Rattling modes and the intrinsic vibrational spectrum of beetle-type scanning tunneling microscopes

J. A. Miwa, J. M. MacLeod, Antje Moffat and A. B. McLean*

Department of Physics, Queen's University,

Kingston, Ontario, Canada, K7L 3N6.

(Dated: January 29, 2003)

Abstract

It is known that the vibrational spectra of beetle-type scanning tunneling microscopes with a total mass of ≈ 3-4g contain extrinsic 'rattling' modes in the frequency range extending from 500 to 1700Hz that interfere with image acquisition. These modes lie below the lowest calculated eigenfrequency of the beetle and it has been suggested that they arise from the inertial sliding of the beetle between surface asperities on the raceway. In this paper we describe some cross-coupling measurements that were performed on three home-built beetle-type STMs of two different designs. We provide evidence that suggests that for beetles with total masses of 12-15g all the modes in the rattling range are intrinsic. This provides additional support for the notion that the vibrational properties of beetle-type scanning tunneling microscopes can be improved by increasing the contact pressure between the feet of the beetle and the raceway.

PACS numbers: 07.79.C, 07.10, 07.10.F, 46.40

I. INTRODUCTION

Since their invention[1], beetle-type scanning tunneling microscopes (STMs) have become extremely popular. They are easy to construct and they have low thermal drift because thermal expansion/contraction of the legs is compensated by thermal expansion/contraction of the scanner. Consequently, they are ideal for variable temperature applications. However, vibrational studies of beetle-type STMs[2], with a total mass of ≈ 3-4g, have identified 'rattling' modes in the frequency range extending from 500 to 1700Hz that interfere with image acquisition[2]. These 'extrinsic' modes lie below the lowest calculated eigenfrequency of the beetle. It has been suggested that they arise from the inertial sliding of the beetle on or between surface asperities on the raceway[2,3] and that they may be a general problem in microscopes that use kinetic motion for coarse positioning[2]. We recently built three beetle-type STMs using two different designs. All three beetles are heavier than the beetles that were studied earlier[2]. Intriguingly, we found that none of these beetles possessed rattling modes. This result provides additional support[3] for the notion that increasing the contact pressure between the feet of the beetle and the raceway improve the vibrational properties of beetle-type STMs as previously suggested[2].

The total masses of our beetles lie in the range 12-15g. Two of these beetles (b1 and b2 for short) are manufactured from an aluminum disk with a diameter of 33.0mm (1.3"). The piezo-tubes used for both the legs and the scanner have a diameter of 3.2mm (0.125") and a length of 12.7mm (0.5") (Fig.1a). The third beetle (b3) has a larger disk, shorter and wider legs (Fig.1b). All three beetles are variants of the Wilms-beetle design[4,5]. Course approach is achieved by inertially sliding the beetle towards the sample. Furthermore, the sample is inclined by 6°, from the horizontal, and the scanner is displaced, from the vertical, by the same angle to keep the tip orthogonal to the surface during scanning. A detailed description of the beetles can be found elsewhere[6,7,8].

All three beetles routinely produce images of silicon surfaces with atomic resolution in ultra high vacuum[7]. After these beetles were constructed, we measured their vibrational spectra by exciting the bending mode of the scanner with a sinusoidal waveform (10V pp) and measuring the in-phase piezoelectric voltage on the legs with a lock-in amplifier[2,3,9,10,11,12]. We also calculated the eigenfrequencies using an approach that has been described before[2]. These estimates of the eigenfrequencies allowed us to identify the frequency ranges in which the principal eigenmodes should appear and in some cases assign individual modes.

The b3 beetle is different from the other two. It was designed from the outset to have higher eigenfrequencies. The length of the piezo-tubes that were used for both the legs and the scanner was reduced from 12.7mm (0.5") to 7.6mm (0.3") and the diameter was increased from 3.2mm (0.125") to 6.4mm (0.250"). The wall thickness of 0.6mm (0.024") was unaltered. These changes increased the stiffness of the piezo-tubes and, as expected, stiffening the piezo-tubes shifted the modes to higher frequency.

II. CALCULATION OF EIGENFREQUENCIES

It is convenient, when studying the vibrational properties of beetle-type STMs, to start with the eigenmodes of a massless tube of length L, inner diameter d and outer diameter D (Fig.2) with one end rigidly fixed. We define bending ($\perp$), torsional (ϕ) and flexing ($\|$) modes with respect to the high symmetry axis of the tube. The eigenfrequencies of the tube, associated with these three modes, are: $\omega_\perp = \sqrt{\kappa_\perp/m}$, $\omega_\phi = \sqrt{\kappa_\phi/I}$ and $\omega_\| = \sqrt{\kappa_\|/m}$. The corresponding spring constants[2,13,14,15] are:

$$\kappa_\perp = \frac{3\pi}{64} E \frac{D^4 - d^4}{L^3}, \tag{1}$$

$$\kappa_\phi = \frac{\pi}{32} G \frac{D^4 - d^4}{L} \tag{2}$$

and

$$\kappa_\| = \frac{\pi}{4} E \frac{D^2 - d^2}{L}, \tag{3}$$

where E is the Young's modulus, $G = E/2(1+\nu)$ is the shear modulus, ν=0.31 is Poisson's ratio for the piezo-ceramic and $\omega = 2\pi f$. These expressions can be used to calculate the eigenfrequencies of the scanner and the legs. The 'internal' eigenfrequencies of the disk can be ignored[2,16]. They are much higher than any of the other frequencies that are calculated below.

The eigenfrequencies of the scanner are straightforward to calculate. They are tube eigenmodes. Because the top end of the scanner is glued to the aluminum pin, only the bottom end of the scanner can bend, twist and flex. The corresponding eigenfrequencies can be calculated by using the mass and the moment of inertia of the tip assembly in the equations given above.

The eigenmodes of the legs are slightly more complicated. The piezo-tubes are once again glued into aluminum pins and the top of the leg piezos do not move relative to the disk. The leg flexing mode produces a vertical displacement of the disk and the leg bending mode produces a horizontal displacement. The eigenfrequencies of both modes can be calculated using the mass that loads the legs (m_L). This mass is taken to be one third of the total beetle mass minus the combined mass of a piezo-tube and a sapphire ball. Another important mode is the torsional mode of the disk and the eigenfrequency of this mode can be calculated from the bending eigenfrequency of the leg[2]; $\omega_\phi^{\text{beetle}} \approx \sqrt{2}\omega_\perp^{\text{leg}}$. Because the (unidirectional and circumferential) bending and flexing modes of the legs induce motion of the disk we often refer to these modes as the bending ($\perp$), torsional (ϕ) and flexing ($\|$) modes of the beetle, respectively. Note that torsional motion of the legs is only possible if the bottom of the legs twist because the top is rigidly fixed.

III. MEASUREMENT OF EIGENFREQUENCIES

We have calculated the principal eigenfrequencies for both beetle designs and the location of the eigenmodes is indicated on both Fig.3 and Fig.4. In Fig.3 there are a number of strong resonance peaks extending from just below 2.0kHz to 4.5kHz. The lowest two correspond very well with our estimates of the bending and torsional modes of the beetle. The beetle flexing mode lies at $\approx$ 11.5kHz and there is a resonance peak close to this frequency. Additionally, we have calculated that the bending, the torsional and the flexing modes of the lifting assembly are 3.5, 4.4 and 37.3 kHz, respectively, when the lifting bar is located 16.5mm (0.65") above the disk. The lifting assembly was designed for ease-of-use. The lifting bar is located above the center of mass of the beetle to allow the beetle to be lifted and lowered safely. This is important because the wall thickness of the piezo-legs is only 0.6mm (0.024") and the legs are relatively fragile. We found, as expected, that lowering the lifting bar shifted the resonances associated with the lifting assembly to higher frequency (not shown).

The vibrational spectrum of b3 is presented in Fig.4 as is the calculated location of the beetle bending mode. The torsional and flexing modes are calculated to be 14.1 and 21.5kHz respectively (not shown). The vertical axis has been multiplied by a factor of 5.0 relative to that of Fig.3. Although the same excitation voltage (10V pp) was used, the amplitudes of the peaks are smaller in Fig.4 because the piezo-tubes are stiffer.

The beetle modes are proportional to $1/\sqrt{m_L}$. Consequently, loading the beetle with an additional mass[3,11] Δm will produce a shift in the eigenfrequency $\omega(m_L + \Delta m_L) = \gamma(m_L, \Delta m_L)\omega(m_L)$ by the following multiplicative factor:

$$\gamma(m_L, \Delta m_L) = \frac{1}{\sqrt{1 + \Delta m_L/m_L}}, \tag{4}$$

where Δm_L is the mass per leg ($\Delta m_L = \Delta m/3$). This allows us to separate beetle modes from both scanner modes and lifting assembly modes. For example, in Fig.5 an additional mass Δm=15g has been added to b3. The mass shifts the vibrational spectrum to lower frequencies, moves the peaks closer together and reduces their amplitude. Similar effects have been observed by others[11]. The results presented in Fig.5 confirm our conjecture that the modes in this frequency range are predominantly beetle bending modes. Note that there is a feature, marked by an arrow, in both spectra that is unaffected by the addition of the mass, suggesting that it is not associated with the legs. It could, for example, arise from the scanner. It is very important that the additional mass is added in such a way that the loading on all three legs is even. We added disk shaped weights that had a radial slots cut in them that allowed the weight to be slipped around the lifting assembly in such a way that the center of mass was coincident with the center of the beetle disk.

IV. THE RATTLING REGION

We now turn to describe the low frequency behavior between 500 and 1700Hz: the rattling region. Previous cross coupling measurements of a $\approx$ 3g (the quoted mass of the disk) beetle-type STM found $\approx$ 16 peaks in this range. It was also noted that lifting the beetle off the raceway with the manipulator and re-positioning it would cause the peaks to shift slightly (Fig. 2 of Ref.[2]).

In Fig.6 we present two vibrational spectra taken using b1. Although there is a band of peaks in the 350-550Hz range, the rattling range is devoid of peaks. This figure also illustrates the results of a control experiment that was done to test whether the low frequency vibrational spectrum depended on the geometry of the raceway. The bottom spectrum is the b1 beetle on a stainless-steel Frohn-like raceway[1] and the top is the b1 beetle on a flat stainless steel surface. These vibrational spectra are strikingly similar considering that they were taken on two different surfaces.

Fig.7 illustrates the results of another control experiment with b3, to test whether the vibrational damping stack that the beetles are mounted on during normal operation influenced the low frequency spectrum. Coupling between beetle and stack modes has been observed when beetles are placed on plates that have a relatively small mass and moment of inertia[12]. First, we note that all three spectra do have peaks in the rattling region. However, the number of peaks is substantially smaller than the ≈ 16 detected earlier[2]. The band of peaks located near 1.4kHz are produced by the lifting assembly even although they are well below the calculated bending frequency (3.6kHz). The lifting assembly comprises a vertical post and a horizontal bar. The lifting post is threaded into the disk and, although it is tightly screwed into the disk, we suspect that the post can still move relative to the disk. When the post is unscrewed and completely removed, this band of peaks completely disappears. Furthermore, when the beetle is lifted off the raceway the band of peaks vanished, as expected. However, the low frequency range is unchanged. This means of attaching the lifting assembly to the disk was only used in b3. We have not been able to positively identify the peak at 500Hz, although, by process of elimination, we think that it is associated with the tip holder in the scanner. Curve(a) was taken with b3 on two stainless steel disks separated by viton hung suspended using three viton chords. Curve(b) was measured with the beetle on a stainless steel disk that was suspended using three viton chords. Curve(c) was the beetle on the fully assembled stack. Clearly, these results show that the details of the stack construction do not affect the low frequency vibrational spectrum or that they all affect the spectrum in exactly the same way. The latter of these two conclusions is more implausible. They also show that, to first order, the vibrational spectrum is the same on three different surfaces, consistent with the results presented earlier in Fig.6.

We performed several other control experiments that produced null results that we will only describe here briefly. We performed loading measurements with the b3 beetle in the rattling range and found that the low frequency peaks were not perturbed by the addition of an extra mass. This is consistent with our suggestion that the low frequency peaks are intrinsic vibrational peaks that are not associated with the legs. We also removed the fine control wires one-by-one from the beetle, and performed a resonance scan after each one had been removed, until we were left with only the wires that were necessary to perform the cross coupling measurement. We saw no change in the low frequency vibrational spectra. Although these are both null results, they do suggest that the low frequency peaks are intrinsic and it is reassuring to know that the fine wires are mechanically damped by their attachment to the beetle disk[6,7,8].

V. CONCLUSIONS

We have measured the vibrational spectrum of three different beetles (b2 is essentially identical to b1) with two different designs and identified many of the principal eigenmodes. For example, we were able to positively identity the bending, torsional and flexing modes of all three beetles. The use of loading measurements to check the assignment of the beetle modes was demonstrated using the b3 beetle bending mode. We also found strong modes that we could positively attribute to the lifting assembly. To our knowledge, these have not been discussed in the literature before and it is clear that the lifting assembly has to be designed to keep the eigenfrequencies above the beetle bending mode. We found that moving the lifting bar nearer to the disk shifted these modes out of harm's way. In fact, mounting the lifting bar directly onto the beetle disk is probably best[1]. We also studied the rattling range (500-1700Hz), in detail, because it is commensurate with STM scanning frequencies. There were no extrinsic 'rattling' peaks that we could identify. Moving our beetles to different positions on the same surface or to other surfaces had no effect on the low frequency vibrational spectrum. Lifting the beetle off the raceway caused the eigenfrequencies that we positively associated with the lifting assembly to disappear. However, the low frequency range was otherwise unaltered. We compared the low frequency spectrum generated by the beetle on a flat surface with the spectrum generated by the beetle on a Frohn-style raceway[1] and found them, within experimental uncertainly, to be identical. Adding additional masses to the b3 beetle did not change the low frequency vibrational spectrum. Furthermore, we placed the beetle on three different support structures and found that the low frequency vibrational spectrum was unchanged.

Why do our beetles not have 'extrinsic' rattling modes ? The answer may simply be that our beetles are heavier than those studied previously: 12-15g rather than 3-4g. In our beetles, the contact pressure is 3-4 times larger and this could attenuate the rattling modes, by elastically or plastically deforming asperities on the surface of the sapphire ball or on the surface of the raceway, much in the same way that the bending mode was attenuated (Fig.5). The contact pressure can also be increased using magnetic clamping[3] and our results provide additional support for the idea that the vibrational properties of the beetle can be improved by increasing the contact pressure between the feet of the beetle and the raceway.

Acknowledgments

This research was supported by the Natural Sciences and Engineering Research Council of Canada and Queen's University at Kingston, Canada.

* mclean@physics.queensu.ca; http://www.physics.queensu.ca/~nanophys

[1] J. Frohn, J. F. Wolf, K. Besocke, and M. Teske, Rev. Sci. Instrum. **60**, 1200 (1989).

[2] S. Behler, M. K. Rose, D. F. Ogletree, and M. Salmeron, Rev. Sci. Instrum. **68**, 124 (1997).

[3] T. Michely, K. H. Besocke, and M. Teske, J. of Microscopy **152**, 77 (1988).

[4] M. Wilms, diploma thesis, Institut für Physikalische und Theoretische Chemie, Universität Bonn, Germany (1994).

[5] G. B. M. Wilms, M. Schmidt and K. Wandelt, Rev. Sci. Instrum. **69**, 2696 (1998).

[6] A. Lucas, diploma. thesis, University of Stuttgart (2000).

[7] J. A. Miwa, Master's thesis, Queen's University (2002).

[8] J. M. MacLeod, A. Moffat, J. A. Miwa, A. G. Mark, G. K. Mullins, R. H. J. Dumont, G. E. Contant, and A. B. McLean, Rev. Sci. Instrum. (to be published) (2003).

[9] M. H. Jericho, D. C. Dahn, and B. L. Blackford, Rev. Sci. Instrum. **58**, 1349 (1987).

[10] B. Gasser, A. Menck, H. Brune, and K. Kern, Rev. Sci. Instrum. **67**, 1925 (1996).

[11] B. Fischer, Ph.D. thesis, Ecole Polytechnique Fédérale de Lausanne (1998).

[12] H. Jödicke, Ph.D. thesis, Ecole Polytechnique Fédérale de Lausanne (1998).

[13] O. W. Eshbach, *Handbook of Engineering Fundamentals* (John Wiley and Sons, Inc, New York, London, Sydney, 1952).

[14] L. D. Landau and E. M. Lifshitz, *Theory of Elasticity* (Pergamon Press, Oxford, 1986).

[15] C. J. Chen, *Introduction to Scanning Tunneling Microscopy* (Oxford University Press, New York, Oxford, 1993).

[16] J. Au, Engineering physics design thesis, Queen's University (1998).

Figures

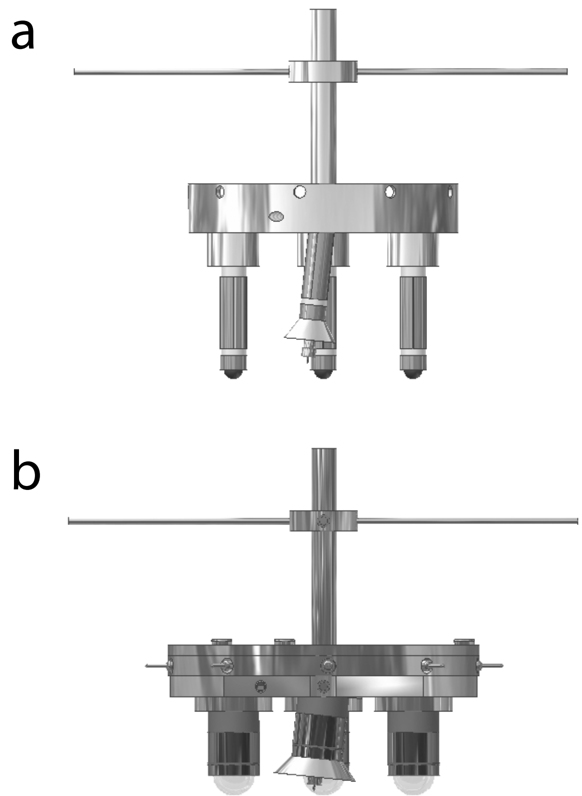

Fig.1 Side views of the two beetle designs drawn to scale. (**a**) b1 (b2 is essentially identical) and (**b**) b3. The diameter of the b1 disk is 33.0mm (1.3").

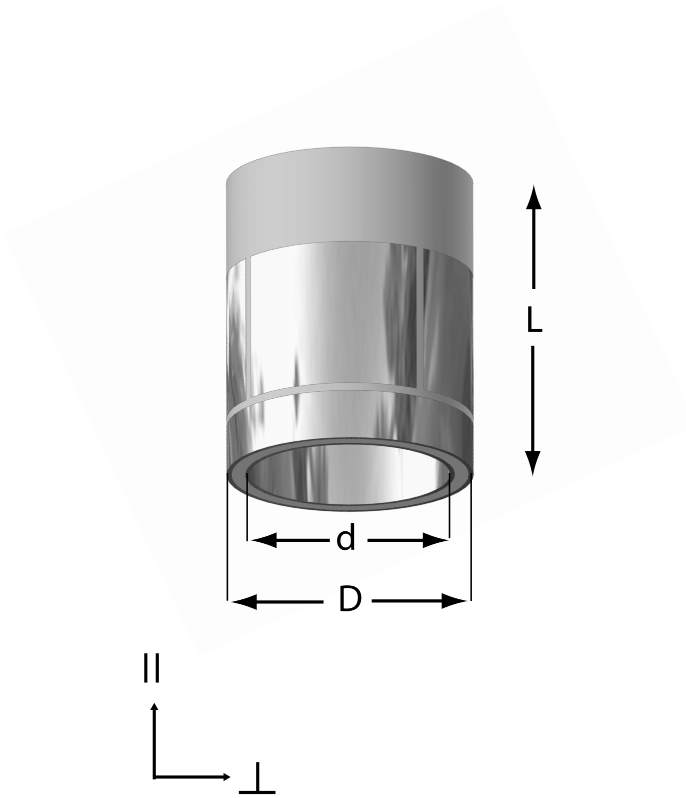

Fig.2 A schematic drawing of the piezo-ceramic tube showing inner tube diameter (d), outer tube diameter (D), length (L), the parallel ($\|$) and perpendicular ($\perp$) directions.

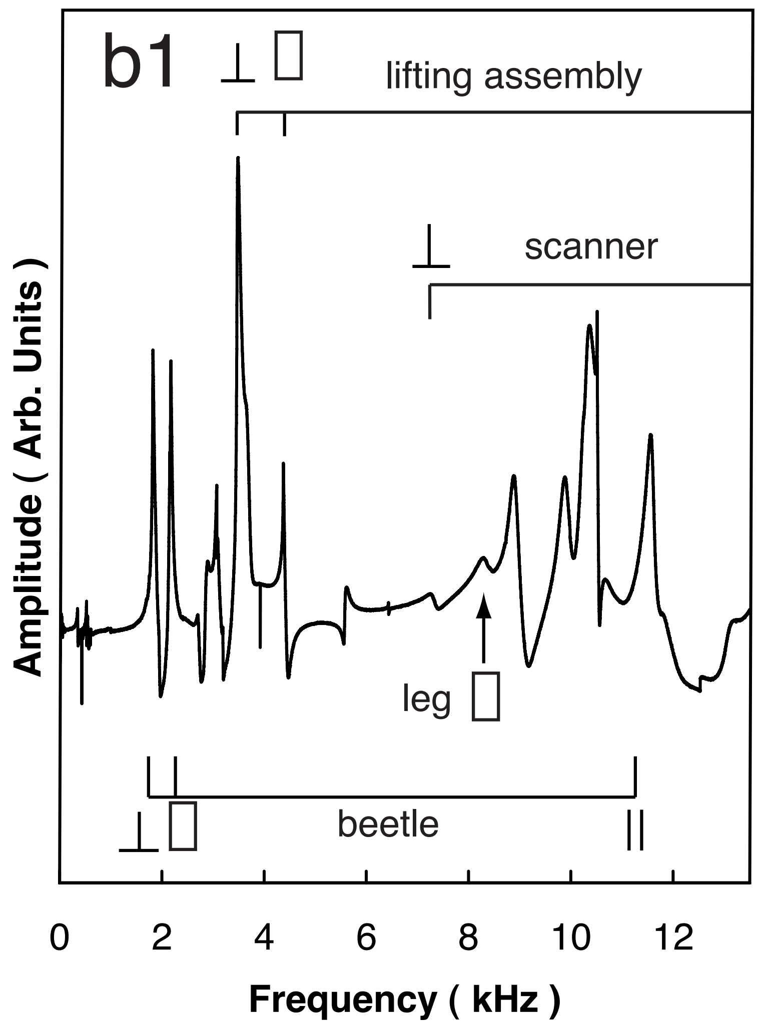

Fig.3 The vibrational spectrum of b1 and the calculated eigenfrequencies. The peaks occurring at 1.7, 2.1 and 11.7kHz correspond closely to the calculated bending ($\perp$), torsional (ϕ) and flexing ($\|$) modes of the beetle, respectively. Two other peaks, found at 7.4 and 8.2kHz, are assigned to the bending mode of the scanner and the torsional mode of the legs, respectively.

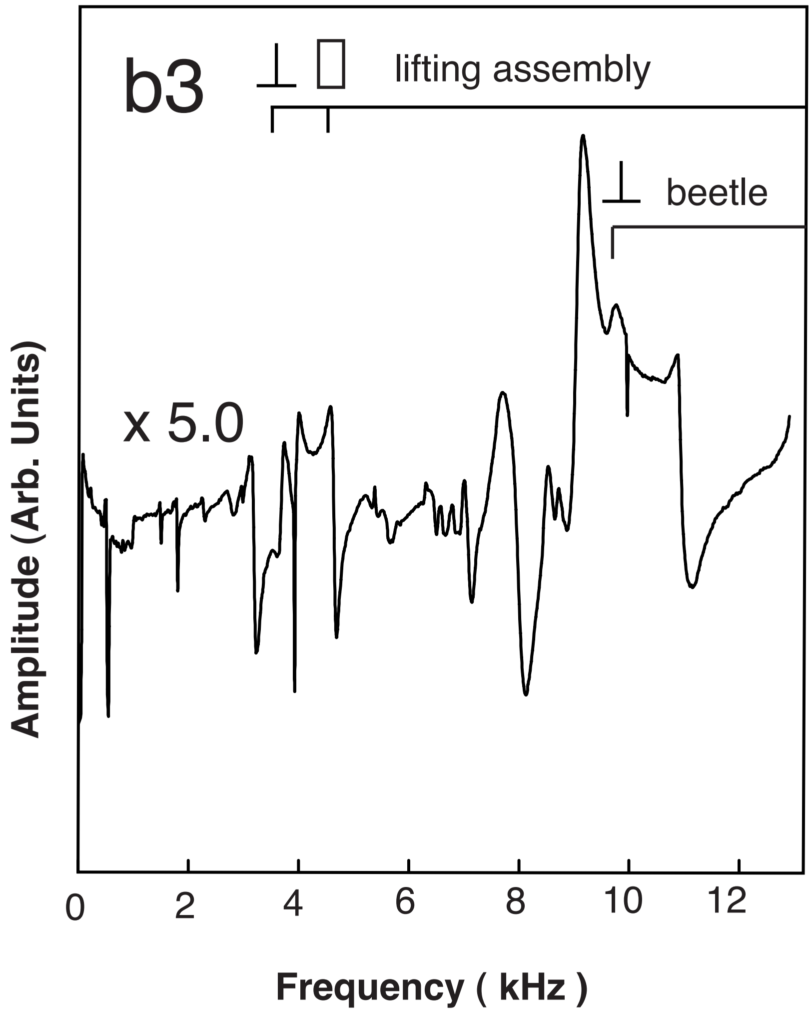

Fig.4 The vibrational spectrum of b3. The peak at 9.5kHz is attributed to the beetle bending mode (⊥). It is close to our calculated eigenfrequency for this mode. The torsional and flexing modes of the beetle are located at higher frequency, as are the bending, torsional and flexing modes of the scanner.

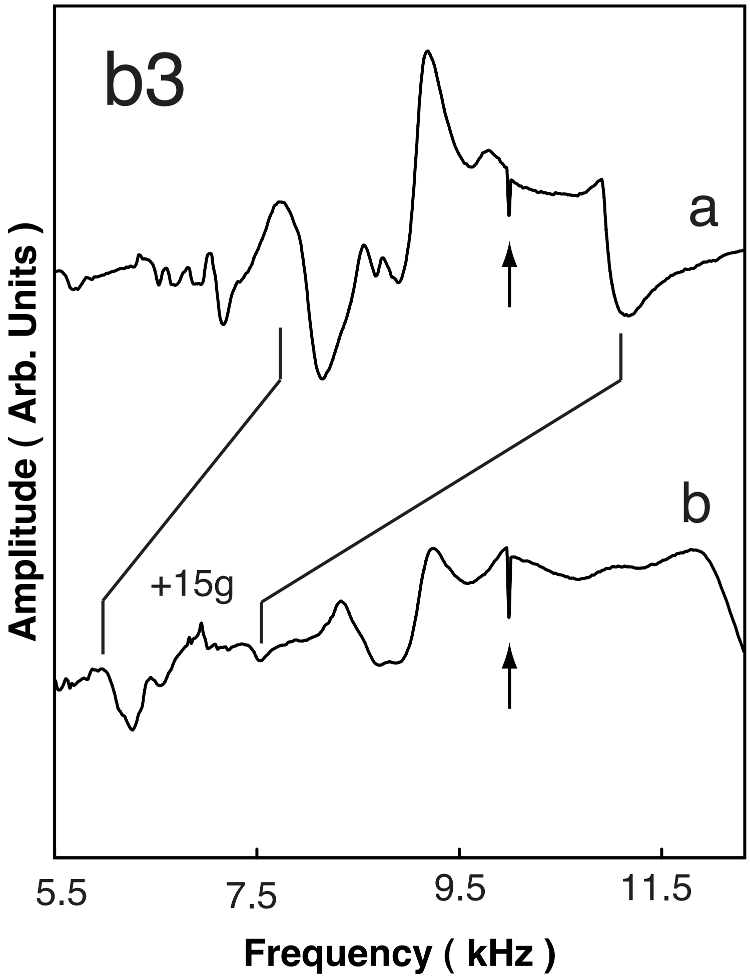

Fig.5 Loading measurements performed on b3 in the frequency range that is dominated by the beetle bending mode. (a) Beetle with no added mass. (b) Beetle with additional Δm=15g mass. Notice that within the region confined between the two lines curve (b) is a compressed version of curve (a). The peak marked with an arrow is unaffected by the addition of the mass and so it is not associated with the beetle legs.

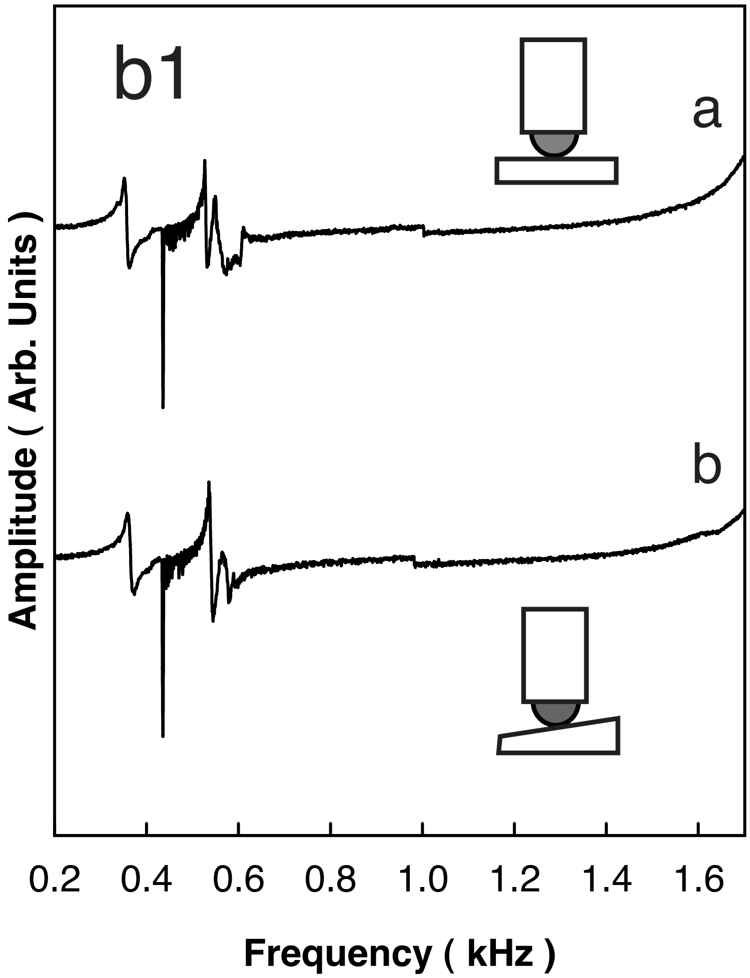

Fig.6 A control experiment that was performed to see if the vibrational spectrum was dependent upon the orientation of the raceway. The top spectrum was taken with b3 on a flat surface. The bottom spectrum was taken with b1 on a Frohn-style raceway[1] that was manufactured for this measurement. The vibrational spectra are very similar. This absence of peaks in the rattling range, 500-1700Hz, and the similarity between the two vibrational spectra on the two different surfaces, suggests that neither the position of the beetle on the raceway nor the type of raceway influences the vibrational spectrum.

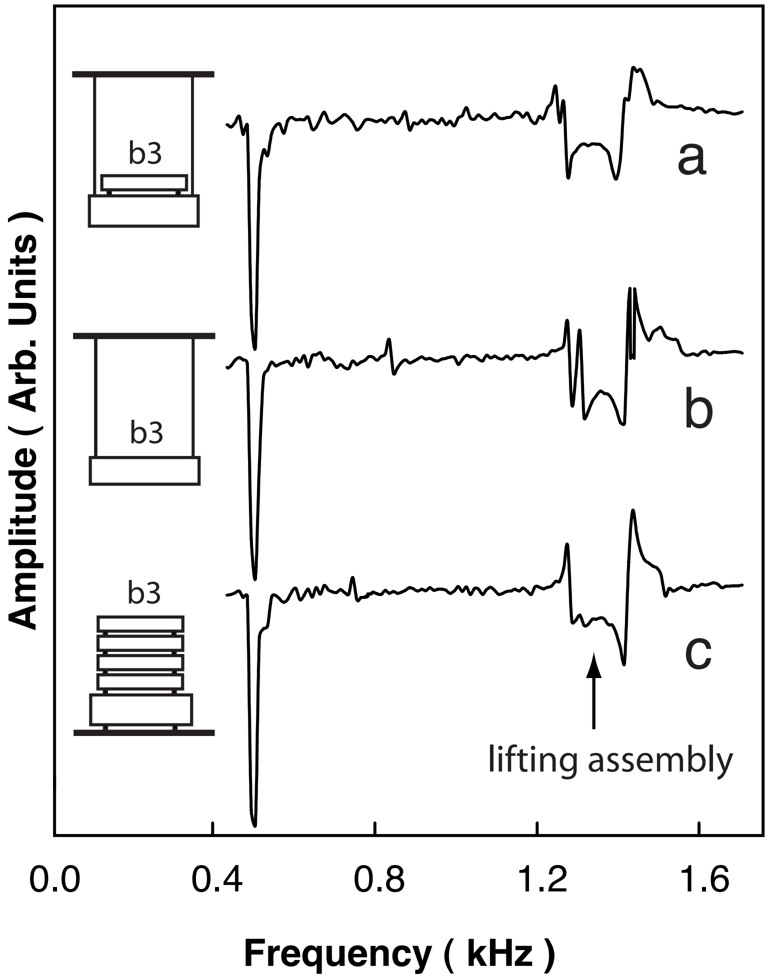

Fig.7 Curve (a) is the low frequency vibrational spectrum of the b3 beetle for two stack elements suspended by three viton chords. Curve (b) is a single stack element that was suspended by three viton chords. Curve (c) is b3 on a fully assembled viton stack (the normal configuration during scanning). The peak at $\approx$ 500Hz was not positively identified.