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Vibration Isolation Effectiveness of Inertia Pads Resting on Soil

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Large concrete inertia pads resting on soil are commonly believed to provide a high degree of isolation from ground vibration. Our vibration measurements on existing installations show that inertia pads provide little or no vibration isolation in the frequency range below about 20 cps. Vibration spectra measured on and off inertia pads are presented. A simple passive vibration isolation system using springs is considered.

Introduction

Rapid progress is being made in the performance of inertial instruments; there is approximately a ten-fold improvement in the null stability and threshold performance every five years. At present, gyro uncertainty ranges between 10^{-3} and 10^{-4} deg/hr, and accelerometer uncertainty, or threshold, ranges between 10^{-5} and 10^{-6} g. To evaluate effectively the performance of gyros and accelerometers in inertial guidance systems, it is essential that the testing platform have a stability comparable to or better than the instruments being tested.

The purpose of the present study was to establish design criteria for inertia pads to be mounted on earth at the new Guidance, Control, and Aeroballistic Facility at the Redstone Arsenal at Huntsville, Ala. The study comprised four phases: 1) review of data from various locations in the United States to determine the level of the microseisms that may be expected at the Huntsville site, 2) measurements at the Huntsville site to determine amplitude-frequency characteristics of the earthborne cultural noise (man-made vibration), 3) investigation of the vibration-isolation properties of inertia pads resting on earth, and 4) development of a design philosophy for the inertia pads to be constructed at Huntsville.

Ground Vibration

Under Project VELA-UNIFORM, as part of the U. S. Nuclear Test Detection System, several seismological observatories have been established in remote, seismically quiet areas. Ground vibrations in the frequency range from 0.001 to 10 cps are detected and recorded at these observatories. The level of the microseisms at these observatories is generally less than 10^{-7} g over this frequency range.[1] From discussions with several seismologists, we have concluded that the natural ground vibrations (other than earthquakes) at the Huntsville site will not exceed 10^{-6} g peak-to-peak acceleration.[2, 3] Therefore, the ground vibration sources of principal interest are vehicle traffic and other local man-made disturbances,[4] such as test firings of large rocket engines in other areas of the Arsenal.

Vibration from Trains

In December 1962, personnel from the U. S. Army Engineer Waterways Experiment Station under the Corps of Engineers at Vicksburg, Miss., made measurements at the Redstone Arsenal[5] to determine the ground vibration caused by a moving train 2000 ft from the desired test site. Because of inherent limitations in the sensitivity of the available instrumentation, they were unable to detect vibration at the site, but useful measurements were obtained at distances of 50, 250, and 500 ft from the railroad track. Acceleration measurements were made simultaneously in the three mutually perpendicular axes. The maximum peak-to-peak acceleration and predominant characteristic frequency were recorded as the train passed the measuring station at speeds up to 25 mph. Measurements were made for the train engine alone and for the engine plus several loaded cars. Fifty feet from the track, the maximum peak-to-peak acceleration ranged from 10^{-2} to 10^{-1} g. At 250 ft, the range was 10^{-3} to 10^{-2} g; at 500 ft, 2×10^{-4} to 1.7×10^{-3} g. The amplitude was approximately the same in the vertical and horizontal directions. The predominant frequencies ranged between 16 and 33 cps. From these measurements, the Vicksburg group estimated the peak-to-peak vibration at the site 2000 ft from the track to be approximately 10^{-6} g with the train operating as described previously.

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At the time of the test, we conducted some brief measurements at the site (2000 ft from the train). We were not able to measure acceleration levels lower than 10^{-5} g with confidence, but the results indicated that the maximum peak-to-peak acceleration at the site was less than 10^{-5} g in the three mutually perpendicular directions.

Vibration from Autos and Trucks

To avoid disturbing signals from other vibration sources in the Arsenal, the measurements described previously were conducted on a Saturday. To determine effects of automobiles and trucks on a week-day, ground vibration measurements were made at a point approximately 1400 ft from a main road and 100 ft from a lightly traveled access road, both at noon and between 4 and 5 p.m. All construction and other activity near the site was suspended during our measurements. Typical spectra are shown in Fig. 1. The highest vibration levels occurred near 4:30 p.m. (16:20 and 16:30) due to heavy traffic on the main road. The vibration level was slightly lower near noon (12:05), and it was considerably lower at 16:55 when traffic was light on the main road. The bottom curve is a frequency analysis (made at 16:10) of the electrical noise in the measuring system with the measuring accelerometer disconnected; this noise floor represents the minimum acceleration-measuring capability of the system. From this curve we conclude that the actual ground acceleration levels are lower in the frequency range between 2.5 and 5 cps than the data would indicate.

Similar measurements were made in the horizontal plane with the measuring accelerometer positioned in both the east-west direction and the north-south direction. The curves (Fig. 2) are similar in character but somewhat lower than those for vertical accelerations. We have found that the vertical acceleration component is higher than the horizontal component for the majority of ground vibration measurements.

The spectra shown in Figs. 1 and 2 represent the rms acceleration levels in $\frac{1}{3}$-octave frequency bands. When we are considering the vibration disturbance to inertial guidance instruments, we are more concerned with the peak-to-peak acceleration than with the rms acceleration. Because of phase distortion in all frequency analysis instruments, there is no simple, direct method for measuring the peak-to-peak acceleration vs frequency. Therefore, we measure rms acceleration vs frequency with narrow band-width filters, and we measure peak-to-peak acceleration over a wide frequency band that includes all frequencies of interest.

Table 1 Peak-to-peak acceleration due to autos and trucks measured at Huntsville site (Guidance, Control and Aeroballistics Facility), February 1963

Time	Direction	Amplitude, $10^{-5}g$	Remarks
12:05	vert.	7	Medium traffic at $\frac{1}{4}$ mile
12:06	vert.	55	Large truck at 100 ft
12:07	vert.	30	Pick-up truck at 100 ft
12:08	vert.	35	Empty flat bed trailer at 100 ft
12:16	vert.	4	No activity within 1000 ft
12:20	N-S	4	No activity within 1000 ft
12:25	E-W	4	No activity within 1000 ft
16:05	vert.	8.5	Heavy traffic at $\frac{1}{4}$ mi
16:06	vert.	17	Auto at 100 ft
16:15	...	0.3	System noise floor
16:30	vert.	40	Auto at 100 ft
16:40	vert.	5.5	Medium traffic at $\frac{1}{4}$ mi

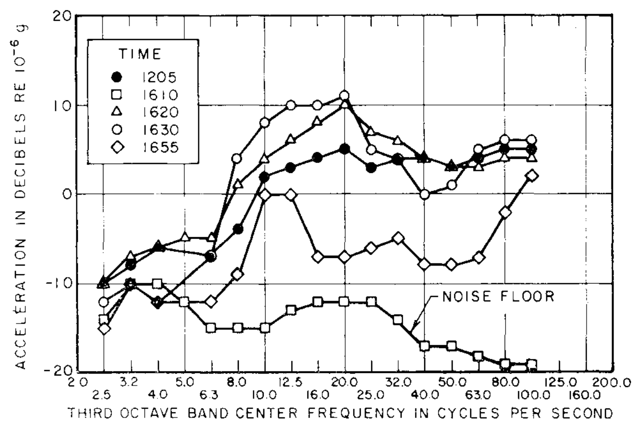

Fig. 1 Background vibration at Huntsville site (vertical acceleration).

The peak-to-peak acceleration measurements summarized in Table 1 were obtained at approximately the same time as the data shown in Figs. 1 and 2. They show that the ground vibration at the site ranges between 4×10^{-5} and 8.5×10^{-5} g when there are no moving vehicles nearby. Figures 1 and 2 indicate that the maximum acceleration occurs at frequencies above 10 cps. (We have no measurements below 2.5 cps, because experience indicated the ground acceleration levels are always lower below 2.5 cps.) Table 1 shows that the peak-to-peak acceleration may increase by a factor of 10 when a vehicle passes within 100 ft. The typical frequency spectra for passing vehicles are shown in Fig. 3. Maximum accelerations occurred between 10 and 25 cps; these accelerations represent the maximum rms values that occurred in each $\frac{1}{3}$-octave frequency band as the vehicle passed the measuring position.

In recent months we have made ground vibration measurements at several other locations in the United States (see, e.g., Fig. 3). We have observed that the frequency of maximum excitation generally coincides with the resonant frequency of the surrounding soil. The natural resonant frequency of soil ranges from approximately 10 to 35 cps.[6]

Vibration Measuring System

The vibration criterion established for the inertia pads to be installed at Huntsville was that the vibration on the pad should not exceed 10^{-5} g on any axis throughout the frequency range from 0.2 to 50 cps. A review of seismic observations made by others[1-3] showed that the acceleration levels will normally be below 10^{-6} g for frequencies below 2.5 cps; hence the principal frequency range of interest is between 2.5

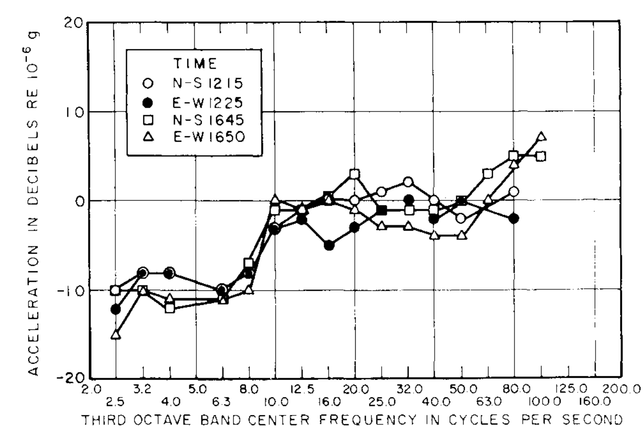

Fig. 2 Background vibration at Huntsville site (horizontal acceleration).

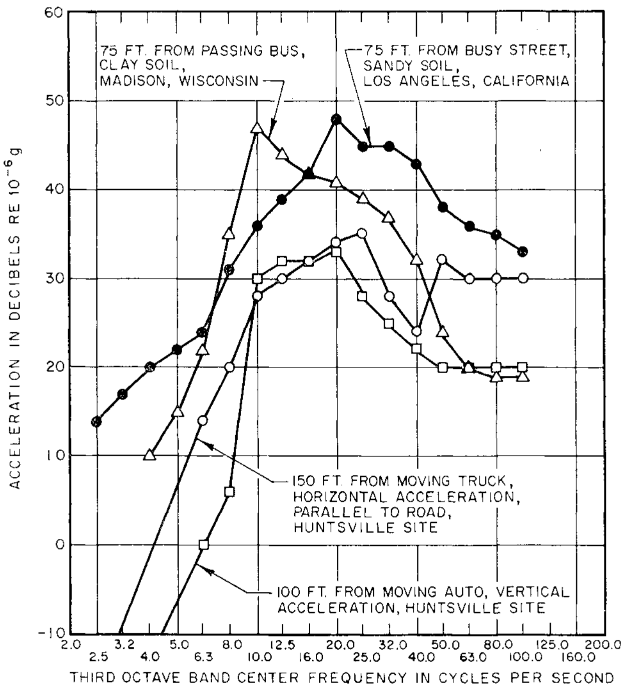

Fig. 3 Vibration due to passing vehicles.

and 100 cps. Figure 4 outlines in block diagram form the vibration measuring system that was used for most of the measurements. To measure acceleration levels down to 10^{-6} g, we constructed a special piezoelectric accelerometer having a sensitivity of 5 v/g, a principal resonant frequency of 600 cps, and (operating in conjunction with the General Radio preamplifier) a uniform (± 0.5 db) response from 1 to 100 cps. The noise floor was less than 2×10^{-7} g (rms) in all $\frac{1}{3}$-octave frequency bands from 1 to 100 cps. A Sanborn strip chart recorder was used to display over-all acceleration levels vs time and to record peak-to-peak acceleration. Because of the wide dynamic range of the vibration excitation as a function of frequency, little frequency information was obtained from this record. A 1-min sample of the signal from the

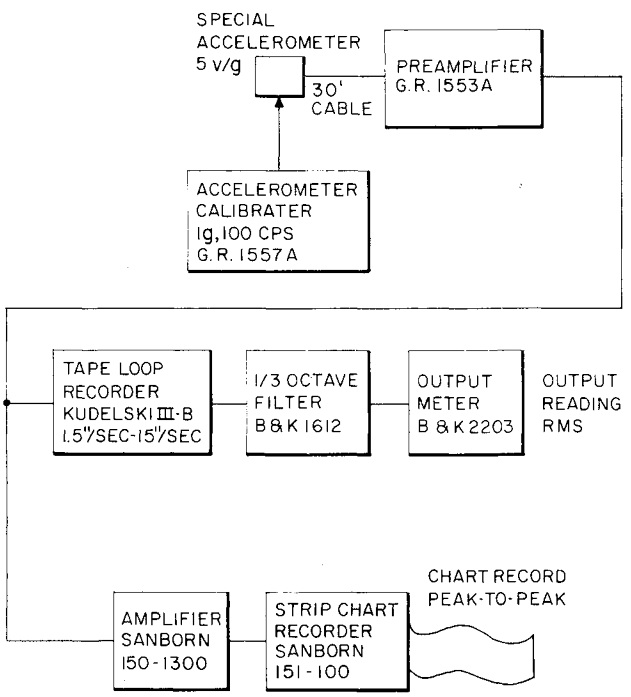

Fig. 4 Block diagram of vibration measuring system.

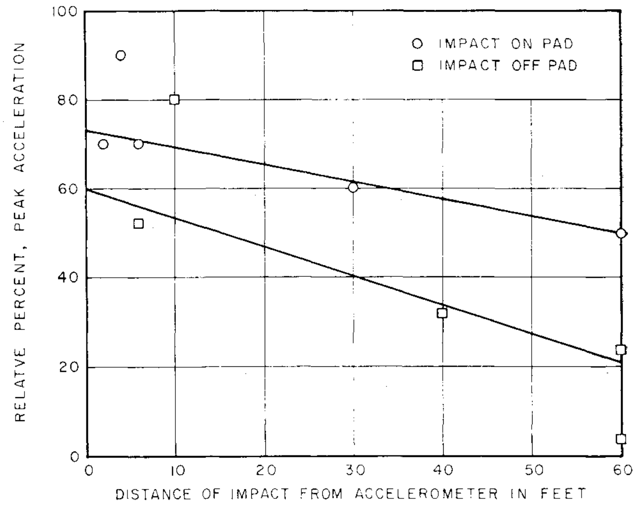

Fig. 5 Shock isolation provided by an inertia pad (vertical acceleration measured on pad).

accelerometer was obtained by a tape loop recorder at a recording speed of 1.5 in./sec. The tape-recorded loop was then reproduced at 15 in./sec to permit rapid frequency analysis of the signal with the Bruel and Kjaer $\frac{1}{3}$-Octave Band Frequency Analyzer. At frequent intervals, the over-all sensitivity of the system was checked by attaching the measuring accelerometer to the General Radio Vibration Calibrator.

The measuring accelerometer was buried under 1 ft of soil for the majority of the ground vibration measurements. Measurements were made with and without the soil covering the accelerometer to determine whether air-borne sounds were being detected; this test proved that the air-borne noise was not an influencing factor on the acceleration measurements.

Inertia Pads

Vibration measurements were made on and off a large inertia pad to evaluate the vibration-isolation characteristics of inertia pads resting on soil. The pad tested was approximately 3 ft thick and had a surface area of over 500 ft². There was no structural tie between the floor surrounding the pad and the pad itself. The pad was separated from the surrounding floor by a 1-in. glass-fiber insulating board around the perimeter.

Vibration reduction effectiveness was measured by striking the pad with a hammer and striking the floor approximately 2 ft off the pad with the same hammer and observing the difference in the peak acceleration measured on the pad. The measuring accelerometer was placed on the pad approximately

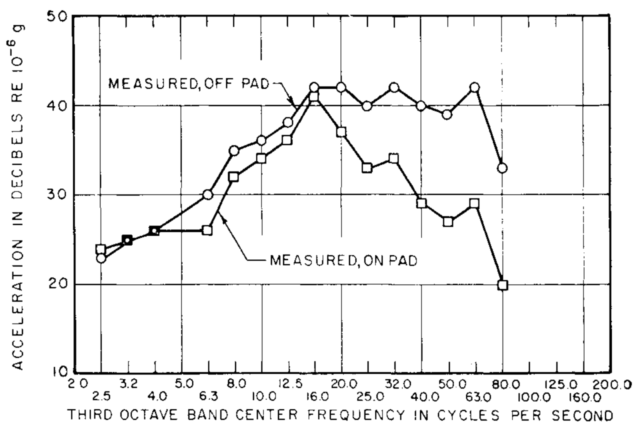

Fig. 6 Inertia pad background vibration (vertical acceleration).

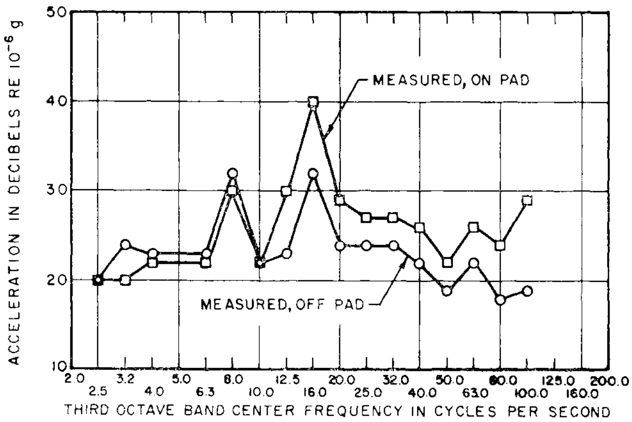

Fig. 7 Inertia pad background vibration, horizontal acceleration parallel to pad axis.

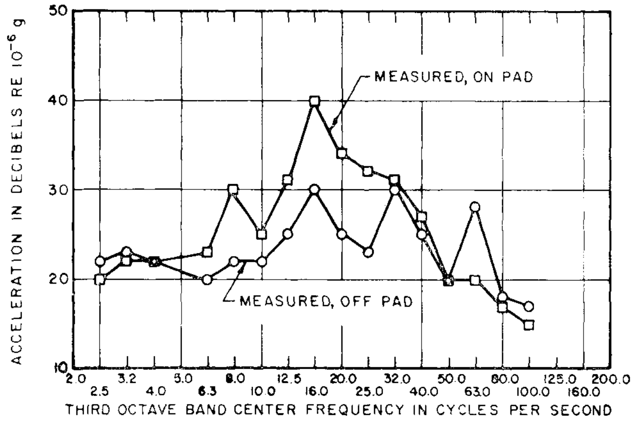

Fig. 8 Inertia pad background vibration, horizontal acceleration perpendicular to pad axis.

one-third of the distance from the end of the pad and oriented to detect vertical acceleration. The results are shown in Fig. 5 (distances along a line parallel with the major axis of the pad). One can see that the hammer striking the floor gave only slightly lower acceleration levels than did the hammer striking directly on the pad.

The rms background acceleration levels vs frequency are summarized in Figs. 6–8. The effective vibration isolation provided by the inertia pad can be derived by comparing the vibration levels on the pad with the vibration levels off the pad. These differences are plotted in Fig. 9. This inertia pad provides no significant isolation at frequencies below 20 cps. The resonant frequency of the inertia pad with the compliance of the soil under the pad appears to be between 16 and 20 cps. At frequencies above 16 cps, the inertia pad does provide vibration isolation in the vertical plane. In the horizontal plane, however, the vibration levels are equal to or higher on the pad than off it at all frequencies. The peak-to-peak acceleration levels were approximately the same from hour to hour. Typical readings are shown in Table 2.

We also made vibration measurements on a small inertia pad, a 4-ft-diam concrete cylinder extending 6 to 8 ft into the ground, which was separated from the floor by 1-in. polyurethane foam around its perimeter. A strong 60-cps vibration component was traced to rotary power supplies mounted outside the building approximately 75 ft away. With the power supplies turned off, the peak-to-peak vertical acceleration on the inertia pads decreased by a factor of 6; this example demonstrates the importance of vibration isolation of all mechanical equipment in the vicinity. The rms accelerations vs frequency are shown in Fig. 10. No vibration isolation was provided by the pad below 32 cps. Even at frequencies above 32 cps, the maximum isolation is only 8 db, less than a factor of 3.

Thus, inertia pads give very little protection against ground vibration at frequencies below approximately 20 cps. Other investigators[7] studying the problem of foundations for large engines report that the natural frequency of a pad on soil will correspond to the curve shown in Fig. 11; even a 10-ft-thick pad is expected to have a resonant frequency slightly above 10 cps. We conclude that an inertia pad resting on soil will provide little or no isolation from ground vibration in the frequency range of maximum excitation due to nearby vehicle traffic and building resonances.

Table 2 Peak-to-peak acceleration measured on an inertia pad resting on soil

Direction	Amplitude, $10^{-4}g$	On or off pad
Vertical	8.5	On
Vertical	7	Off
Horizontal, parallel	7	On
Horizontal, parallel	8.5	Off
Horizontal, perpend.	8.5	On
Horizontal, perpend.	8.5	Off

Supporting an Inertia Pad on Springs

Some attempts to isolate inertia pads from the ground vibration have not been successful in the past for two principal reasons: 1) the compliant suspension system was not designed to produce the desired resonant frequency (hence the vibration amplitude on the pad was higher than the amplitude off the pad), and 2) long term drift occurred. The vibration problem can be overcome and the long-term stability problem minimized by the proper support of an inertia pad on simple steel springs. We propose a rectangular concrete inertia pad having a maximum length of 40 ft, a minimum width of ~12 ft, and a thickness of 5 ft, supported at the corners by four poured concrete piles extending to rock approximately 60 ft below the ground surface. The concrete piles extending down to rock may help to improve the long term stability of the pad; however, they will not reduce the amount of earthborne vibration transmitted to the pad.

An inertia pad mounted on springs presents two problems that must be solved. The principal resonant frequency of the inertia pad resting on springs must be sufficiently low to provide adequate vibration isolation over the frequency range of maximum ground excitation. Furthermore, the suspension system must be capable of supporting uneven loading of the inertia pad and must not exceed a reasonable criterion for tilt or rotation of the pad. To achieve maximum stability in

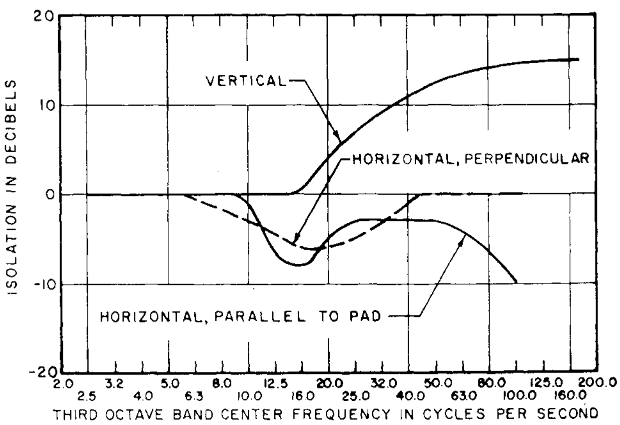

Fig. 9 Effective ground vibration isolation provided by inertia pad.

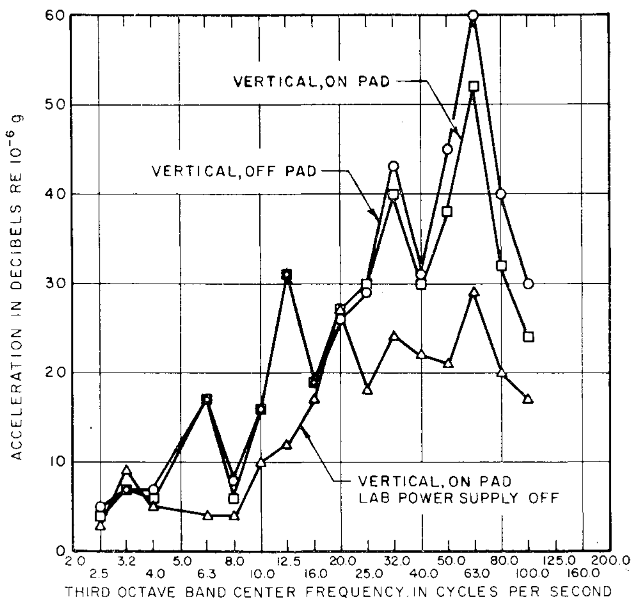

Fig. 10 Small inertia pad background vibration (vertical acceleration).

all six degrees of freedom, we recommend that the spring suspension be provided at the four base corners. To provide adequate vibration isolation, we recommend that the resonant frequency of the pad and spring system be set at 2 cps.

The concrete pad described will weigh ~360,000 lb. Its initial deflection in the middle due to its own weight will be ~0.05 in. If we consider the 40-ft concrete pad as a free-free beam, the lowest-frequency flexural beam mode is 40 cps, but the addition of reinforcement steel in the pad may raise the lowest resonant frequency by a factor of 2 or more. It is desirable to have the lowest frequency beam mode removed as far as possible from the natural resonant frequency of the pad and the suspension system to achieve maximum isolation from ground vibration and also to be above the major frequencies of ground excitation.

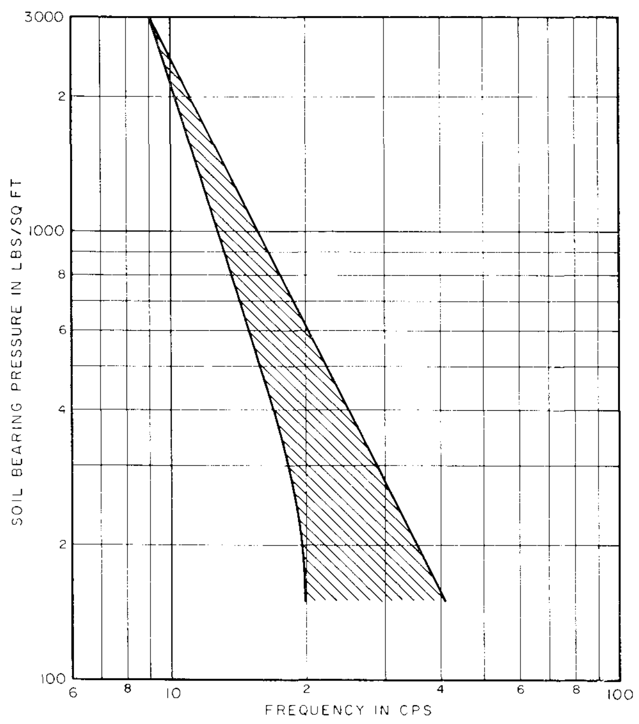

Fig. 11 Natural frequency of inertia pad on clay soil.

The springs that we recommend for the support of the inertia pad obey the ordinary linear load-deflection relationship, compressing 2.5 in. for a 2-cps resonant frequency under load. We propose that four springs be positioned at each of the four corners under the pad. To insure long term stability of the pad, 1) the springs should be designed for a maximum stress of 30,000 psi; 2) alternate springs may be wound in the opposite direction; 3) the springs could be fabricated of "Isoelastic," an iron-nickel material with a constant Young's modulus with temperature; 4) air circulation around the springs should be minimized and temperature should be kept as constant as possible; and 5) a ribbed rubber pad should be inserted in series with the springs to reduce vibration transmission into the pad at the resonant frequencies in the steel springs themselves.

The 5-ft-thick inertia pad can be formed and poured directly over a 1-ft-thick pad foundation with two layers of waterproof paper covering the surface of the foundation to prevent the pad from adhering to the foundation. Spring mounts are made to accommodate a hydraulic jack for elevating the inertia pad to the proper height above the foundation. We recommend that the springs be adjusted to support the inertia pad 6 in. above the foundation slab. The 6-in. air space will provide a spring constant of 16,000 lb/in., which is little more than $\frac{1}{10}$ the total spring constant of the steel supporting springs. With the inertia pad supported in this manner, the over-all peak-to-peak acceleration levels on it should not exceed $3 \times 10^{-6}\ g$ because of traffic on the main road 1400 ft away. We estimate that the peak-to-peak acceleration from trucks and autos passing at a distance of 100 ft from the pad will be reduced from $5.5 \times 10^{-4}\ g$ to less than $1 \times 10^{-5}\ g$ with the spring isolation.

The inertia pad described previously was designed with four top surface pedestals, each 5 ft in diameter and 10 ft on centers. The spring constant is 144,000 lb/in. From this we can determine the rotation, or tilt, of the pad due to uneven loading of the four top pedestals. The worst condition is an applied point load at the outer edge of a pedestal (nearest the long side of the pad). A 70-lb differential load at this point will tilt the pad 1 sec. If we assume the pedestals are center-loaded, then a 220-lb differential load on one of the outer pedestals, or a 670-lb differential load on one of the inner pedestals, will cause the pad to tilt 1 sec.

A factor-of-two reduction in the pad tilt sensitivity can be had for approximately a factor-of-two reduction in vibration isolation by increasing the resonant frequency of the suspended system. A better approach might be to increase the width of the pad. Then the spring constant could be increased without loss in vibration isolation by constructing a larger and heavier inertia pad.

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