Vibration Considerations When Planning a Facility

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Introduction

This paper is designed to offer realistic approaches to solve ground vibration problems by anticipation, identification, analysis, design and test. A wide variety of offerings are discussed ranging from the seismic "in-ground" pad, to the "overkill" method of suspending whole floors. The discussion includes wave propagation of the soil, vibration of foundations, isolation of seismic masses, design trade-offs, and vibration survey field measurements by recent techniques. Additional subjects such as vibration generated by machinery and human factor engineering are discussed.

Vibrations

Vibration is a phenomenon which exists and presents itself in many ways, such as heartbeat, car travel or earthquakes to name a few. This paper considers only ground and ground related vibrations which cause objectionable effects in industry where buildings, machinery, sensitive equipment and humans must be considered.

Vibration may be categorized into the microseism range which is ever present in the earth's crust and the induced vibrations which are caused by man and nature such as earthquakes, wind, water and storms. Microscopic vibrations at the atomic/molecular level are considered nil and not discussed in this paper.

Microseisms appear at the earth's surface as a result of motion from within the earth. Seismological centers around the world record such ground vibrations from a period of 16.67 seconds to frequencies of approximately 10 Hz. Microseisms usually have an amplitude of less than 10^{-7} g over the same frequency range (Alsup, 1963). It may be concluded that microseisms should not be considered in the vibration control criteria.

Ground vibrations are composed of a surface wave (R-wave or Rayleigh wave), a shear wave (S-wave) and a compression wave (P-wave). The surface wave has vertical and horizontal components comprising 67% of the vibration while the shear wave and compression wave make up the balance (Miller and Pursey, 1955). The surface wave decays due to ground damping much slower with the distance than that of the other waves, based on an amplitude reduction of $1/r^2$ (Ewing, 1957). Therefore, the surface wave propagation is the major phenomena to be considered when vibration isolation is required.

"Soil Mechanics" was born in the early 1900's. Vibration attenuation became a concern when heavy industrial machinery and equipment induced vibration and shock pulses into the soil. Since that time, we have been concerned not only with vibrations, but also with damping of ground vibrations, which is dissipation of energy. Ground vibration decay has many variables, but is primarily a function of soil pressure, frequency and amplitude of vibration, degree of saturation and granular characteristics of the soil. It should be noted that soil damping and energy dissipation due to geometry of a foundation are two distinct forms of energy losses.

Soil damping and geometrical damping can be expressed for surface wave, half space attenuation by the following (Bornitz, 1931):

$$W = W_1 \sqrt{\frac{R_1}{R}} \text{ Exp. } [-\alpha\, (R - R_1)]$$

Where: α = Coefficient of attenuation $\left[\frac{1}{ft}\right]$

R = Distance from location to question [ft]

R_1 = Distance from source to point of known vibration [ft]

W = Vertical single amplitude of surface wave at distance R.

W_1 = Vertical single amplitude or surface wave at distance R_1

Testing from various sources (Barkan, 1972) shows the steady-state coefficient of attenuation in Table 1:

Nominal Source Frequency	α (F_t^{-1})
20 Hz	.006 - .009
27 Hz	.030 - .090
200 Hz	.070 - .090

Table 1

The above suggests that high frequencies attenuate at a greater rate than lower frequencies in soil. When evaluating the vibration/soil phenomenon, wave-propagation velocities in granular soil will not always agree with the theoretical values of evaluating perfect spaces. This information should be used only as a guide, allowing experimental methods, which are expensive, or a field vibration survey, which is more economical, to gather accurate data. Typical damping factors (percent of critical) in some soils are shown in Table 2.

Type of Soil	Damping Factor	Reference
Dry sand and gravel	0.03 - 0.07	Weissmann and Hart (1961)
Dry and saturated sand	0.01 - 0.03	Hall and Richart (1963)
Dry and saturated sand/gravels	0.05 - 0.06	Barkan (1962)
Clay	0.02 - 0.05	Barkan (1962)
Silty sand	0.03 - 0.10	Stevens (1966)

Table 2
Typical Damping Factor in Soils

Vibration Sources

This paper is concerned with only vibration control where objectionable ground vibrations are natural, induced or resulting effects of noise. Normally, building vibration of walls and floors range from 3 Hz to 100 Hz. The magnitude of vibration in this range can be detrimental to structures, floors and ceilings. Building vibration damage usually occurs from 8 Hz at 3900 microinches to 100 Hz at 400 microinches.

Mechanical vibration sources are of many types such as machinery, water, air handling, transportation, electrical, hydraulic, man-made and earthquakes. Tall buildings greater than 30 stories, which are buffeted by winds, have a natural frequency from 0.1 Hz to 5 Hz. These buildings sway through large displacements causing horizontal motions and at times, motion sickness. Table 3 will help to identify some sources of vibration and expected ground inputs. More often, a more exact identification will be required, so a vibration survey is recommended.

COMMON VIBRATION SOURCES		
Types	Frequency (Hz)	Amplitude (Inches)
Air Compressors	4 - 20	10^{-2}
Handling Equipment	5 - 40	10^{-3}
Pumps (A)	5 - 25	10^{-3}
Building Services	7 - 40	10^{-4}
Foot Traffic	0.5 - 6.0	10^{-5}
Acoustics (B)	100 - 10,000	Various
Air Currents	(C)	(C)
Punch Presses	Up to 20	10^{-5} - 10^{-2}
Transformers	50 - 400	10^{-5} - 10^{-4}
Elevators	Up to 40	10^{-5} - 10^{-3}
Railroad	5 - 20	±0.15 g Nom.
Highway Traffic	35 MPH	± 10^{-3} g
Earthquakes (D)	0.3 - 8.0	0.5g Nom. (E)
Nuclear Detonations	Similar to Earthquakes	Similar to Earthquakes

* (A) Vacuum, compressible and non-compressible fluids
* (B) White noise - will drive light structures
* (C) Optical laboratories and clean room environments inputs vary
* (D) Design criteria
* (E) Horizontal

Table 3

These vibrations are transmitted to the surrounding areas, thus disturbing precision machine tools, measuring instruments such as coordinate measuring machines (CMM's) and sensitive manufacturing processes.

Equipment which is vibration sensitive is sometimes located near production areas which induce ground vibration. This results in a lesser quality product from precision manufacturing operations, uncontrollable readings from instruments such as coordinate measuring machines, digital read-outs and faulty performances of sensitive equipment.

Vibration sources must be identified and considered during the planning stages of a facility.

Air flow which is normally not oscillatory can cause a structure to oscillate. This self-induced or self-excited vibration results in a conversion of non-oscillatory energy into oscillation excitation within itself at its natural frequency. The classical example of this phenomena was the Tacoma Narrows suspension bridge in 1940.

A more common and noticeable example are weights or wind guides, usually less than one cubic foot in volume, hanging on electrical power and telephone lines to influence the line natural frequency and prevent wind induced "galloping" of the lines.

Vibration Measurement (Survey)

Vibration measurement (survey) establishes the degree and magnitude of a vibratory environment. Usually vibration surveys are performed in various locations, so portable equipment should be used. Some major companies have the capabilities of acquiring their own measurements, however, most rely upon consultants or companies in the field of shock and vibration control.

The normal displacement range of interest in a vibration survey is less than 5 microinches for installation locations of very sensitive equipment to 5000 microinches for motions of large structures.

Seismic vibration sensors used in field vibration surveys should be rugged velocity transducers or accelerometers. Velocity transducers are normally larger than accelerometers in size and produce a greater output (25 to 50 v/in/sec) without using amplifiers. Accelerometers have less of a voltage output in volt/g. Accelerometers are smaller, and since they have a small voltage output, amplification is required to raise the signal output from the diagnostic instrumentation noise levels. Vibration surveys should identify the disturbing frequencies with respect to amplitude of displacement, velocity and "g" level in the vertical and horizontal (X and Y) directions when sensors are attached firmly to the floor or ground. Good instrumentation will allow a resolution of at least one microinch displacement from 1 Hz to 100 Hz. See Figure 3.

Vibration surveys can determine:

1. Direction of the vibration source.
2. If the ground vibration exceeds the limit (sensitivity level) established by the equipment manufacturer of the equipment in question.
3. If isolation is required.
4. Power Spectrum Density (PSD) of the source.
5. Performance of an isolation system by comparing the floor vibration with respect to the isolated equipment.

Reputable manufacturers of vibration isolation equipment will supply test equipment for field testing of the supplied isolation system during equipment installation.

Survey test equipment should also measure vibration outside the range of interest thus allowing for unexpected vibration inputs such as beat frequencies, shock pulses and transients, all of which occur often in real life.

Vibration measurement of a rigid seismic mass, pad or structure can reveal not only amplitudes in the vertical and horizontal directions but modes of vibration. When using at least two transducers, the translation mode and/or rotation can be measured simultaneously.

Multi-channel measurements are used to determine mode shapes of structures. A rigid structure vibrating in the vertical direction, such as a floating seismic mass or a concrete base, could have all vertical motion at any point in phase. By using one transducer as a reference and by placing at least two other transducers near the edge of the structure, a phase and amplitude comparison is achieved, indicating a predominant mode. Horizontal motion is identified in the same manner using horizontal transducers. When rocking motion is present, the relative vertical amplitudes increase linearly with distance on the horizontal line. A phase shift of 180° will be noticed when crossing the zero point on the same line. When identifying a twisting motion, horizontal vibration in a direction perpendicular to a radius of the axis of rotation, the amplitude will increase in direct proportion to the distance from the rotational axis, with a 180° phase shift on opposite sides. The output from all transducers may be recorded on a direct writing, multi-channel oscillograph or on magnetic tape for later analysis. By examining the wave forms, the mode shapes of the structure, whether flexible, torsional or fundamental can be determined.

Vibration measurement data in many ways depends on how much and how in-depth a diagnostic study is required. If frequencies of interest are confined to a known bandwidth such as 1 Hz to 100 Hz, then signals generated by the sensors can be amplified and conditioned by band-pass filters having variable high and low cut-off frequencies. The signals are monitored and then recorded. This technique allows a manual frequency spectrum analysis while providing the capability of observing selected frequencies and band widths for short periods of time. A more versatile approach uses a Frequency Sweep Analyzer in which a very narrow band-pass is automatically swept through the frequency range resulting in a display of amplitudes versus frequency. These two methods require that the vibrations remain unchanged (steady-state) during the 2 - 5 minutes it takes to sweep through the frequency range. The most current approach uses the Real Time Signal Analyzer which displays the frequency spectrum instantaneously and continuously. In this manner, rapid analysis is gained while realizing a change in frequency content due to input variations which might be missed during a sweep analysis. See Figure 4.

Vibration Isolation Criteria

When considering the location and installation of equipment which is sensitive to vibration or equipment which induces shock or vibration into the ground or surrounding structures, major questions will arise. Serious vibration consideration should be given when designing a new facility in a new or existing building.

The first design step should be an analysis which clearly describes the vibration influences of all variables involved and which will then permit intelligent decisions to be made regarding location, performance and cost trade-offs. An essential ingredient when redesigning or relocating an existing facility is having a vibration survey performed which defines present vibration levels. When designing new construction, vibration criteria from equipment manufacturers and an analysis should be given to the architect. Some of the design considerations of the proposed installation using sensitive equipment are as follows:

> Determine the threshold sensitivity of the equipment to be installed, that is, the lowest frequency at a specific amplitude at which the equipment can operate satisfactorily without degradation due to vibration input. As an example, for a typical coordinate measuring machine (CMM), the threshold sensitivity would be 10 microinches at 5 Hz to 100 Hz in all three axes. Sometimes the manufacturer will specify limits in velocity or acceleration amplitudes with respect to frequency.
>
> Ambient vibrations are determined by vibration surveys or by analysis of the architectural structural design. Both cases should allow for vibrational growth which always develops with time. This permits equipment usage with typical increase of industrial and environmental vibration levels without affecting performance.
>
> Many times the human environmental impact due to vibration and noise is overlooked, resulting in persons being affected physiologically and psychologically, so work in the immediate vibration zone should be considered. An acceptable level should be planned and provided for. Standards defining these levels are available. Safe levels would be at or below a velocity of 10^{-3} inches/second with "g" level of less than 10^{-4}.

A special type of vibration phenomenon which sometimes is present in structures, such as a suspended upper floor or balcony, is referred to as a "beat frequency". This periodic vibration usually is less than 1 Hz and is considered a rectilinear vibration occurring as a result of two sinusoidal frequency components that differ by a small amount as compared to either frequency component. The beat wave form is similar to a sinusoid having an increasing and decreasing amplitude which is equal to the difference of the two component frequencies. A typical example would be a hotel or industrial building where air conditioning units, compressors, pumps or electrical generators are located. The beat frequency is difficult to predict but can be isolated at the source level. Note that beat frequencies are easily noticeable to humans and are very distracting, particularly when riding in a multi-engine aircraft with unsynchronized engine RPM.

Basically, there are two methods of isolation: 1) Isolating equipment that induces shock or vibration into the ground, 2) Isolating floor-borne vibrations.

First would be the foundation of the classic "in-ground concrete pad". This is usually designed by the architect or his structural engineer. Isolation of this type is predictable and tends to change with load. This approach is permanent; so if the equipment is moved, isolation is lost and new construction would be required. Foundation or in-ground pad isolation as shown in Figure 1 (Dynamic Tests, 1962) is usually effective above 20 Hz. The least expensive form of isolation is placing sensitive equipment far away from a vibrational source; however, in most cases, it is not practical. When an in-ground concrete pad can be used, the pad natural frequency and the type of base the pad is poured onto cannot be overlooked, since amplification may occur, thus defeating the purpose of the pad. Increased isolator efficiency can be enhanced by providing a trench around the pad. See Figure 2.

The second method would be to isolate the equipment from the supporting floor by means of a low frequency vibration isolation system. This approach may use the following basic types: metal springs, elastomeric springs, pneumatic isolators and/or a combination of the same. These elements have been used for many years as the principal resilient media for attenuation of mechanical vibration. The critical properties of these elements are deflection, stiffness (spring-rate), load-carrying capacity, damping, natural frequency and exposure to temperature, water, solvents and radiation. When given a seismic mass and payload, the natural frequencies of the system are determined by the isolator stiffness and mass stiffness separation. Seismic isolators normally have vertical and horizontal natural frequencies of 0.4 Hz to 5 Hz.

Metal springs have been used for vibration isolation for over 100 years. Leaf, extension and compression springs are some of the more common types used for vibration isolation. Note that metal springs have negligible inherent damping and usually require separate dampers such as in automobiles. Moreover, undamped helical springs have a surge which impairs isolation. By using another spring in series, metal springs surge would be minimized but not eliminated. Helical springs are normally not considered when low frequency isolation is required, since helical spring length would be excessive and stability becomes of much concern.

Elastomeric (rubber) types have also been used in many forms for at least a century. Although elastomeric isolators are the most common, they are normally not used for low frequency isolation, since the natural frequency lower limit is 6 Hz to 8 Hz when used in compression or shear. A special case, an elastomeric isolator of low horizontal frequency made of laminations of elastomer and metal plates, is used for isolating buildings and bridges. These isolators, which have high vertical stiffness and low horizontal stiffness, are used to isolate structures from the horizontal surface wave of an earthquake. Note that elastomers have a nominal damping range from 5% to 17% of critical.

Pneumatic isolators (air springs) are widely used when low frequency isolation is required for instruments, equipment or large shock displacements. One type of pneumatic isolator which is used in vehicle suspensions is of the bellows type. See Figure 5. This type of isolator has low stiffness vertically and normally poor lateral stability. When using the bellows type for seismic isolation, restraints are required to ensure lateral stability. The bellows concept has variable volume and little hysteresis damping due to the rubber bladders. These thick bladders transmit vibrations at low amplitude inputs.

Another type of pneumatic isolator is the pneumatic-elastomeric type which is described by Schubert (1974), shown in Figure 6. This type of isolator offers natural frequencies of 3 Hz to 5.5 Hz depending on the pressure required to support the load. This unit has a vertical to horizontal stiffness ratio of approximately one. The prime advantage is the thick elastomeric wall which acts as a secondary isolator of approximately 10 Hz when deflated, unlike the thin wall of the bellows type which offers no support. The pneumatic-elastomeric type also acts as a snubber if vertical shock is realized. As in the bellows type, damping is inherent due to the elastomeric material. Other isolators of a similar nature which offer shock and vibration control are also in wide use.

A more widely used pneumatic vibration isolator is the "piston-in-a-cylinder concept," shown in Figure 7, where a very thin single-ply elastomeric diaphragm (0.015 inch to 0.060 inch) reduces the transmission path for micro "g" amplitude inputs. This isolator uses a constant effective area diaphragm. The dynamic performance characteristics of these isolators also provides static stability and automatic level control for varying loadings within a wide load-carrying capability.

When using the laws of gas compression to derive the increase in pressure associated with the reduction in volume, the stiffness and natural frequency of the pneumatic isolator supporting a mass depends primarily on the volume of the isolator. If the load is changed and the pressure is adjusted to keep the height the same, the vertical natural frequency is constant. The theoretical basis of vibration isolation using air springs with servo control is discussed by Cavanaugh (1976).

Automatic height control is valuable when instruments and equipment must be kept level when the load and/or its distribution is changed. Air isolators have been developed (Kunica, 1965) which incorporate a mechanical or electronic pneumatic servo valve to control the internal pressure supply. When the load is increased, the air pressure is increased, and when the load is reduced, the pressure is also reduced, maintaining the spring at a constant height. The basic design of this isolator consists of a metallic air chamber which also supports the load when the isolator is depressurized. A flexible diaphragm seals the cylinder and the piston which supports the payload. The diaphragm operates nominally at zero deflection because the load is maintained at a constant height by the servo valve.

Pneumatic isolators with a constant natural frequency of 1.5 Hz to 2.3 Hz are normally "off the shelf" isolators. These isolators can be modified to lower the natural frequency by increasing the volume of air. In this way, a vertical natural frequency of less than 1 Hz can be realized. By contrast, mounting on helical springs having a vertical natural frequency of 1 Hz is unthinkable because the springs would have a static deflection of about 10 inches.

To summarize, the pneumatic isolator air spring has natural frequencies of 0.5 to 5 Hz and is impractical with any other form of isolator. It is readily adaptable for use with a height sensing valve to maintain the height, level and natural frequency when the load or its distribution changes. The mounting is designed so that if for any reason the air spring becomes deflated, the seismic mass will drop only 0.25 inch to rest on the isolator body.

The design of a system is not a "do-it-yourself" recipe. The decision depends on the size, complexity and importance of the proposed installation. It would be advisable to seek a specialist in vibration, such as a major supplier of vibration isolators, who is experienced in the design and application of their products, and who offers services ranging from technical advice to system design, supply and installation of complete isolating systems and performing vibration surveys.

When isolating a seismic mass in a pit, design requirements should include access for cleaning, drainage of the pit, lighting and accessibility to inspect, adjust and maintain. The design should be such that either the load can be removed from the isolators or the isolators may be unloaded individually. Ample space is allowed between the inertial block and the sides of the pit for access to the isolators.

If isolators are supporting a "floating floor", access can be made from above the floor. By leaving holes for the isolators, the slab is then raised by using screws in cover plates fixed over the holes.

The isolator should have a metal housing that can support the load if the isolator fails. Normally when air is lost, the system will drop approximately 0.25 inch very slowly, resulting in a "graceful failure". When using other types (e.g. air bellows), provision should be made for the load to be transferred to a suitable support if the isolator fails or is deflated. Also with the bellows type, side stops should be provided so that the lateral deflection cannot exceed the permissible amount.

The design of the seismic mounting allows the seismic mass to be coupled only through the isolators. Other connections, such as hoses and electrical cables, must be flexible so that the transmission of vibration and noise between equipment and supporting structure is minimized.

Severe vibration of a seismically mounted machine can cause loosening of pipe joints and even cracking of pipes, as well as malfunction of the machine itself. This is particularly so if the machine has angular as well as translational vibration because of the magnification of the amplitude with distance from the axis of rotation.

The design basis for the seismic block natural frequency assumes that the seismic mass is a rigid body with a stiffness at least 100 times more than the isolator. In practice, this is a reasonable assumption for inertia blocks. With vibration sources, sensitive equipment installations are usually assessed only on overall performance. The installation is accepted if the equipment attains the required standard of performance or output, such as a surface finish produced by a grinding machine or resolution of an electron microscope.

Costs

The discussion of cost is limited to an overview of the discussed isolator types, construction cost and portability. When vibration problems are anticipated in a new or existing facility, an analysis or a vibration survey is a must to avoid costly oversights or guessing. Since elastomer and metal springs inherently have a higher natural frequency meaning less isolation, pneumatic isolators must be considered.

Construction costs for isolation pads, seismic masses and the like are additive to the isolation system cost. With small items such as a coordinate measuring machine with a 4 foot by 6 foot granite base, isolators alone are required. Large concrete seismic masses and bases introduce additive cost but are required for large payloads.

Normally, pneumatic isolators of this type are portable or at least semi-portable, so consideration should be given for future use at other possible locations. When using concrete, it is assumed the installation is permanent and will not be relocated. When vibration isolation is required, a non-permanent system is less costly and can be relocated at a later time. In any event, the isolator should always be movable. Floating floors are only isolated seismic inertia blocks of another shape and are not always used, since vibration induced into one corner will always be transmitted to other areas of the floating floor with little attenuation.

Use standard or semi-standard pneumatic isolators to reduce costs; however, there is no substitute for special isolators (0.4 Hz to 1.0 Hz) when circumstances require it.

Summary

The comparisons between servo-controlled pneumatic isolators, rubber and metal springs isolators were discussed. This paper states that for the isolation of low-level/wide-frequency disturbances, pneumatic thin diaphragm isolators constitute a far superior solution. The added benefits of static stability, constant natural frequency and automatic precision-leveling independent of the supported mass, make the servo-controlled pneumatic isolators unique, but appropriate, for isolating precision equipment from vibration.

In most cases, self-leveling pneumatic isolators are designed for application involving sensitive medical, scientific, manufacturing, assembly, test or Q.C. equipment. When high isolator efficiency (12 dB/octave) is required, conventional elastomer or metal spring cannot match the performance of pneumatic isolators. Pneumatic system technology permits a wide range of variations for exceptional needs.

An inertia block may be necessary for some installations. The design of these blocks is critical and best left to the experts. A poorly designed inertia mass may be worse than none at all and a costly mistake.

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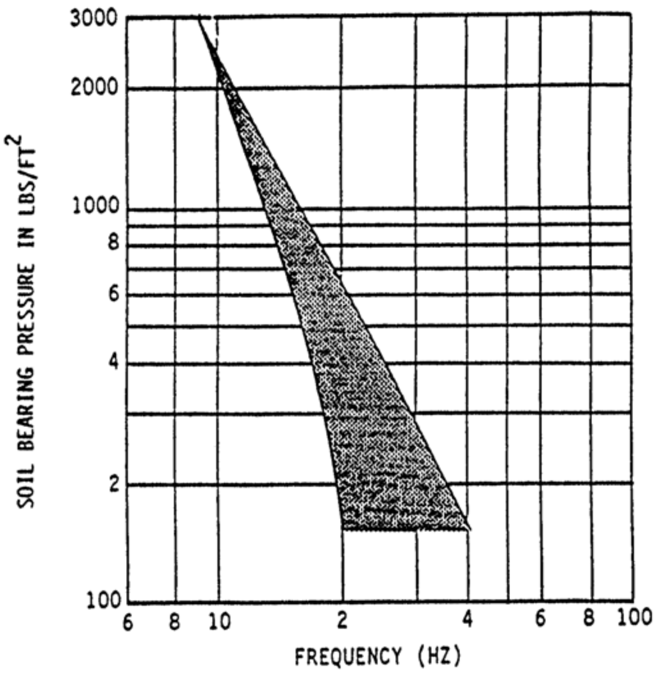


NATURAL FREQUENCY OF A STIFF INERTIA PAD ON CLAY SOIL

FIGURE 1

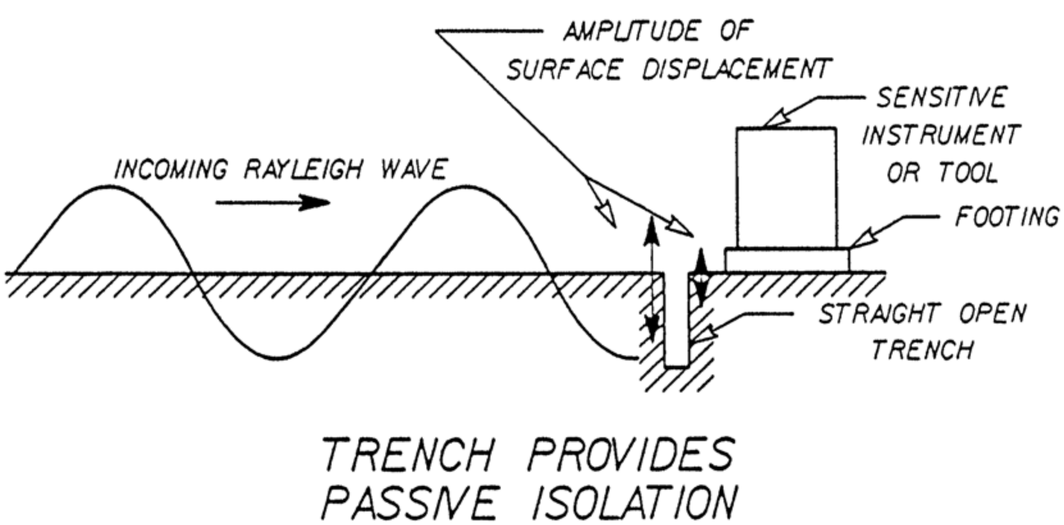
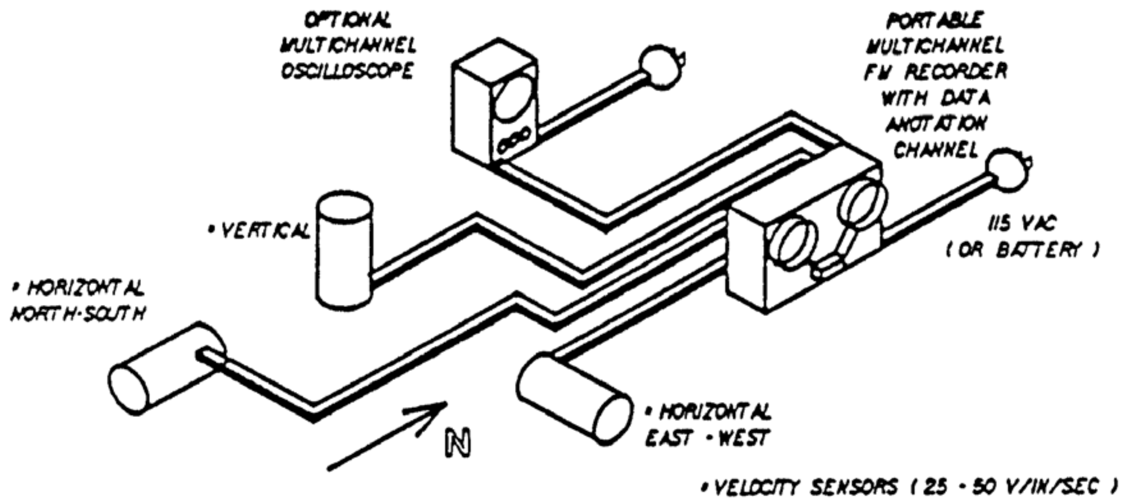
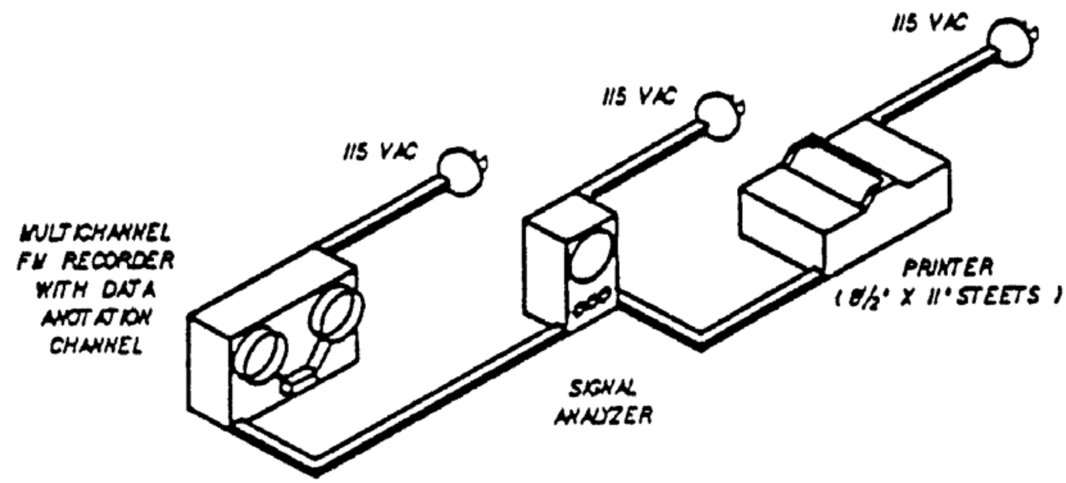


Figure 2



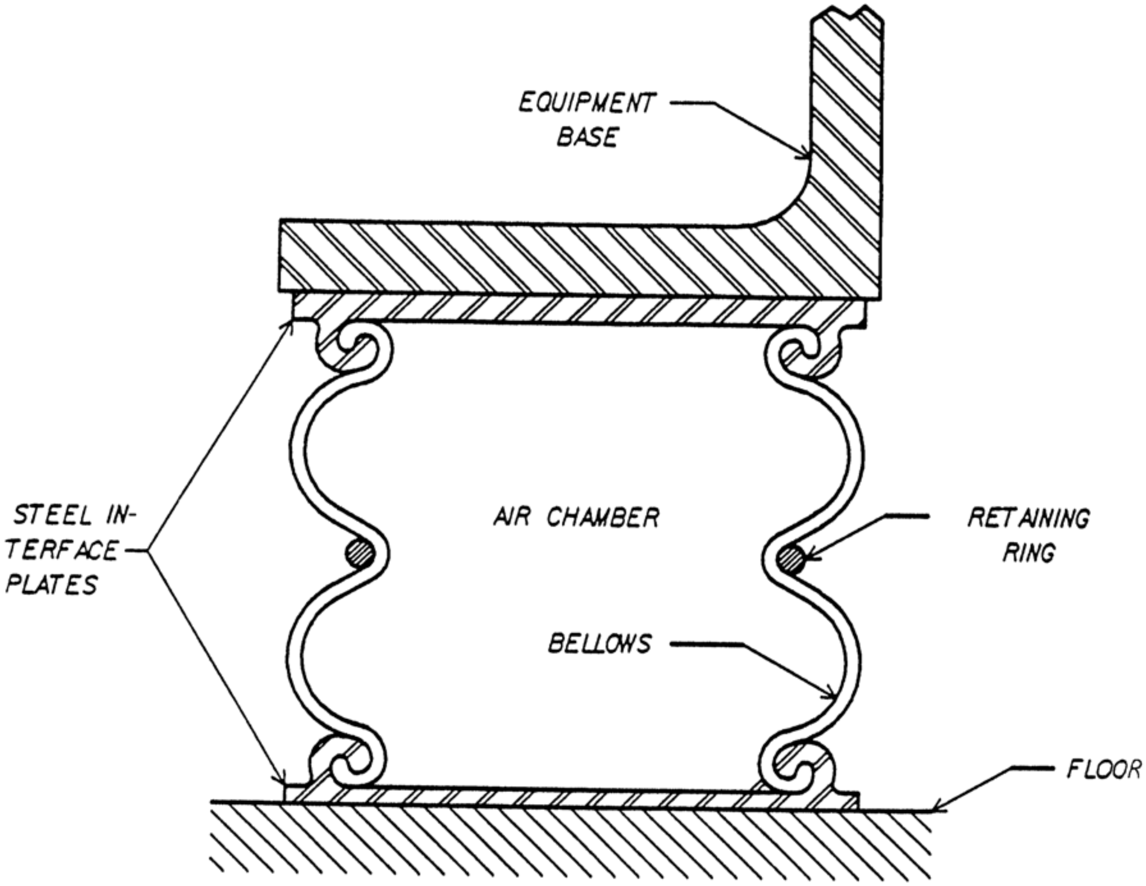
TYPICAL FIELD VIBRATION SURVEY SET - UP

FIGURE 3



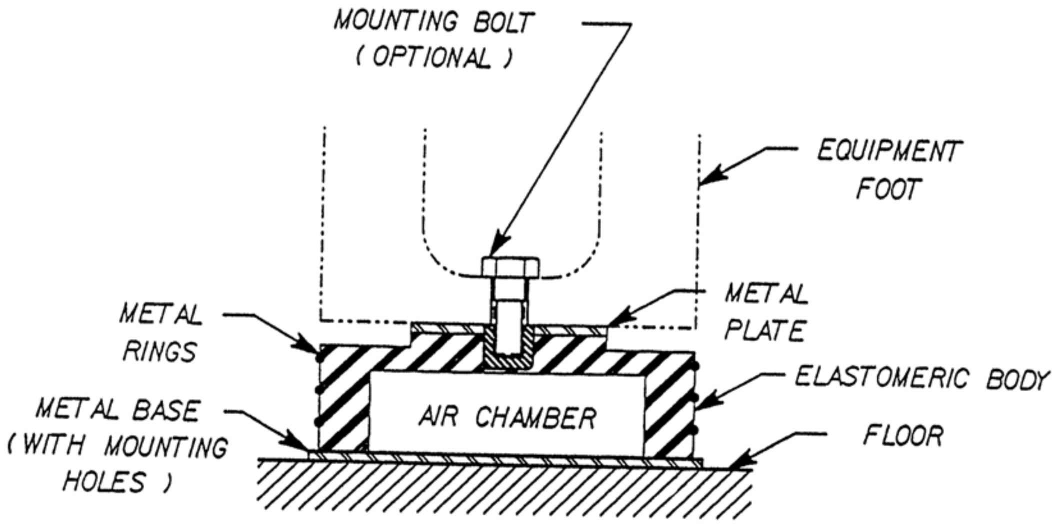
TYPICAL DATA ANALYSIS SET - UP

FIGURE 4



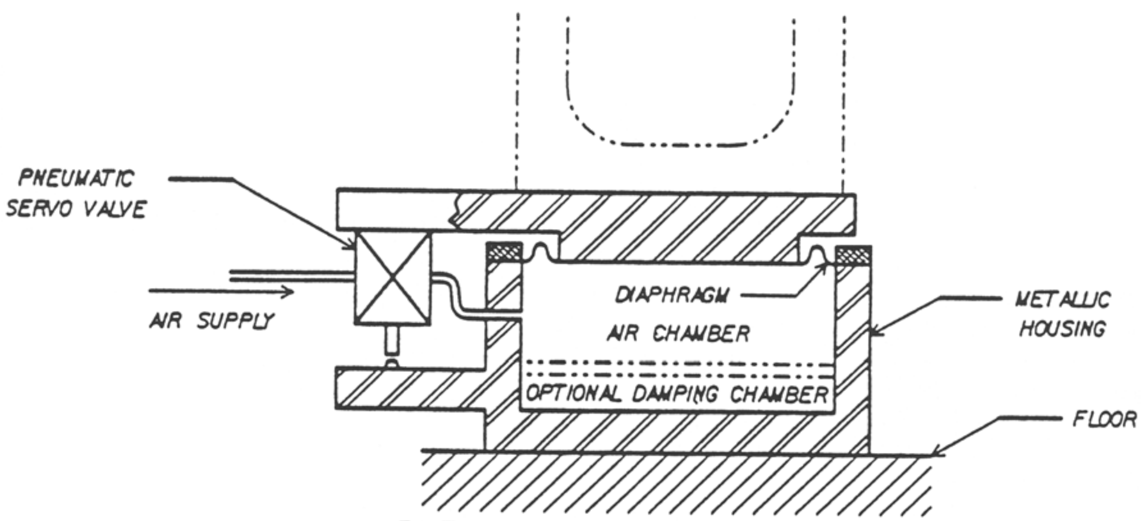
TWO-CONVOLUTION BELLOWS TYPE ISOLATOR

FIGURE 5



PNEUMATIC - ELASTOMERIC ISOLATOR

FIGURE 6



PNEUMATIC ISOLATOR, DIAPHRAGM TYPE, SELF LEVELING

FIGURE 7