Proc. of SPIE Vol. 1619, Vibration Control in Microelectronics, Optics, and Metrology, ed. C G Gordon (Feb 1992) Copyright SPIE

The influence of bases and benches on the performance of vibration-sensitive equipment

Colin G. Gordon and Yung Q. Tran

Colin Gordon & Associates
San Mateo, California 94402

ABSTRACT

In most state-of-the-art microelectronics facilities, process equipment (tools), including vibration-sensitive equipment, is set on a structure to bring the equipment to the level of the raised access floor. Depending upon their design these bases can amplify, through resonance, the vibration amplitudes that travel from the structural floor to the equipment base. Similarly, benches that are commonly used to support microscopes and other equipment will often amplify the floor vibrations. Data are presented from recent measurements that illustrate the nature and magnitude of these effects. The concept of "rigid body rotation" as a source of horizontal vibration on bases and tables is discussed briefly.

1. INTRODUCTION

In a parallel paper by Gordon[1] and in a number of other papers presented or published at this conference and elsewhere, the issue of the vibration requirements for vibration-sensitive equipment is discussed in some detail. Necessarily, these requirements can only describe the vibration conditions that must not be exceeded at the base of the equipment. In situations where the equipment is supported solidly on the structural (concrete) floor of the cleanroom, the equipment requirements (generic or otherwise) become the design criterion for the floor. It then becomes the responsibility of the design team (which generally includes a vibration specialist) to develop the building design accordingly; there is little doubt about what the goals are.

In most modern microelectronics cleanrooms, however, the equipment does not sit directly on the structural floor:

1) Many small items of equipment [such as microscopes, probe/testers, wire bonders (used in assembly) and certain metrology systems] will be supported on benches which rest either on the structural floor, or in many modern instances, on the raised (access) floor.

2) Major items of equipment (including steppers, SEMs and metrology inspection systems) will be supported on structural bases that raise the equipment to the height of the operating (access) floor.

Benches and bases (and, in some cases, access floors) can amplify the vibrations on the structural floor. The equipment is then exposed to vibration that is higher in level than the design goal for the facility.

The selection of benches and the design of bases generally lie outside the scope of work of the facility design architect and his team. In many cases neglecting these issues can lead to vibration problems in a facility that is, otherwise, well-designed vibrationally.

In this paper we shall briefly discuss some of the issues that are involved in the design of bases and in the selection of benches. We shall present some measured data that illustrate the potential problems. The data shown are not extensive; we have had little past need or opportunity to make comprehensive measurements on bases and benches. Hopefully, however, this presentation will provide some encouragement for future studies of these issues which are increasingly important — especially in the case of bases — as the vibration needs of the microelectronics industry become increasingly stringent.

2. GENERAL DISCUSSION

The bases and benches that are discussed here are rigid in the sense that they form a non-isolating connection between the equipment and the floor of the facility. Isolating benches and tables are available — some developments in the latter area are discussed in parallel papers[2,3] — that in some instances, and to various degrees, can be used to isolate equipment from the floor. Our assumption in this paper, however, is that the vibration "quality" of the structural floor is good. The purpose of the well-designed base or well-selected bench should be to transfer the "good" vibrations of the floor to the equipment with as little amplification as possible.

Bases and benches, in general, are complex structures which have many resonances. When a system resonates, the impedance it offers to incoming vibration is small and the system will respond with maximum amplitude, often amplifying the amplitude of the incoming signal. The amount of amplification will be limited only by the damping of the structure.

The goal of a good base or bench design should be to move the lowest of these resonance frequencies to as high a frequency as possible, for at least two reasons:

1) High-frequency vibration can be isolated (attenuated) relatively easily. For equipment with "built-in" isolation, high-frequency vibration is therefore rarely a problem. Equipment with no such isolation can be set on relatively modest and inexpensive isolation tables or pads.

2) The vibrational environments on most floors contain less high-frequency energy that they do low-frequency energy. The vibration spectrum on a well-designed suspended (column-supported) slab will generally reach its maximum around the fundamental resonance frequency of the slab (typically 5 to 10 Hz horizontally, 25 to 35 Hz vertically).

Since the resonance frequency of a simple resonator is directly proportional to the square root of the resonator stiffness and inversely proportional to the square root of the resonator mass, the "ideal" bench should be massless and infinitely stiff.*

In practice, the normal goal that we use for equipment base designs is to achieve lowest (fundamental) resonance frequencies of 50 Hz or higher horizontally and 150 Hz or higher vertically. These goals take into account the fact that at the higher frequencies horizontal vibration levels on typical floors are substantially less than vertical vibration levels. This performance should be achieved with the process equipment in place. Thus, the design should take into account the "unsprung" weight of the equipment and, horizontally, the height of its center of gravity.

In the case of "off-the-shelf" benches — typically cleanroom benches — resonance performance of this sort is rarely available. The typical bench structure uses relatively flexible structural elements with a minimum of cross-bracing.

3. DATA PRESENTATION

In this section we present data that have been gathered recently on typical bases and benches.

3.1 Equipment bases — example 1

Three bases (designated Bases 1 through 3) were evaluated in this recently-constructed facility. The floor of the facility is of slab-on-grade design. At the time of the measurements all cleanroom systems were in operation. The process equipment was installed but not in operation. The bases are twenty-eight inches high and substantially formed using structural steel members with diagonal braces.

Figure 1 shows the one-third octave band vibration levels (used for "certifying" the facility) on one of these bases (Base 1). Figure 2 shows the "difference" spectra (representing floor-to-base-top amplification) for all three bases vertically and for one base horizontally (useful horizontal data were acquired only on Base 1).

---

* This is in contradiction to the oft-expressed notion that benches should be as stiff *and* massive as possible.

The bottom and top data were not acquired simultaneously — a single-channel measurement system was used. The period, however, between the respective measurements was small. Conditions were such as to give us some confidence in the "stability" of the vibration environment at the time.

Figure 2 shows that vertically the bases do not significantly change (amplify or attenuate) the floor vibration. Horizontally, however, the single base measured shows significant (≥ 10 dB) amplification above about 10 Hz. The amplification increases still further above 31.5 Hz, reaching 30 dB in the 80 Hz band.

Finite element analysis of this design, using incomplete data about the unsprung weight of the process equipment, suggested that the vertical resonance frequency would exceed 200 Hz and that the fundamental horizontal resonance frequency would lie in the range 50 to 80 Hz. Perhaps it is this latter resonance that produces the high-frequency amplification shown in Figure 2b.

The narrowband amplification spectra shown in Figure 2c suggest that the horizontal performance is not strongly dominated by resonance effects for frequencies below about 50 Hz. Some other phenomenon is contributing to the amplification at these frequencies. At the higher frequencies, starting at about 58 Hz we may be seeing some influence from resonances. Even here, however, some other phenomena appear to be active.

3.2 Equipment bases — example 2

Two bases were evaluated in this relatively old, fully-operational facility. The floor, as in Example 1, is of slab-on-grade design. The bases studied were thirty inches high, substantially formed of steel tube and braced.

Figure 3 shows the one-third octave band spectra measured on one of these bases (Base 2). Because of access difficulties, only one horizontal (E/W) direction was measured. Figure 4 shows the difference spectra for both bases. Again, horizontal data on Base 1 was acquired only in one horizontal (N/S) direction because of access problems. Also, the bottom and top data were not acquired simultaneously. Since this was a fully-operational facility, the data may be "contaminated" to some extent by ongoing processes.

The vertical amplification data of Figure 4 are quite similar to those of Figure 2; vertically, this base design does not significantly amplify the floor vibration. Horizontally, however, this base amplifies the floor vibration by 10 to 20 dB over much of the spectrum. Some part of this may be due to contamination — including, possibly, vibration generated by the base-mounted process equipment.

Finite element analysis of this base, again using incomplete data as regards the process equipment, showed vertical resonance at 150 Hz or above. The fundamental horizontal resonance appeared in the range 25 to 40 Hz.

The conclusions to be drawn from the narrowband amplification spectra of Figure 4c are similar to those discussed in the earlier example. Resonances are certainly affecting the response. They do not, however, appear to be dominating it. Some other phenomenon may be playing a role.

3.3 Laboratory benches

Two radically different bench designs were evaluated in a nonclean laboratory building.

Bench 1 was of very stiff design — formed of concrete legs and top slab. It was located at the fifth floor level. The floor here is of relatively soft design, prone to vibration excitation. Bench 2 was a very conventional and simple wooden table located in the basement on a slab-on-grade floor. Both benches carried vibration-sensitive equipment and were of conventional height (about 30 inches).

The measured vibration data are shown in Figure 5. Only Bench 2 was measured horizontally. Figure 6 shows the difference (amplification) spectra. Again, bottom and top data were not acquired simultaneously. The vibration conditions at the time of measurement were quite stable, however, and the data are considered to be reliable.

The vertical amplifications of these two bench designs (Figure 6a) show radially different characteristics. The flexible (wooden) bench shows amplification in the range 5 to 15 dB over much of the spectrum. The stiff (concrete) bench, on the other hand, performs admirably (with little amplification) up to 25 Hz. Resonance response of the concrete slab clearly occurs in the vicinity of 40 Hz, when amplification reaches 15 dB.

The horizontal response amplification of Bench 2, shown in Figures 6b and 6c in one-third octave band and narrowband format, respectively, clearly shows the effects of resonances. The lowest resonance frequency lies close to 6 Hz. Amplification at this frequency approaches 30 dB.

4. THE MECHANISM OF RIGID BODY ROTATION

Earlier in this paper we have argued that the ideal equipment base or bench will be infinitely stiff — or at least sufficiently stiff so that resonances do not amplify the floor vibrations in the frequency range of concern. In this section we shall present and discuss a mechanism — which we call rigid body rotation — in which vertical vibration of a floor produces horizontal vibration on top of even the stiffest base or bench. It is a process that may be responsible for some of the non-resonant "amplification" noted in the earlier data.

The mechanism is illustrated in Figure 7, for the simple case of a propagating ground wave which excites an on-grade slab. Two extreme cases are illustrated:

(a) When the horizontal dimension of the base is small in comparison with the wavelength of the ground vibration, and

(b) When the base dimension exceeds the wavelength.

For Case (a) it is clear that the vertical axis of the rigid (non-resonant) base rotates as the slope of the ground plane — caused by passage of the wave — changes. This rotation causes the top of the base to move back and forth horizontally. In effect, the phenomenon provides a mechanism whereby vertical vibration of the floor, on which the base rests, is converted into horizontal vibration at the top of the base.*

By simple analysis it can be shown that the ratio of top horizontal vibration (V_T) to bottom vertical vibration (V_B) is given by the expression

$$\frac{V_T}{V_B} = 2\pi \left(\frac{H}{\lambda} \right) = \frac{2\pi f H}{C} , \qquad (1)$$

where H is the height of the base, λ is the wavelength of the ground wave (assumed large in comparison with the horizontal base dimension), f is frequency and C is the wave speed.

When the ratio V_T/V_B exceeds unity the mechanism of base rotation effectively amplifies the floor vibration — producing horizontal amplitudes that exceed the vertical amplitudes on the floor. This condition is established when

$$H > \frac{\lambda}{2\pi} = \frac{C}{2\pi f} . \qquad (2)$$

Assuming wave velocities in the range 300 to 600 ft/sec, typical of many soils (and generally unaffected by the presence of an on-grade slab) we find that onset of amplification will occur for the "critical" base heights shown in Table 1.

---

* This component of horizontal motion will be in addition to the horizontal motion of the floor. This latter motion will be transferred directly, without change, to the top of the rigid base.

Table 1. Critical base heights and wavelengths (wave speeds in range 300 to 600 ft/sec).

Frequency (Hz)	Critical Base Height (ft)	Wavelength (ft)
10	5 to 10	30 to 60
20	2.5 to 5	15 to 30
40	1.2 to 2.5	7.5 to 15
80	0.6 to 1.2	3.8 to 7.5

For normal bases (and benches) with heights in the range 2 to 3 ft the phenomenon of base rotation may provide amplification at frequencies in excess of about 20 Hz. No amplification will occur at lower frequencies. At these lower frequencies the mechanism will produce horizontal motion that is less than the vertical motion of the floor.

The values of wavelength included in Table 1 show that within the frequency range covered by this analysis, most bases will have horizontal dimensions that are substantially less than the wavelength — satisfying the requirements of the model.

When the horizontal dimension equals or exceeds the ground wavelength (see Figure 7b) the base effectively "straddles" the wave. Rotation of the axis of the stiff base will rapidly decrease to zero and the phenomenon of rigid base rotation will no longer be active.

To test the validity of this model we show in Figure 8 an amplification plot for Base 1 of Equipment Base — Example 1. This plot is different from those of Figure 2 in that the plot shows the ratio of horizontal vibration on top of the base to the vertical vibration on the floor on which the base rests.

Included in the plot are the values of amplification derived from Equation 1 using a ground velocity (C) of 350 ft/sec. The dotted portion of the curve represents the likely behavior as the horizontal base dimension (about 3 ft) begins to approach the wavelength.

Figure 8 indicates that in the frequency range 10 to 60 Hz, rigid body rotation may be the primary mechanism of vibration on top of the base.

The mechanism of rigid body rotation may also be expected to apply to suspended (column-supported) floors. Here the maximum vertical response occurs, typically, at the fundamental (lowest) resonance frequency of the floor. At this frequency the amount of rotation will depend upon position, being less — approaching zero — at the center of each bay.

5. DISCUSSION AND RECOMMENDATIONS

On the basis of very limited data this paper has illustrated the fact that bases and benches used to support vibration-sensitive equipment can play a critical role in determining the vibration environment to which the equipment is exposed. Unfortunately, the issues of base design and bench selection are often neglected since they lie in the "grey" area between the building design team and the facility user-group. Because of this the "good" vibration conditions on the structural floor of a well-designed facility can be significantly degraded in terms of its effect on vibration-sensitive equipment.

In this paper we have identified two mechanisms that influence the performance of bases and benches. The first of these — structural resonances — is obvious and well-known. The second — rigid body rotation — is less known. If our analysis of this mechanism is correct, it is a mechanism that is much more fundamental in that it can affect the horizontal performance of even the ideal (infinitely rigid) base.

As regards the resonance performance of bases and benches: We generally recommend that the lowest resonance frequencies be designed as high as possible — 150 Hz or higher vertically; 50 Hz or higher horizontally. With such a design, vibration problems due to resonance amplification are unlikely to occur, and if they do they can be resolved using relatively simple isolation systems. Clearly, it would be beneficial to incorporate efficient damping into these designs to help control amplification.

In almost every instance it is the horizontal motion of the base or bench that is the hardest to deal with effectively. It is necessary in an effective design to incorporate bracing elements (generally diagonal) to counter the horizontal flexibility of the long, often slender, legs that support the base or bench.

The base rotation mechanism clearly requires further study. If in-situ measurements show that the mechanism is real and significant in its effect, it suggests that bases, used increasingly to support vibration-sensitive equipment, should be as low (in height) as possible. The mechanism also adds weight to the argument[1] that generic vibration criteria used in facility design must be conservative if the facility it to serve its long-term purpose.

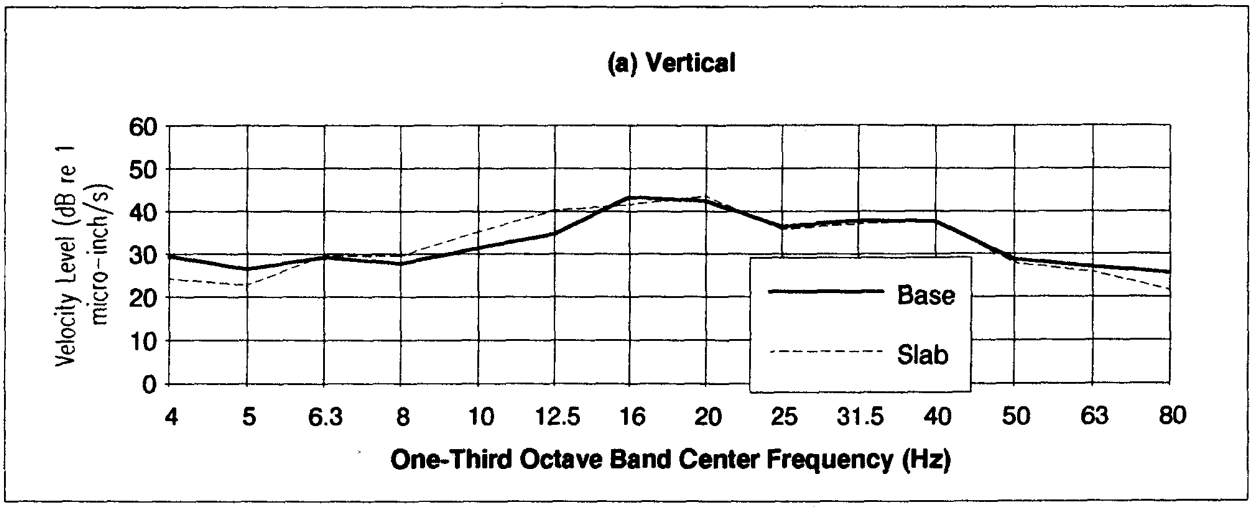
REFERENCES

1. C.G. Gordon, "Generic Criteria for Vibration-Sensitive Equipment," *Vibration Control in Microelectronics, Optics and Metrology,* SPIE Proceedings vol. 1619 (to be published), 1992.

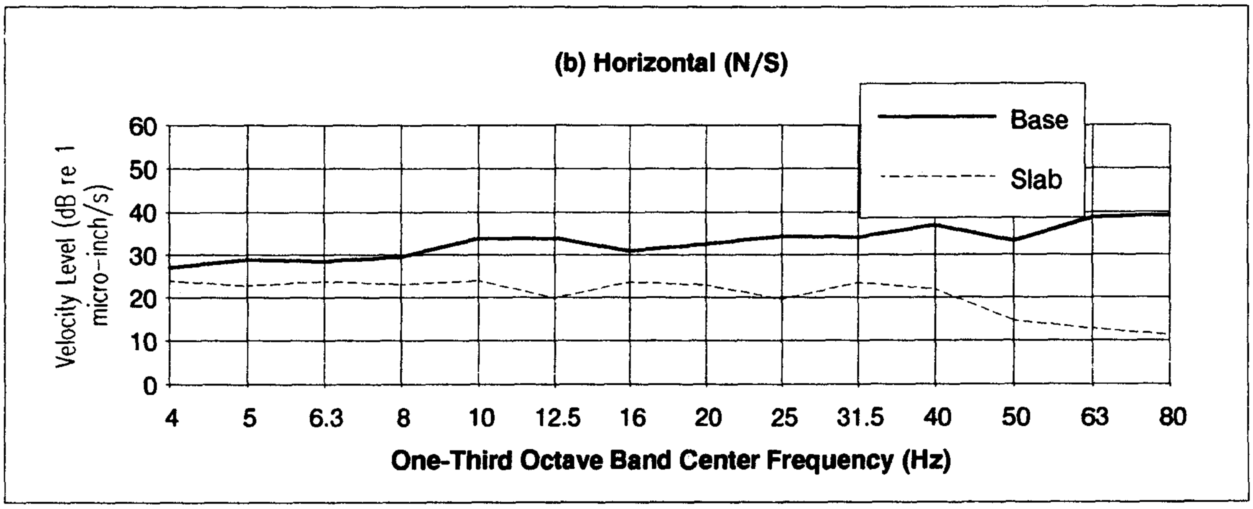
2. P. Heiland, "Recent Advances in Active and Passive Vibration Control Systems for Microelectronics Manufacturing and Inspection Equipment," *Vibration Control in Microelectronics, Optics and Metrology,* SPIE Proceedings vol. 1619 (to be published), 1992.

3. D.L. Platus, "Negative-Stiffness-Mechanism Vibration Isolation," *Vibration Control in Microelectronics, Optics and Metrology,* SPIE Proceedings vol. 1619 (to be published), 1992.

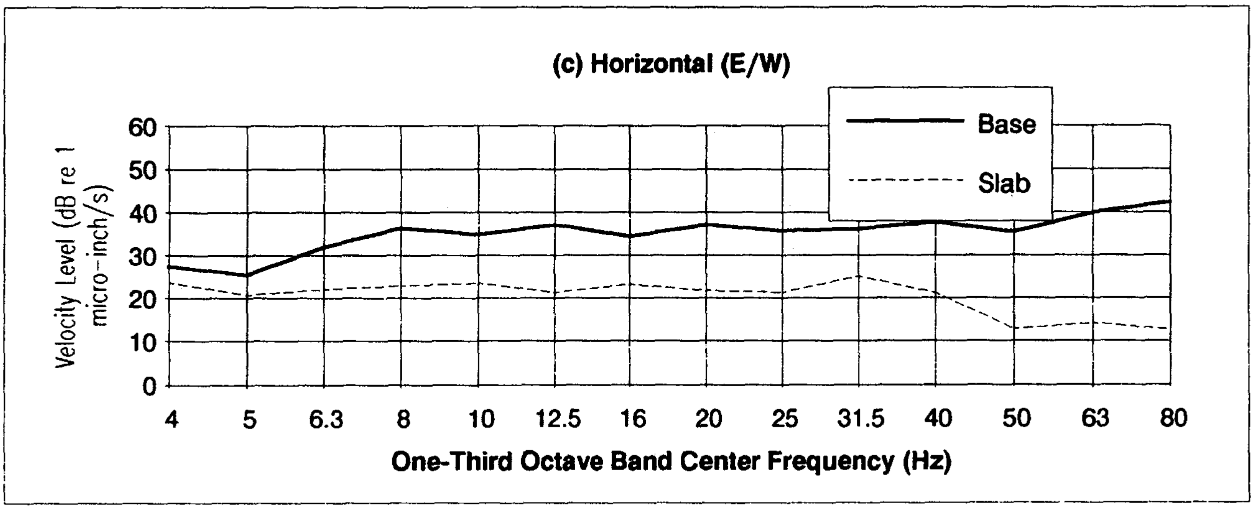
Figure 1: Equipment Bases - Example 1. One-Third Octave Band Vibration Spectra at Bottom and Top of Base 1.



(a) Vertical

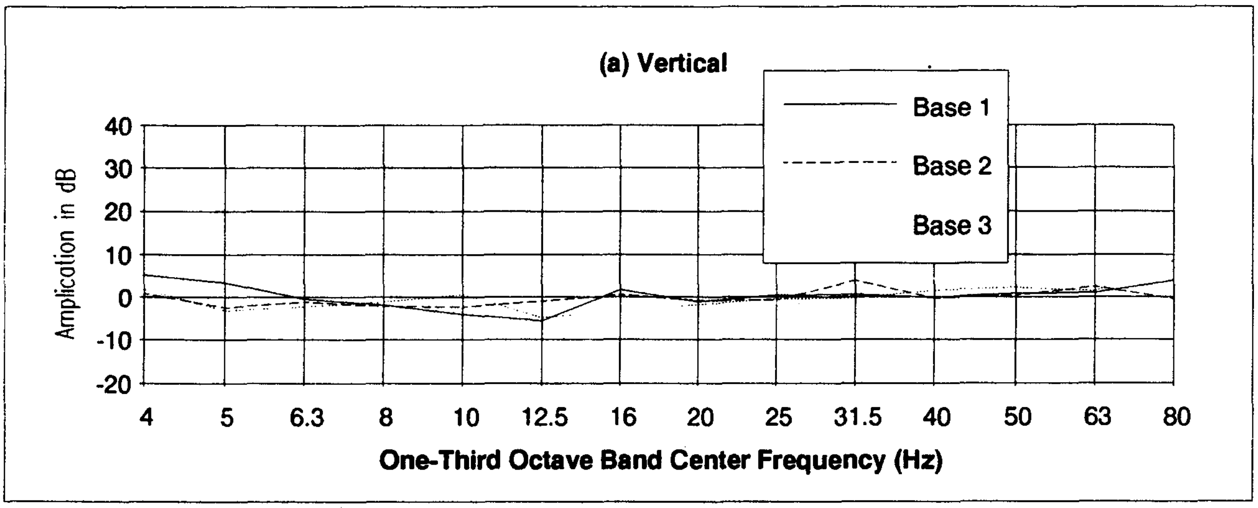


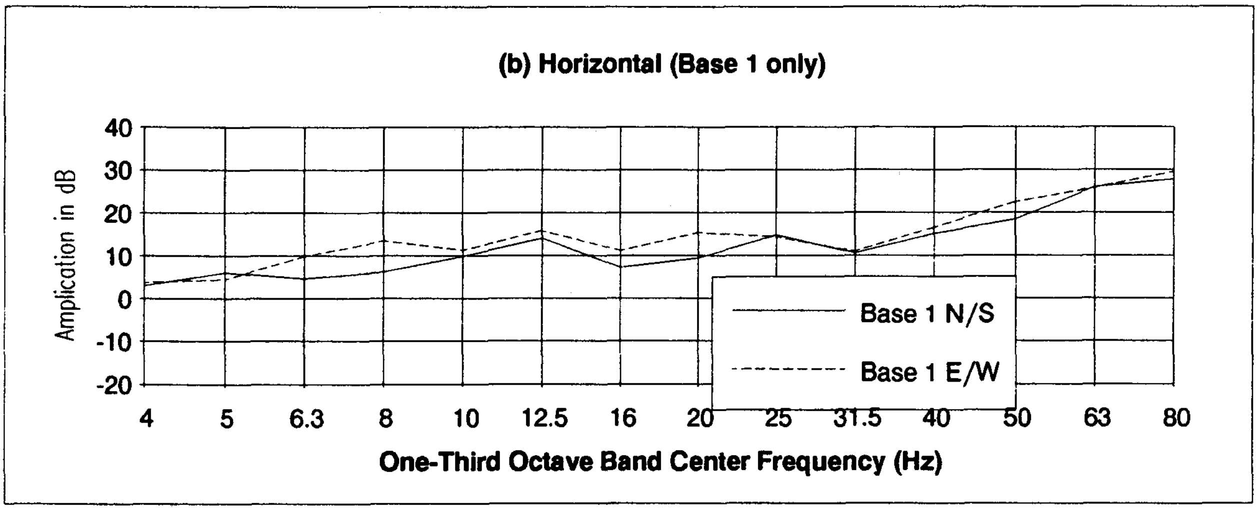
(b) Horizontal (N/S)



(c) Horizontal (E/W)

Figure 2: Equipment Bases - Example 1. Vibration Amplification Spectra.





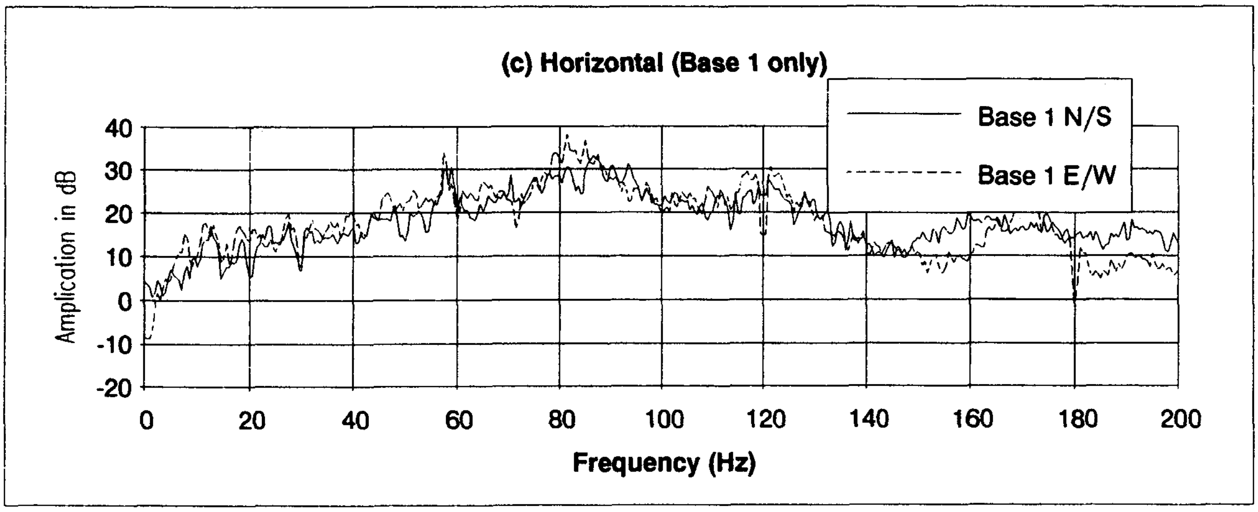
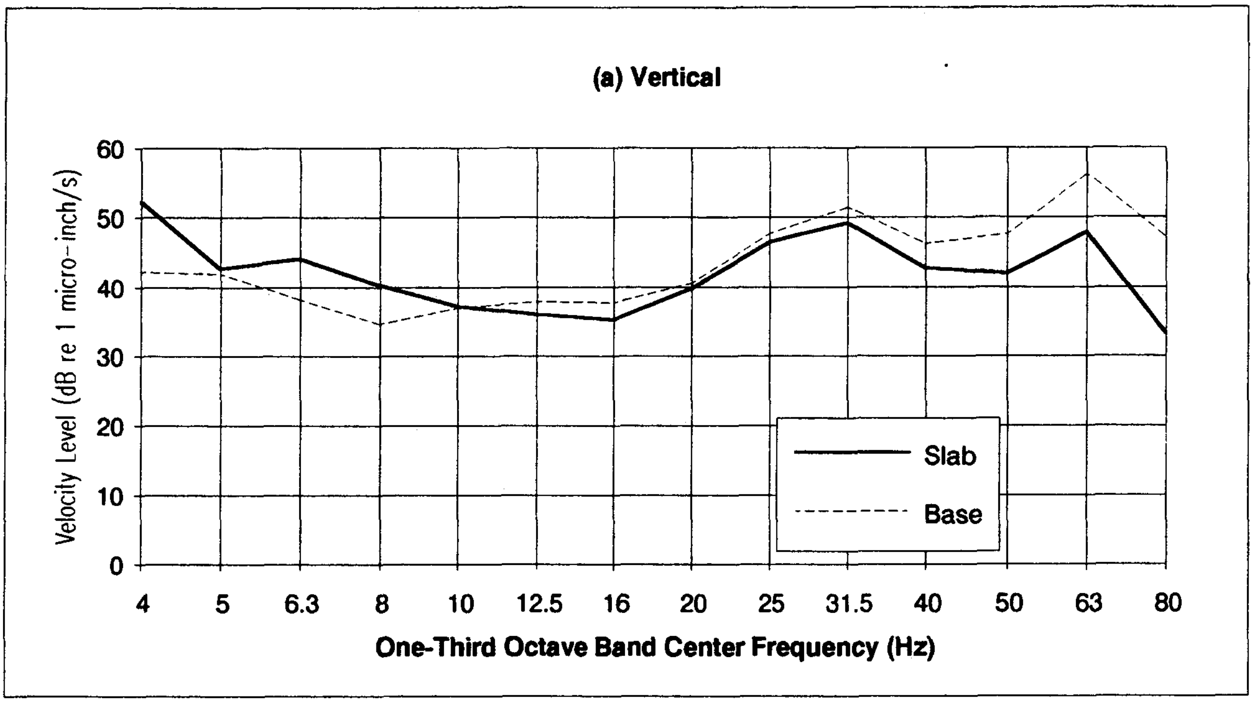
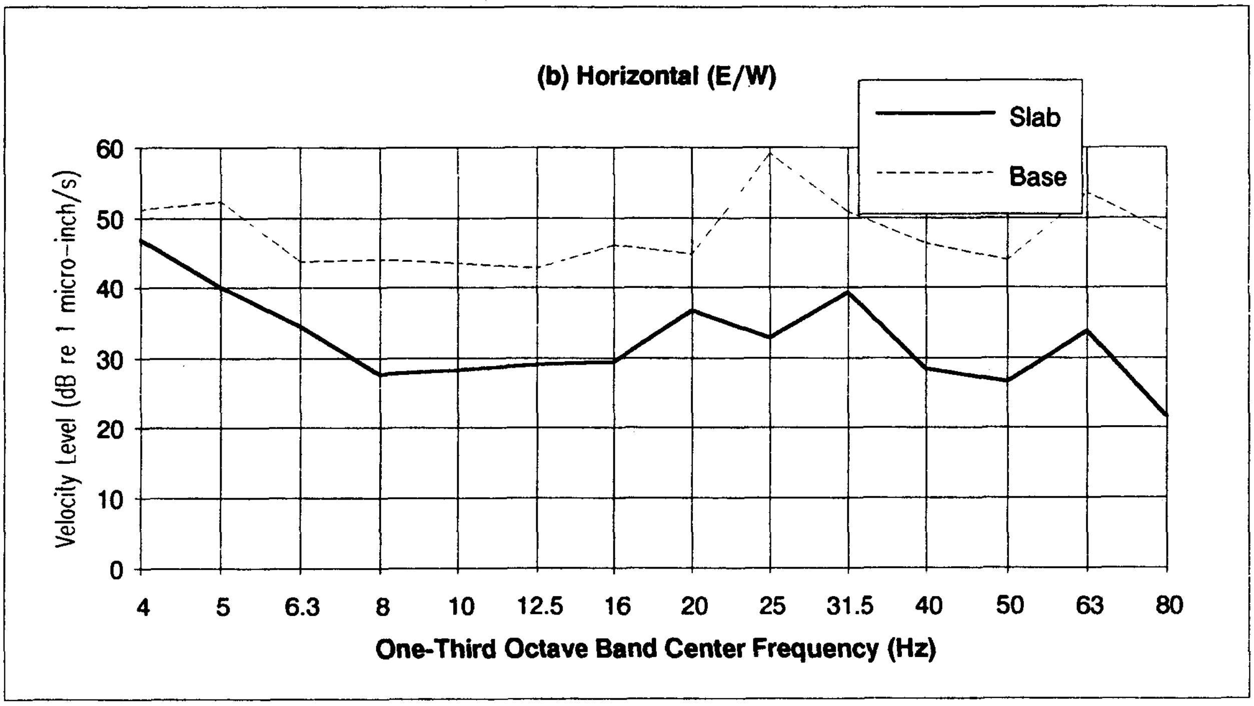


Figure 3: Equipment Bases - Example 2. One-Third Octave Band Vibration Spectra at Bottom and Top of Base 2.

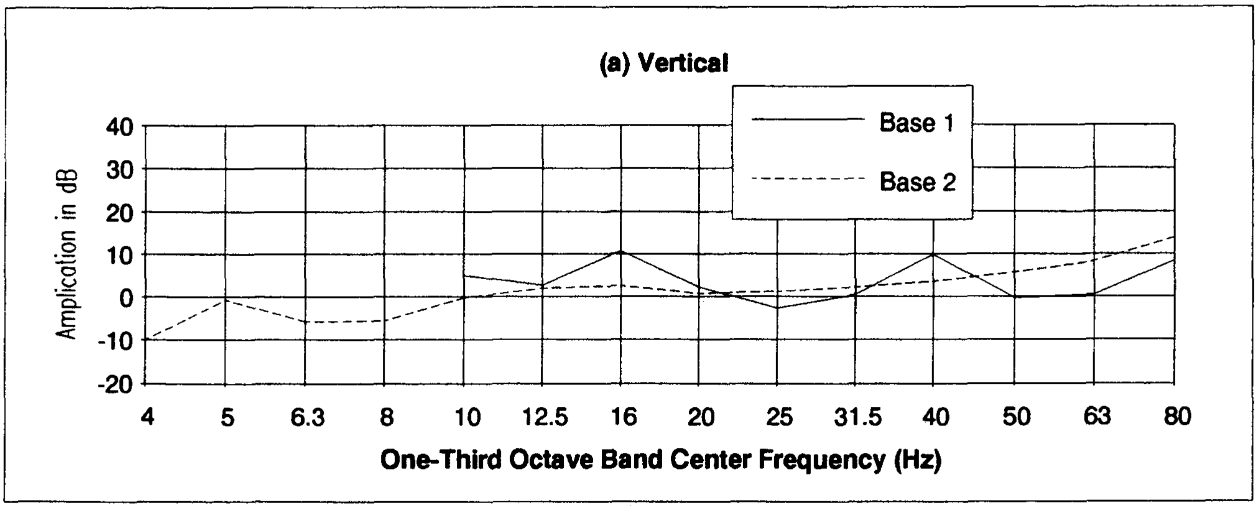


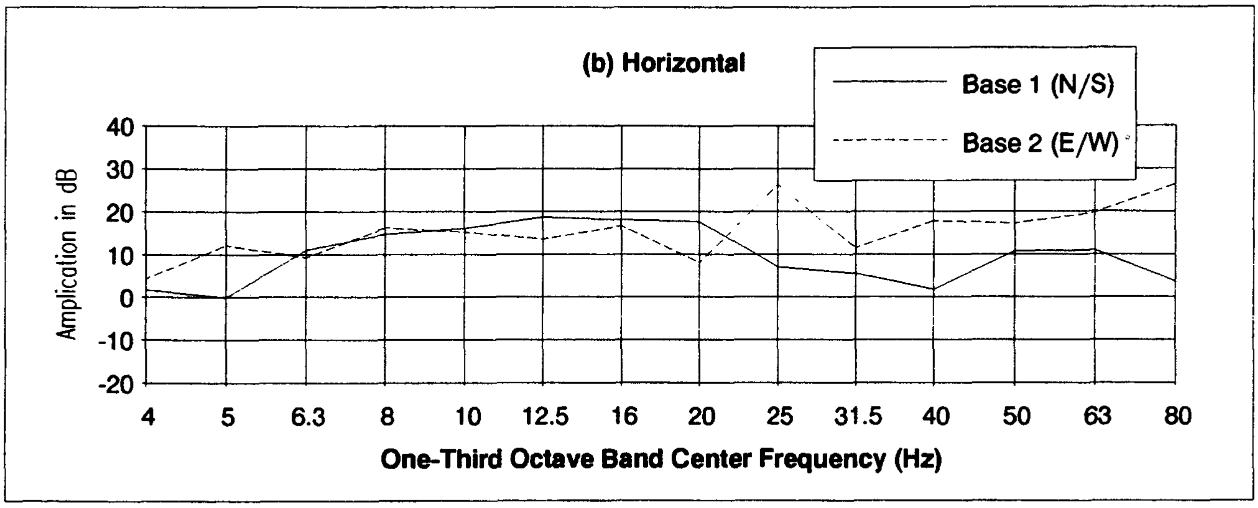
(a) Vertical



(b) Horizontal (E/W)

Figure 4: Equipment Bases - Example 2. Vibration Amplification Spectra.





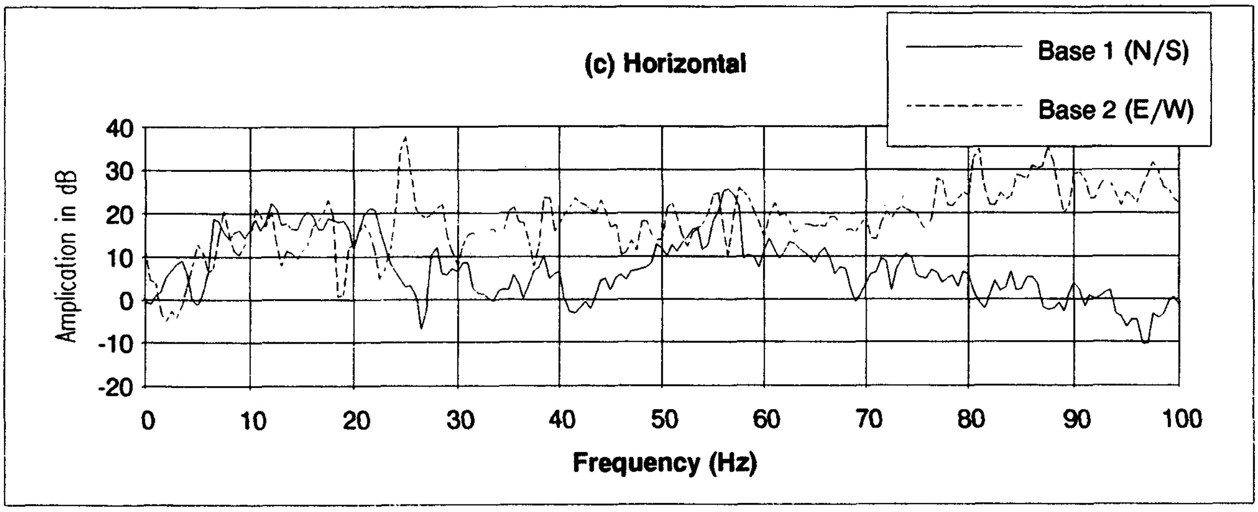
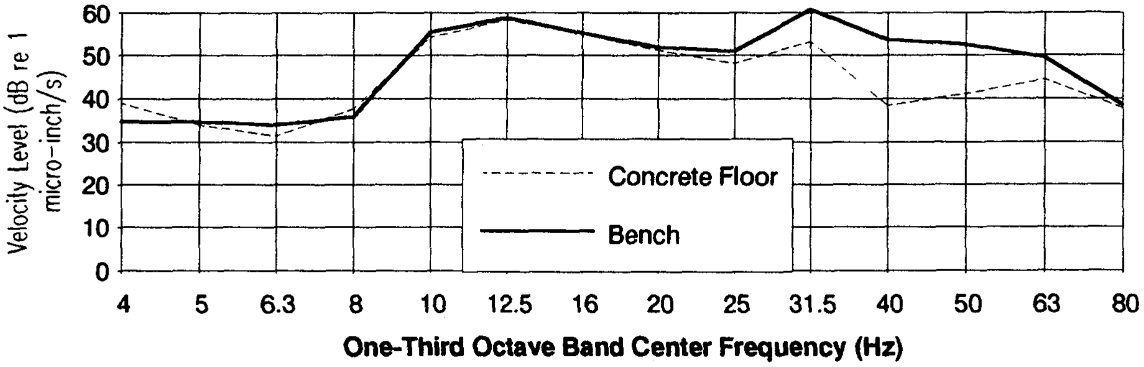
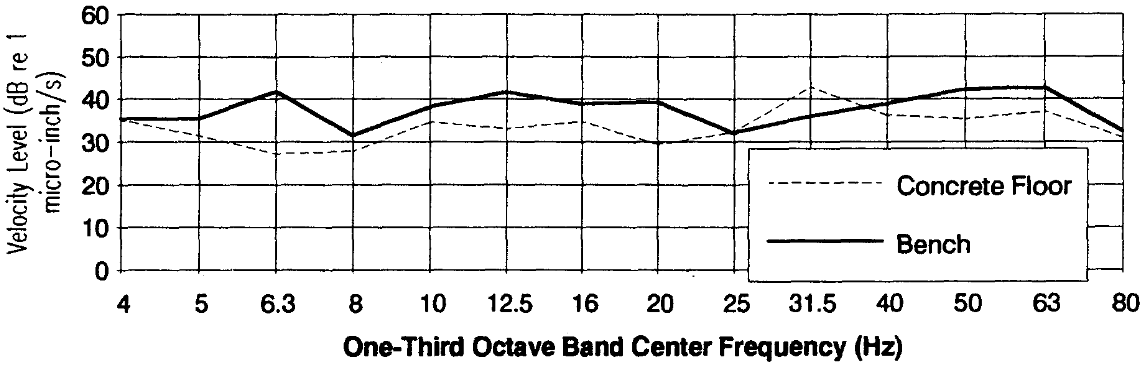


Figure 5: Laboratory Benches. One-Third Octave Band Vibration Spectra at Bottom and Top of Benches 1 & 2.

(a) Bench 1 Vertical



(b) Bench 2 Vertical



(c) Bench 2 Horizontal

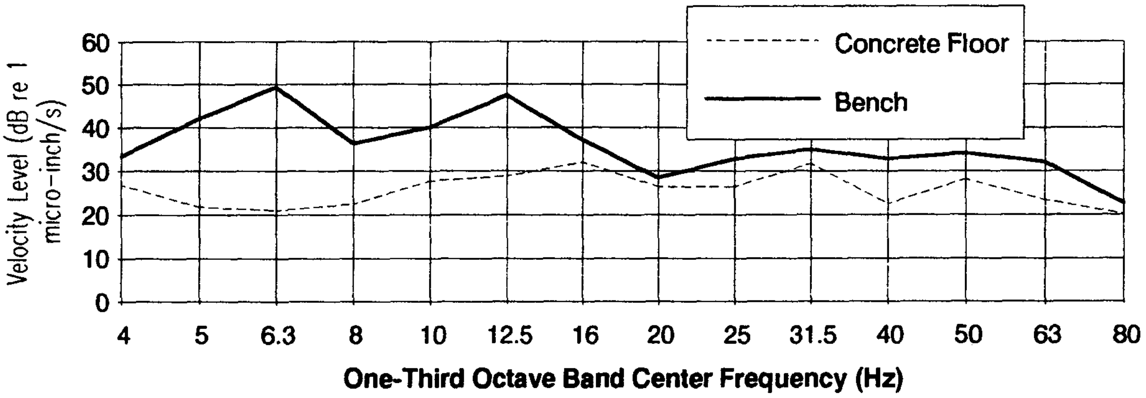
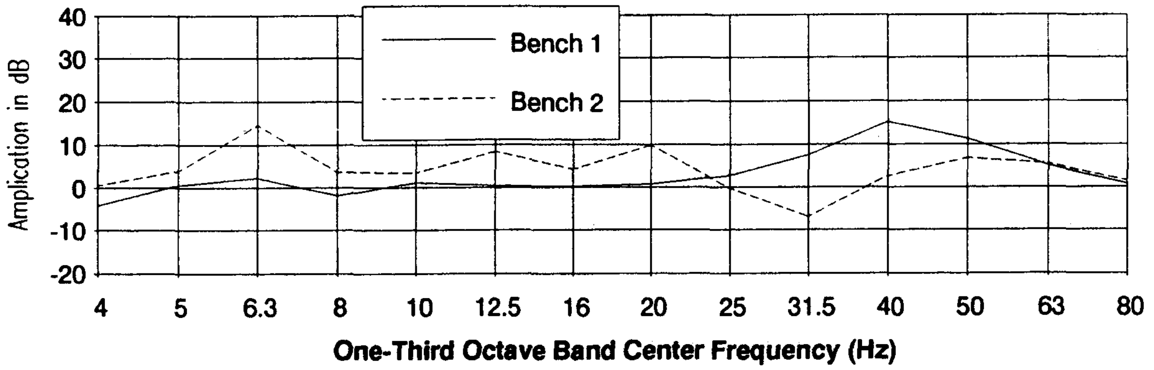
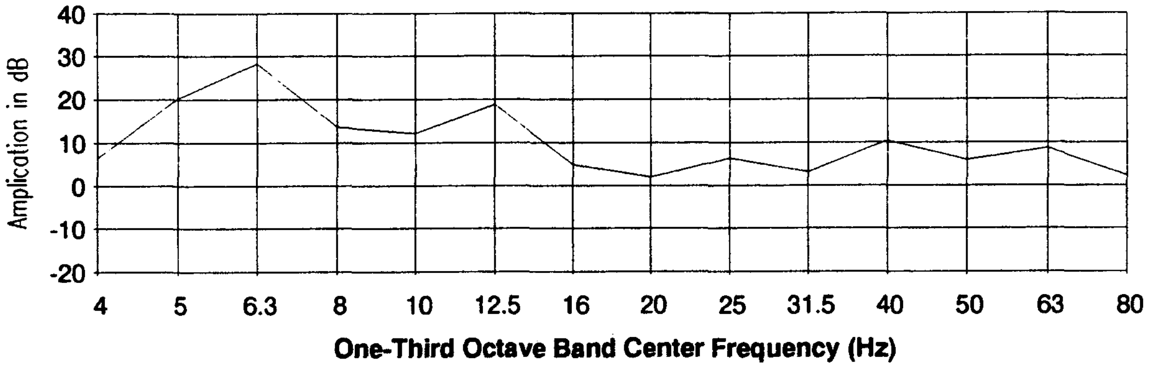


Figure 6: Laboratory Benches. One-Third Octave Band Vibration Amplication Spectra.

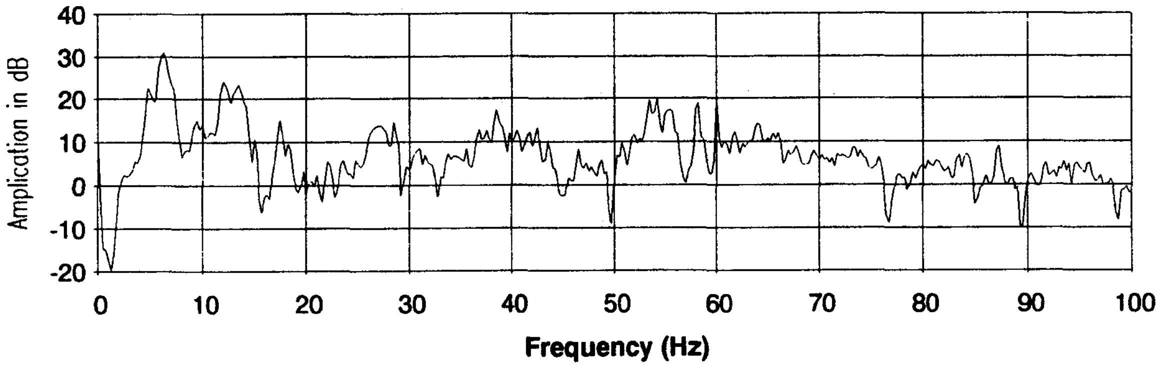
(a) Vertical



(b) Horizontal (Bench 2 only)



(c) Horizontal (Bench 2 only)



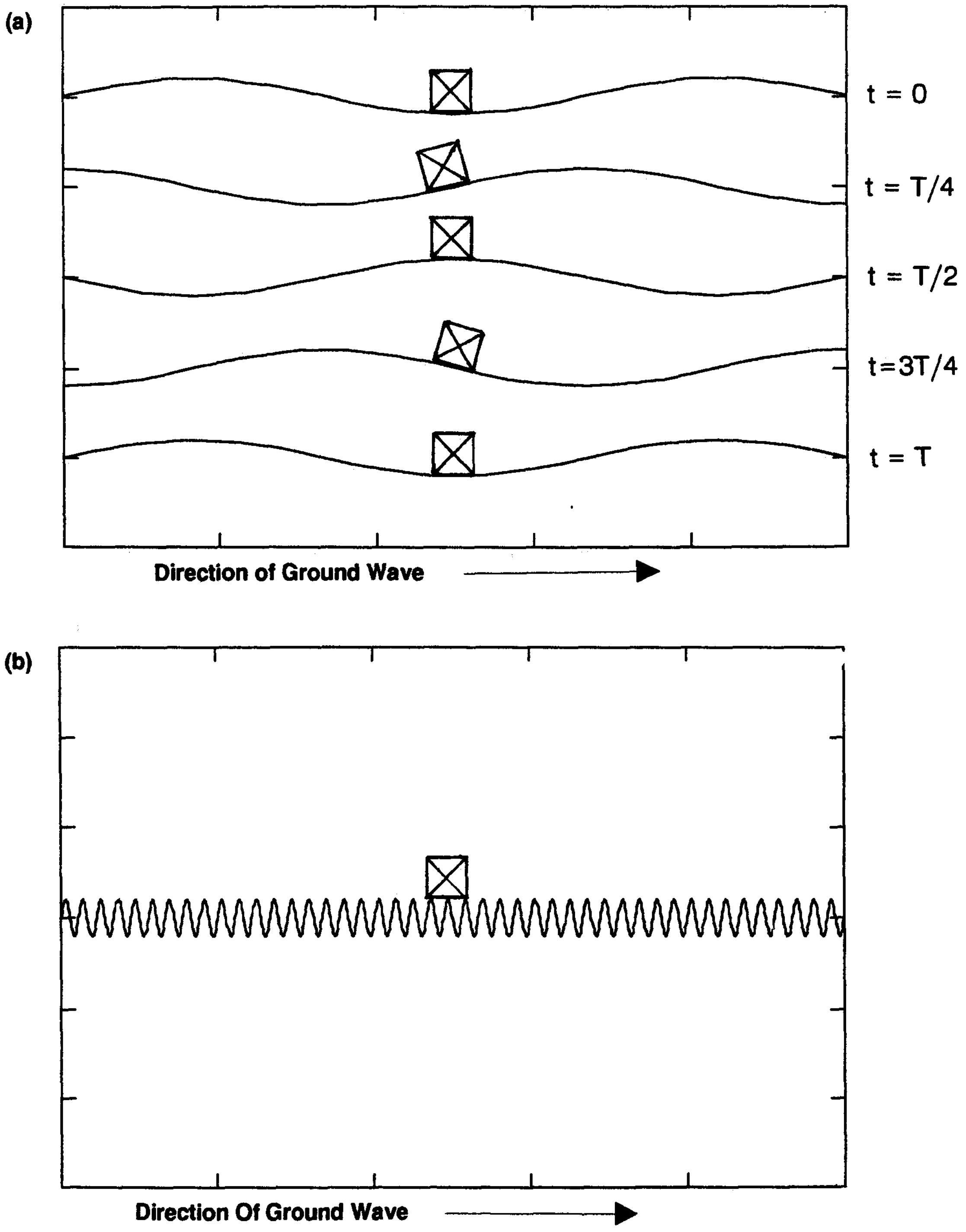


Figure 7: Sketch Showing Rigid Base on Propagating Ground Waves
(a) Base Horizontal Dimension Small Relative to Wavelength
(b) Base Horizontal Dimension Equal to or Larger than Wavelength

Figure 8: Rigid Base Rotation Mechanism. Showing Floor Vertical to Base-top Horizontal Amplification for Equipment Base Example 1, Base 1. Showing also Theoretical Curve (Equation 1) for C = 350 ft/sec.