested in this paper, in which the resonant vibrations of four flexible cantilever beams were used to generate the driving forces. The driving principle was elaborated as two sub principles, based on vertical bending vibrations and horizontal bending vibrations, respectively. According to the mode analysis and the harmonic analysis by the finite-element method, a prototype named Resbot was designed and fabricated. Experiments were carried out on two kinds of surfaces. The size of the Resbot was 99 mm × 148 mm × 28 mm, and its maximum speed was measured to be about 17.2 cm/s, which proved the feasibility of the proposed driving method for small legged robots. The relationship between the frequency of the driving force and the velocity of the Resbot demonstrated the availabilities of the two different driving sub-principles. The advantages of the proposed Resbot were that it was not only simple in structure for no intermediate transmission system, but also easy to be miniaturized, since there was no need to design the gaits; furthermore, it used an extremely simple control system.

INDEX TERMS Legged robot, driving method, resonant vibration, miniaturization.

I. INTRODUCTION

The good motility and adaptability to various environments have given legged robots potential for many applications, such as planetary exploration, seafloor detection, post-disaster rescue, et al. The substantial numbers of legged robots are bionic robots, which are conducive to executing tasks in disguise of real animals. There are various ways to classify the legged robots, and one common method is using the number of legs. In this viewpoint, legged robots are classified into four kinds: two-legged, four-legged, six-legged and others.

Firstly, two-legged robots are often human-inspired[1]–[5], so they are mainly researched for the entertainments and services. Secondly, four-legged robots [6]–[9] are also an important research field as they could realize stable movements more easily by comparing with the two-legged robots, and they generally have better performances on anti-interference [10]. Therefore, four-legged robots could be used in more rugged environments. Despite the complicacy of the transmission and control system, there are some four-legged robots in very small sizes [11], [12], which embody the hope of miniaturization. The inspirations of a number of six-legged robots are from insects [13]–17], which might be sorts of more complicated than four-legged robots. But six-legged robots often have even better motion stabilities. In recent years, researchers have been seeking to develop the maneuverability of six-legged robots. Haldane *et al.* [18] presented the relationship between oscillations in height and roll angle and the robot's turning behavior; aerodynamic forces were used by Kohut *et al.* [19] in SailRoACH for turning. Besides, there are some robots not belonging to those three kinds. For instance, STriDER presented by Morazzani *et al.* [20] was a three-legged robot. Hoffman and Wood [21] presented a segmented myriapod robot with 20 legs.

The common driving method of the legged robots is that actuators (e.g., electromagnetic motors, hydraulic actuators and piezoelectric actuators) drive legs to swing or rotate, and then send the extremities of the legs to touch the ground repeatedly, which generates frictional forces between the interfaces and then pushes robots into movements. Under this driving method, the motion harmonies of the legs need ensuring to keep the center of mass moving stably. So it's usually important to design and control the gaits of the legs, which demands a relatively complicated transmission system and control system.

In this paper, a new driving method that will not require the design of gaits is proposed, which greatly simplifies the mechanism design of the legged robot. The simplification is quite meaningful for the reliability, the miniaturization and the cost reduction of a robot. The proposed driving method is based on the bending resonant vibration of a cantilever beam; a prototype named Resbot is designed and fabricated to illustrate this method. Different from the previous works, a DC motor and eccentric wheel system is used to excite the bending vibration of a leg directly, and a desired displacement is generated at the extremity of the leg, where there is an elastic foot. This driving method needs just a very simple driving system and control system as it avoids designing and controlling the motion sequences of the legs.

This paper is organized into seven sections. The operational principle is explained in section II in detail. The modeling is mentioned in section III. And the simulation and verification are carried out in section IV. In section V, the Resbot is manufactured and its motion sequences are exhibited. Section VI reports the experimental results, which is followed by the discussion and conclusion in section VII.

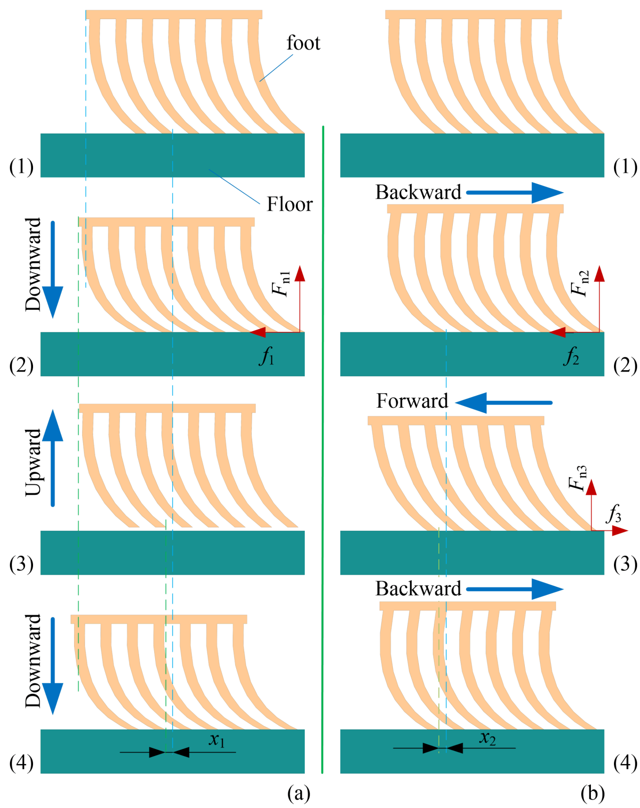

FIGURE 2. Schematic diagram of the resonance driving: (a) based on vertical vibration, (b) based on horizontal vibration.

II. OPERATIONAL PRINCIPLE OF THE RESBOT

The basic structure of the proposed Resbot is shown in Fig. 1. The Resbot consists of four legs, on whose extremities feet are attached, and a trunk, where the other extremity of every leg is fixed. The foot should be made of a sort of soft material, and the leg and the trunk should be manufactured with comparatively rigid material.

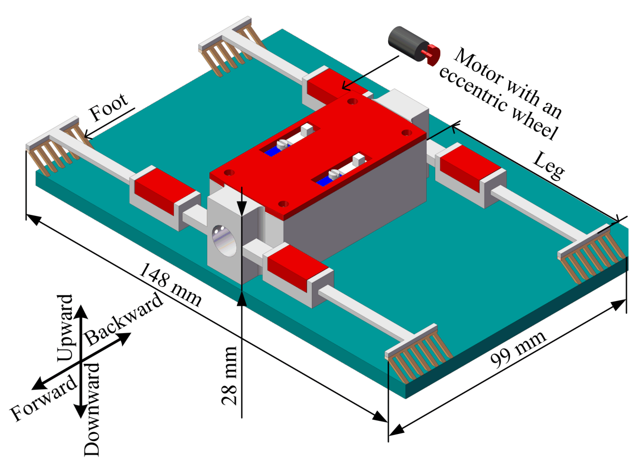

FIGURE 1. The basic structure of the Resbot.

With such a design, the legs of the Resbot can be seen as separated cantilever beams. A DC motor linked with an eccentric wheel is installed in the extremity of the leg near the trunk. When the DC motor works, the rotating eccentric wheel will generate a cyclic inertial centrifugal force, which is equal to the superposition of a horizontal sinusoidal force and a vertical force with temporal shift of 90 degree. Under the sinusoidal force, the bending vibration of the leg can be excited, and the extremity with the foot will have a displacement in the same direction as that of the force. Therefore, the top of the foot moves actively, while the bottom will move passively.

The driving principle includes two sub-principles, which are based on vertical bending vibration and horizontal bending vibration, respectively. The leg is designed to have a different resonance frequency of the first order vertical bending mode from that of the first order horizontal bending mode, so that each resonance could be excited independently.

The first driving sub-principle is based on the vertical bending vibrations of the four legs. When a vertical bending vibration of the leg is excited, the foot will vibrate up and down repeatedly. The motion sequence of the foot is exhibited in Fig. 2(a): step (1) shows the initial status of the foot; then the top of the foot moves downward at step (2), which makes the end of the foot have an increasing deformation. The bottom of the foot, which touches on the floor, will tend to move backward. Under this condition, the foot will bear a frictional force forward, which is illustrated as f_1. Therefore, the top of the foot will move forward as the deformation increasing. But the bottom of the foot will not finish any movements forward at step (2). Step (3) shows that the foot recovers its origin shape as it moves upward, meanwhile the bottom of the foot finishes a step movement forward. Step (4) starts another circle, it accomplishes a displacement, x_1, by comparing with the foot in step (2). In this way, a vertical bending vibration of the leg is able to drive the Resbot to move step-by-step.

Horizontal bending vibrations offer the second driving sub-principle. A horizontal bending vibration of the leg drives the top of the foot back and forth. The motion sequence of one foot is illustrated in Fig. 2(b). The foot in step (1) is in its initial state. Step (2) shows that the top of the foot moves backward, and the bottom of the foot will also have a movement trend backward. So the foot bears a frictional force forward, which is illustrated as f_2. In step (3), the top of the foot moves forward. Now the bottom of the foot has a movement forward. So the foot bears a frictional force backward, as shown by f_3. Because the elastic deformation of the foot in step (2) is bigger than that in step (3), the normal force that the floor gives to the foot, F_{n2}, is bigger than F_{n3}, resulting in that the frictional force f_2 is bigger than f_3. Therefore, as the foot goes back and forth once, the displacement of the bottom forward is bigger than the one in backward. In a circle, frictional forces consequently make the foot move forward. Step (4) starts a new circle. It accomplishes a forward displacement, x_2, by comparing with the foot in step (2), which means that the Resbot could be driven by a horizontal bending vibration of the leg step-by-step.

The operating principles shown by Fig. 2 illustrate the generation process of the driving force produced by only one foot, and the move style of the Resbot shown by Fig. 1 can be seen as the direct superposition of four driving feet. When these four feet vibrate under the same bending mode and also the same frequency, the Resbot can move forward as the four feet can produce the same driving force. When the two DC motors on the two legs of the left-side keep static and the other two DC motors on the two legs of the right-side work to generate the bending vibrations, Resbot can turn leftward; the switching of the exciting voltages of the motors can result in the rightward turning in a similar way.

III. MODELING OF THE RESBOT

It is well known that the bending vibrations will have the maximum vibration intensities under the resonant vibration states, therefore, it's necessary to make sure that the first order vertical bending vibration and the first order horizontal bending vibration are easy to be excited. Because the frequency of the exciting force depends on the rotation rate of the DC motor used in the Resbot, and the highest rotation rate of the motor is about 240 r/s (revolutions per second), the resonance frequencies of the first order vertical bending mode and the first order horizontal bending mode should be lower than this value to ensure that those resonant vibrations could be excited. Resonance frequencies of the Resbot are calculated

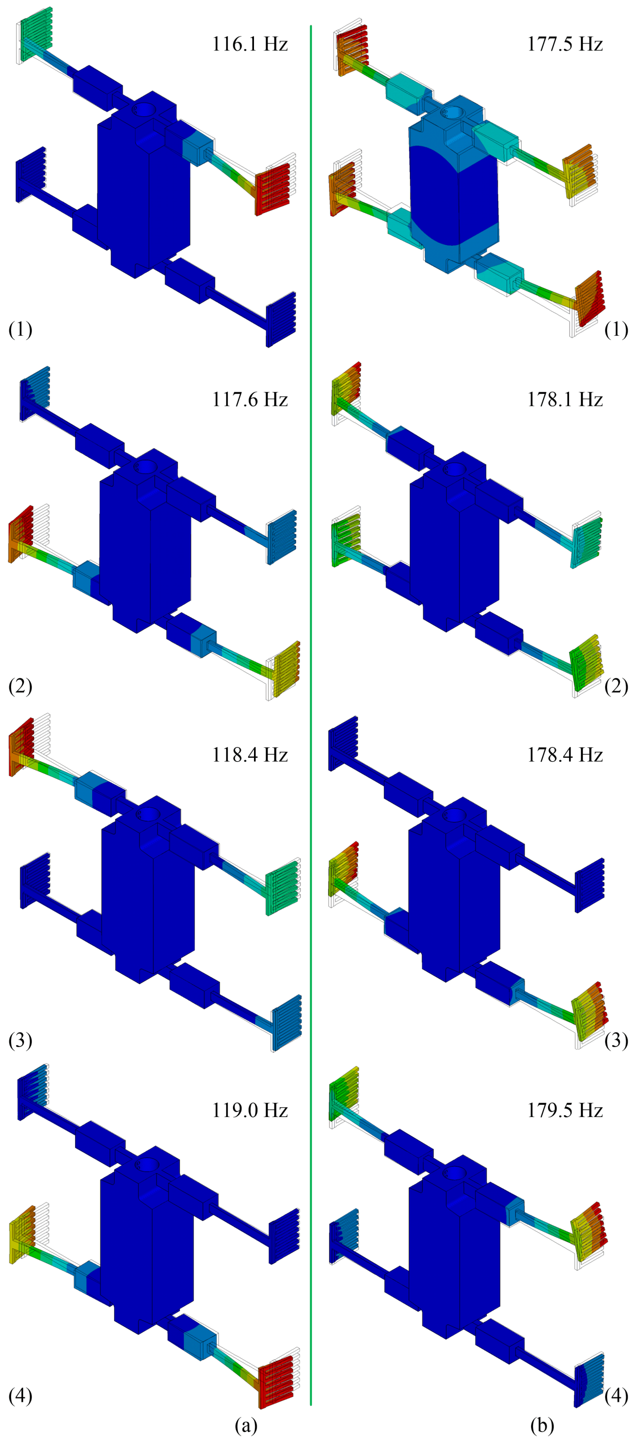

FIGURE 3. Bending vibration modes of the Resbot in two directions: (a) vertical bending vibrations, (b) horizontal bending vibrations.

by finite element method (FEM) mode analysis. The material of the body is set as PA 12 with density of 930 kg/m^3, modulus of elasticity of 1.7×10^9 N/m^2 and Poisson ratio of 0.4. The material of feet is set as PolyFlex from Polymaker with density of 1200 kg/m^3, modulus of elasticity of 1.7×10^8 N/m^2 and Poisson ratio of 0.4. The calculated resonance

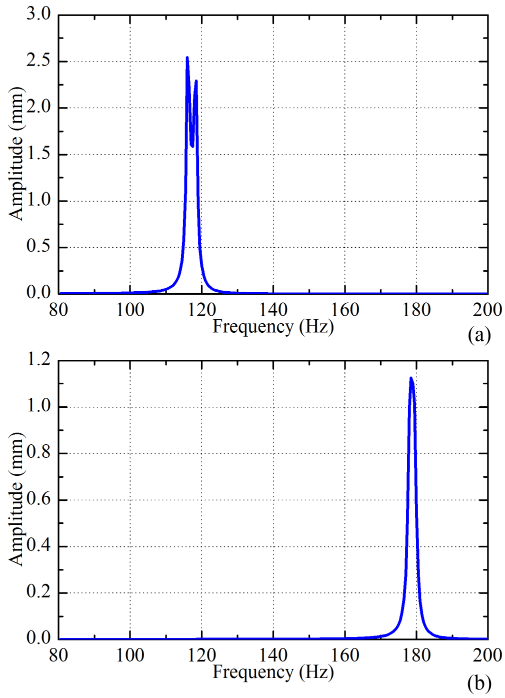

FIGURE 4. The harmonic response analysis results of the displacement of one foot: (a) in the vertical direction, (b) in the horizontal direction.

frequencies of the Resbot are listed in Table 1, and the first order to the eighth order modes of the Resbot are exhibited in Fig. 3.

As shown in Fig. 3(a), the vibration modes from the first order to the forth order are all vertical bending vibrations of the legs. And the fifth to the eighth order vibration modes exhibited in Fig. 3(b) are horizontal bending vibrations. The former ones could be used to drive the Resbot by the sub-principle shown in Fig. 2(a), while the latter ones could drive the Resbot by the sub-principle shown in Fig. 2(b). Every mode could be simply seen as a combination of all the four legs' bending vibrations with a certain set of temporal phase shifts. And four different sets of the phase shifts generate four separated modes of the bending vibrations in each direction, but they have very close resonance frequencies.

IV. VERIFICATION OF THE AMPLITUDE AT THE END OF EACH LEG

Under a certain exciting force, the amplitude of the foot is a fixed value, which significantly influences the driving effect. Therefore, it is important to verify that the amplitude excited is strong enough. FEM (ANSYS software) harmonic response analysis was used to calculate the vibration amplitude of the driving foot under different exciting frequencies. Firstly, the vertical amplitude of the foot was calculated by applying a sinusoidal exciting force of 0.1 N along the vertical direction and the range of the exciting force frequency was set from 80 Hz to 200 Hz, which adequately included all the first eight modes resonance frequencies. The analysis result was shown in Fig. 4(a) and the biggest vertical amplitude of the foot was about 2.5 mm. Besides, it was found that the biggest vertical amplitude of the foot was realized under the frequency from 115 Hz to 120 Hz, which accorded with the calculated results of the mode analysis. Then, the exciting force was changed to be a sinusoidal horizontal force of 0.1 N to calculate the horizontal amplitude of the foot, and the calculation result was shown in Fig. 4(b). The biggest amplitude was approximately 1.1 mm, which was gotten under the frequency of 187.5 Hz. The amplitude of 2.5 mm or 1.1 mm was supposed to be strong enough to drive the Resbot as its small size and low weight.

V. FABRICATION AND EXPERIMENTAL VERIFICATION OF THE RESBOT

The body and feet of the Resbot were fabricated by 3D printing. The material of the body was PA 12 and the material of the feet was PolyFlex, which was from Polymaker. The DC motors were glued to the body, while the linked eccentric wheels were kept away from the glue. Feet were fasten to tip ends of the legs by copper wires. The prototype of the Resbot is shown in Fig. 5. The Resbot weighs nearly 53 g, and its size is 99 mm × 148 mm × 28 mm. Some key sizes of the feet, motors and eccentric wheels are also exhibited in Fig. 5. Besides, the power source was an AAA battery. A rheostat was used to control the voltage applied on the DC motors, which determined the rotation rate of the motor. Fig. 6(a) shows that the Resbot moves on the wood floor, while the motion sequence of the Resbot on the ground tile is shown as Fig. 6(b).

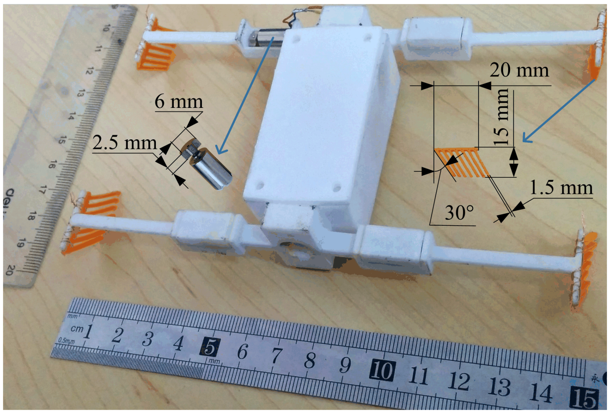

FIGURE 5. The prototype of the proposed Resbot.

VI. CHARACTERIZATION OF THE RESBOT

The vibration modes of one leg of the Resbot were measured by using a scanning laser Doppler vibrometer (PSV-400-M2, Polytec, Germany) to gain the real vibration shapes and the corresponding frequencies. The result of the measurement was shown in Fig. 7, which stated that the two tested vibration modes were both first order bending vibrations; the vertical bending resonance frequency was tested to be about 87.0 Hz, while the horizontal bending resonance frequency

FIGURE 6. **The movements of the Resbot on two surfaces: (a) on the wood floor, (b) on the ground tile.**

was approximately 182.6 Hz. It was evident that first order horizontal bending resonance frequency was extremely close to the eighth order mode frequency of the Resbot listed in Table 1. However, the first order vertical bending resonance frequency was significantly lower than the first order mode frequency calculated by FEM. Because the thickness of a leg was much smaller than its width, the manufacturing errors affected the thickness more heavily. And the thickness had more influence on the first order vertical bending resonance frequency than that of the horizontal mode. Therefore, the tested vertical bending resonance frequency was not very close to the calculated one. But fortunately, this discrepancy between the real resonance frequency and the calculated one hardly has influence on the conclusion.

Firstly, the voltages applied on the DC motors were adjusted to measure its effect on the moving speed of Resbot, and two conditions were used as the contact surfaces would affect the frictional forces: wood floor and ground tile, respectively. The motion velocities of the Resbot under various voltages on the wood floor were shown in Fig. 8(a), and the relationship on the ground tile was shown in Fig. 8(b). Both curves in Fig. 8 had two peak values of the velocity: the first peak value on the wood floor corresponded to the voltage of 0.624 V, and that on the ground tile corresponded to the voltage of 0.638 V; the two voltages were 1.295 V and 1.255 V respectively for the second peak. And the highest velocity of 17.2 cm/s in Fig. 8 was achieved when the Resbot operated under voltage of 1.295 V and moved on the wood floor. Furthermore, the turning radius of the Resbot was measured as about 21 cm. Both the two curves shown in Fig. 8 stated that Resbot achieved higher moving speed by using the horizontal bending vibration modes.

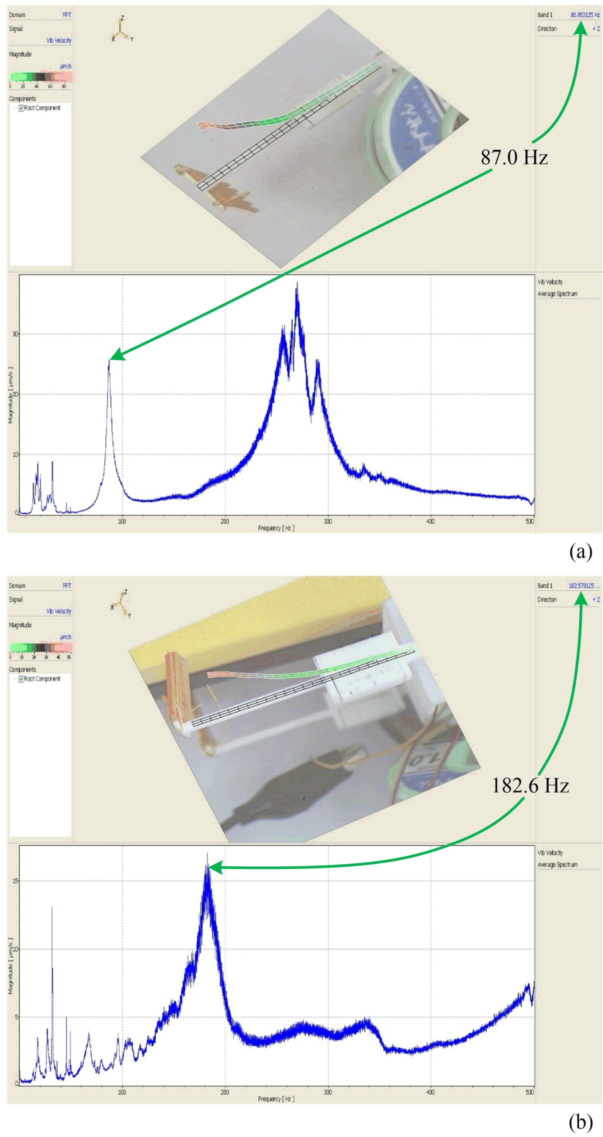

FIGURE 7. **Vibration scanning results of the Resbot: (a) vertical bending vibration, (b) horizontal bending vibration.**

TABLE 1. **The resonance frequencies of the resbot.**

Mode order	Resonance frequency(Hz)
1	116.1
2	117.6
3	118.4
4	119.0
5	177.5
6	178.1
7	178.4
8	179.5

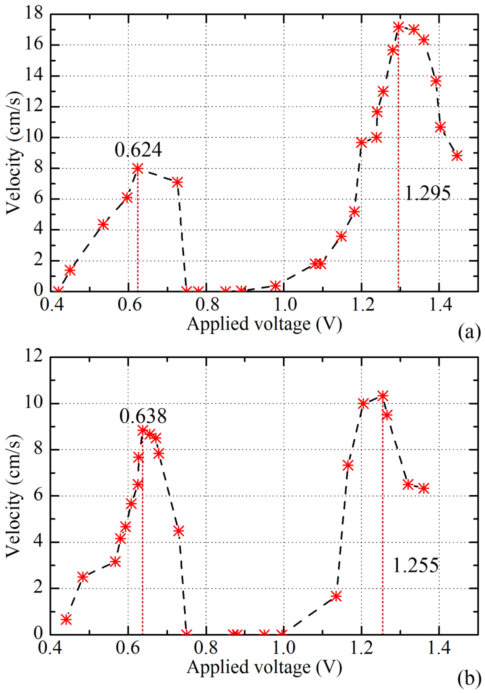

FIGURE 8. **Velocities of the Resbot at various applied voltages: (a) on the wood floor, (b) on the ground tile.**

TABLE 2. **The rotation rates of the motor under various applied voltages.**

Applied voltage (V)	The rotation speed of the motor (r/s)
0.624	95.4
0.638	96.9
1.255	181.7
1.295	185.9

To ascertain the reason for peak velocities in Fig. 8, we measured the rotation rate of the applied motor under those voltages corresponding to peak velocities. And the result is listed in Table 2. In Table 2, the rotation rate of the motor under a certain voltage represents the frequency of the exciting force. Then it's necessary to compare the frequencies of the exciting forces under key voltages corresponding to the peak velocities in Fig. 8 with the real resonance frequencies shown in Fig. 7. First, for the first peak velocity in Fig. 8(a), the frequency of the exciting force is 95.4 Hz. Second, the frequency of the exciting force under the voltage corresponding to the first peak velocity in Fig. 8(b) is 96.9 Hz. Despite the difference, we find that frequencies of 95.4 Hz and 96.9 Hz are close to the first order vertical bending resonance frequency of 87.0 Hz shown in Fig. 7(a). Therefore, the first order vertical bending mode generates the first peak velocity in both Fig. 8(a) and (b). The frequency of the exciting force corresponding to the second peak velocity in Fig. 8(a) is 181.7 Hz, and that value in Fig. 8(b) is 185.9 Hz. It's evident that those two frequencies are very close to the first order horizontal bending resonance frequency, which means that the second peak velocities in Fig. 8(a) and (b)

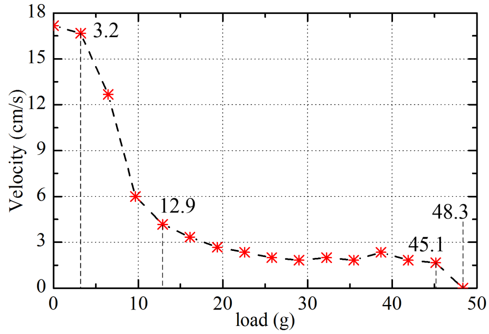

FIGURE 9. **9 Velocities of the Resbot under various loads on the wood floor.**

are engendered by the first order horizontal bending mode.

However, for the first peak velocity in Fig. 8(a) and (b), the difference between the exciting force frequency and the first order vertical bending resonance frequency should not be simply overlooked. Results in Fig. 7 were gotten under free boundary conditions. However, feet bore the gravity of the Resbot when we measured the relationships in Fig. 8. The variation of the boundary conditions caused the deviation between the exciting force frequency and the first order vertical bending resonance frequency. Besides, because of the direction of the gravity, the difference of the boundary conditions had much less influence on the horizontal bending mode, which explained that there was no obvious deviation between the exciting force frequency corresponding to the second peaks of both curves in Fig. 8 and the tested first order horizontal bending resonance frequency.

For each curve in Fig. 8, the second peak achieved a higher moving speed than the first peak did. It was believed that the frequency difference between the two peaks was the main reason. Firstly, a higher frequency of the exciting force meant that more driving cycles were finished. Second, because the exciting force was essentially an inertial centrifugal force, its amplitude increased as the increasing of the frequency. It was intelligible that the bigger exciting force could enhance the driving effect.

Comparing the two curves in Fig. 8, we found that the amplitude of the second peak of curve (a) was much higher than that of the first peak, while the second peak of curve (b) was a little higher than the first peak. The discrepancy between surfaces was considered as a main factor. The wood floor was rougher than the ground tile, which contributed to a better driving effect of the horizontal bending vibration.

Velocities of the Resbot under exciting voltage of 1.295 V and various loads were shown in Fig. 9, which were measured on the wood floor. Firstly, the load of 3.2 g had very little effect on the velocity of the Resbot. The velocity of the Resbot declined significantly as the load increasing from 3.2 g to 12.9 g. Then, the velocity was rather low and relatively steady under the load of 12.9 g to 45.1 g. Finally, the load of 48.3 g stopped the Resbot moving absolutely.

VII. CONCLUSION

A four legged small robot named Resbot was proposed, designed, fabricated and tested, in which the bending vibrations of four cantilever beam type legs were generated to produce the diving forces by the soft and oblique driving feet. It was proved that both the vertical and horizontal bending vibrations of the legs were effective enough to drive the robot. The outstanding advantage of the proposed driving method was that it needed no intermediate transmission, no design of the gait and just an extremely simple control system. The prototype of the Resbot with a size of 99 mm × 148 mm × 28 mm realized a movement velocity of 17.2 cm/s by using the horizontal bending vibrations, which demonstrated the feasibility of the proposed driving method in micro robots. What's more important was that both the first order vertical bending vibration and the first order horizontal bending vibration had pretty good driving effects, i.e. both the two proposed driving sub-principles were available.

In the future, the proposed driving method will be used further to design robot with smaller sizes, and other modules such as vision system will be added to make the Resbot more practical for application.

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