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U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Center for Building Technology
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Bureau of Engraving and Printing
4th and C Streets, S.W.
Vashington, D.C. 20228

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# INVESTIGATION OF FLOOR VIBRATIONS IN THE "D" WING OF THE MAIN BUILDING OF THE BUREAU OF ENGRAVING AND PRINTING

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**NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director***

ABSTRACT

Floor vibrations induced in a Bureau of Engraving and Printing building by a recently-installed perforator were investigated by measuring relative acceleration amplitudes and phase relationships between a reference position and points on a grid laid out on the affected floor. From these measurements, it was possible to determine mode shapes, resonant frequencies and displacement amplitudes. On the basis of the displacement amplitudes, anticipated cyclic stresses in the structural system were estimated. The results of the measurements and analysis were compared with existing data on vibration-induced structural damage and fatigue strength of steel and reinforced concrete. Damping ratios were also determined in a separate test, in order to ascertain at later dates whether any structural deterioration is taking place.

Key words: cyclic strength; fatigue; floor vibrations; machine foundations; reinforced concrete; steel; structural engineering

## 1. Background

Following the installation of two new coiling machine perforators on the first floor of "D" Wing of the Main Building of the Bureau of Engraving and Printing, floor vibrations were observed. In December 1981, the Bureau of Engraving and Printing contacted the Center for Building Technology of the National Bureau of Standards and requested an evaluation of the vibrations in order to determine whether potential structural damage could result. One of the reasons for the concern was the age of the building, which was constructed in the early 1910's.

Following initial explorations by NBS personnel on November 23 and December 3, 1981, it was decided, on the basis of preliminary vibration measurements conducted by the Bureau of Engraving and Printing (see Fig. 1a) and observations of machine operation, to pursue further the investigation and conduct additional measurements. These additional measurements were deemed necessary to determine natural frequencies and mode shapes of the floor vibrations in order to more accurately estimate their potential effects on the structural system, which consists of a concrete joist floor supported by concrete-encased steel girders which, in turn, are supported by concrete-encased steel columns (see Fig. 2). It was also decided to conduct non-destructive tests in order to determine the concrete strength of the floor joists since no data on the concrete mix used were available. The vibration measurements were taken on December 17 and 18, 1981. Concrete impact tests with a Schmidt Hammer were conducted on December 17, 1981.

This report contains a description of the measurements obtained and their interpretation.

## 2. Vibration Tests

Vibration measurements were made on the floor at selected locations on a grid laid out by Bureau of Engraving and Printing personnel. The grid points are shown in Fig. 3. Vibration tests were conducted on the floor systems under both machines because each machine is located differently relative to the columns and girders of the floor system.

The machines operate at variable speeds. The machine speed is defined in terms of the "web speed" (the speed at which the paper advances into the machine in feet per minute, 'fpm') and is set by the operator. Floor vibrations are sensitive to the operating speed as shown in Figs. 1a and 1b. Figure 1b presents the variation of vibration frequency with machine speed and the relative magnitude of floor vibration at two points for each floor studied as a function of machine speed.

Vibrations were monitored by measuring vertical accelerations using two Kistler-type 303-T accelerometers which were set to a sensitivity of 10 volts per 1g. Measurements were taken by keeping one accelerometer at a reference position adjacent to the perforator and moving the other accelerometer to selected points on the grid. These measurements made it possible to determine relative amplitudes and phase relationships between the reference position and the other grid points. These data could then be used to estimate mode shapes. Locations at which acceleration measurements were obtained are shown in Figs. 4, 5, 6 and 7.

Vibration data were analyzed using a Hewlett-Packard spectrum analyzer to obtain auto-spectra and cross-spectra.

With the accelerometers placed in two selected locations, machine speed was varied between 100 fpm and 170 fpm. Subsequent measurements were made at two selected machine speeds which subjectively caused maximum vibrations. On the North machine (see Fig. 2), these speeds were 125 fpm and 155 fpm. These two "critical" speeds on the North machine forced vibrations at two different resonant frequencies of the floor system. Plots of the relative peak accelerations for the two North floor locations are given in Fig. 1b. Square symbols show resonance peaks at about 120 and 155 fpm machine speeds. The 117 fpm speed on the South machine also forced response at a resonance frequency of the floor system. The 160 fpm speed for the South machine was chosen to provide information on vibrations at a high operating speed. Unfortunately, this machine speed did not cause vibration at one of the floor's resonance frequencies. In retrospect, a choice of 165 fpm as the operating speed would have produced higher accelerations (see Fig. 1b). However, it was difficult for the operators to maintain the 160 fpm operating speed during the tests and a 165 fpm speed would have been even more difficult to maintain. Also, because the frequency of the peak response associated with the higher machine speed is 44 percent higher than that associated with the lower machine speed, the deflections related to the high machine speed vibrations, and hence the stresses, would be only about half as large as these caused by the same level of acceleration at the lower frequency of vibration.

In addition to these measurements, floor acceleration caused by an impulse load (the jump of a person) was measured to determine structural damping.

## 3. Concrete Strength Tests

A memorandum on the Schmidt Hammer tests is in Appendix A to this report. Even though the Schmidt Hammer does not provide very accurate information on the concrete strength, it can be deduced from the test that the concrete construction in the building is of high quality. The concrete compressive strength ($f'_c$) can be conservatively assumed to exceed 2500 psi, and probably is above 3000 psi.

## 4. Interpretation of Test Results

### 4.1. Analysis of Vibrations

The auto-spectra measurements obtained from the vibration analyzer were used to determine rms (root-mean-square) acceleration, velocity and displacement at the primary frequency of forced vibration. Peak values were also estimated on the basis of assumed simple harmonic motion ( $\sqrt{2}$ x rms amplitude). The equations used for converting the spectral values to rms values are given below:

$$A_r = \sqrt{S(n)\ 1.1719}$$

$$V_r = \frac{A_r\ (32.2)\ (12)}{2\pi f} = \frac{61.50\ A_r}{f}$$

$$Y_r = \frac{V_r}{2\pi f} = .1592 \frac{V_r}{f}$$

where S(n) = spectral value from analyzer at frequency n in $g^2$/Hz

$A_r$ = rms acceleration in g's

$V_r$ = rms velocity in in/sec

$Y_r$ = rms vertical displacement in inches

The factor, 1.1719, in the equation for $A_r$ is related to the window function used in the spectral analysis and was supplied by the manufacturer of the spectral analyzer. The other equations result from assuming simple, harmonic motion and knowing the acceleration. Typical plots of the auto-spectra at two locations are shown in Fig. 8. Fig. 9 shows a log plot of one of the spectra with the harmonics of the resonant frequency identified.

Mode shapes were estimated from relative vibration amplitudes and phase angles. The phase angles, in turn, were obtained from the cross-spectra. The mode shapes associated with the forced vibration at the two operating speeds for each of the two floor systems are shown in Figs. 10, 11, 12 and 13. Note that the mode shapes indicate that the floor systems acted like large plates.

Rms acceleration levels, A, and relative phase angles, $\phi$, of the floor system response are shown in Figs. 14, 15, 16 and 17. Velocities and displacements are tabulated along with accelerations and phase angles in Tables 1, 2, 3 and 4. During analysis of vibration data from the tests of the South floor, with a machine web speed of approximately 117 feet/minute, it was found that accelerations measured at the reference location varied significantly between different tests. These differences are attributable to either a degradation of the connection between the reference accelerometer and the floor since later tests produced lower accelerations than earlier tests, or to slightly different operating speeds since the machine stopped several times and had to be restarted during the course of testing all the locations. Results presented in Table 3a correspond to actual measurements, while values in Table 3b are corrected to reflect the possibility that different machine speeds caused the observed differences.

The phase angles shown in Figs. 14, 15, 16 and 17 indicate that the vibration propagates out from the middle of the span on which the perforator is located. This is an indication that at the measured frequency the forced vibration induced by the machine was not precisely in resonance with the floor. Therefore, it may be possible to generate a somewhat larger response than that observed in the NBS tests.

The following determinations were made:

1. Natural frequencies of floor systems:

   North floor (distinct 2 modes): 14.07 Hz and 17.97 Hz

   South floor: 13.28 Hz and 19.0 Hz

2. Damping ratio for the south floor: 6 percent of critical damping.

   A trace of the impact test is shown in Fig. 18.

The maximum values of accelerations, velocities and displacements are given in Table 5. Maximum acceleration levels were evaluated against empirical criteria for structural vibrations presented in Ref. [1] and shown in Fig. 17. In Fig. 19, circles denote accelerations for south floor locations and squares denote north floor locations. Note that all vibrations are below the threshold for "minor damage," and that the south floor vibrations are above the line indicating "damage very improbable." All maximum vibrations, however, are above the threshold for "highly annoying vibrations" for work areas. This fact is also corroborated by the perception of workers in the area.

It should be noted that the thresholds in the chart in Fig. 18 are approximate, at best, and should only be used to estimate probable effects.

Since the maximum vibrations are slightly above the threshold for possible (though not probable) structural damage (2.5 mm/s or 0.1 in/s), a more complete analysis of vibration-induced stresses was conducted.

4.2. Analysis of Structural Effects

The procedure used to arrive at approximate vibration-induced stresses is outlined herein.

a) The mode shapes obtained from the vibration analysis indicate that the floor responded as a plate.

b) The mode shapes also provided an estimate of the size of the plate engaged in the vibration.

c) The stiffness of the plate engaged in the vibration was approximated using an orthrotropic plate analysis.

d) Using the maximum estimated deflection at the center of the plate and the equivalent orthrotropic plate stiffness, equivalent static loads were calculated which would produce the same deflection.

e) Stresses induced in the girder and the reinforced concrete floor section were calculated for the static and dynamic load components.

The following maximum stresses were calculated:

1. Steel girders: (Assuming Simply Supported Ends)

| | Static Component | | Dynamic Component | |
|---|---|---|---|---|
| | Bending | Shear | Bending | Shear |
| North Floor | 12,395 psi | 1,309 psi | ± 251 psi | ± 15 psi |
| South Floor | 11,476 psi | 1,317 psi | ± 561 psi | ± 39 psi |

2. Concrete beams: North machine

| | Static Component | Dynamic Component |
|---|---|---|
| Concrete Compression | 497 psi | ± 19 psi |
| Reinforcing steel tension | 1,242 psi | ± 48 psi |
| Concrete shear | 56 psi | ± 2 psi |

South Machine

| | Static Component | Dynamic Component |
|---|---|---|
| Concrete compression | 574 psi | ± 68 psi |
| Reinforcing steel tension | 1,434 psi | ±170 psi |
| Concrete shear | 55 psi | ± 4 psi |

NOTE: Stresses were calculated for the working conditions observed, without consideration of potential extreme loads for which the system was designed.

The calculated stresses can be compared with data on structural performance under cyclic loads, such as ACI Committee 215 report, Ref. [2]. It is reasonable to assume, on the basis of the Schmidt Hammer tests, that the concrete construction is of high quality and the concrete strength ($f'_c$) is at least 2500 psi; $f'_c$ probably exceeds 3000 psi. Thus, calculated stresses caused by the static and dynamic load components are substantially less than the allowable working stresses for the steel and concrete in the slabs. Data on fatigue strength of reinforced concrete, Ref. [1], indicate that it is unlikely that the prevailing stresses could cause any structural damage to the concrete slab.

The allowable stress in the steel girders used in accordance with Ref. [3] is 16,000 psi for static loads and 12,500 psi for "moving" loads. Even though the data available at the time Ref. [3] was written were probably limited, these allowable stresses seem conservative. The calculated combined static and dynamic stresses induced in the steel girder were 12,646 psi and 12,037 psi for critical girders in the north and south floors, respectively. It should be emphasized that these calculated stresses are quite conservative since the beams are at least partially fixed at the ends. Partially fixing the ends could lead to reductions of 30 to 50 percent in the stresses. Also, the effects of the concrete topping and concrete encasement of the girders were neglected. It is unlikely that the expected stresses could cause structural damage to the steel girders.

## 5. Conclusions

On the basis of the data and analysis presented herein, it is unlikely that the vibrations induced by the two new coiling machine perforators could cause any structural damage to the floor system and steel girders. The vibration level is, however, high enough to cause significant discomfort to people working in the area.

The possibility of structural damage, as well as the discomfort to personnel could be substantially reduced by avoiding the following operating speeds:

North machine: speeds between 115 and 130 ft/min and above 150 ft/min.

South machine: speeds between 110 and 125 ft/min and above 150 ft/min.

## 6. Recommendations

1) To ascertain that no structural deterioration occurs, particularly in the vicinity of the concrete floor connection to the girder, it is recommended that periodic vibration tests be conducted. These tests should check the natural frequency and damping of the floor system by placing an accelerometer at the center of the floor spans where the perforators are located and compare the data with values reported herein. A reasonable interval between successive measurements could be one year, or such time that operators notice a change in the critical machine speed.

2) It is suggested that in future purchases of new machines, forced vibrations in the frequency range between 10 and 25 Hz be avoided, or appropriate measures be taken to reduce floor vibrations. It may also be possible to stipulate that induced floor vibrations should not exceed those defined by the "workshop" threshold in Fig. 17.

## 7. Acknowledgment

The work was performed by the Geotechnical Engineering Group of the Structures Division of the Center for Building Technology. Mr. Jim Woodward from the Bureau of Engraving and Printing supplied all the technical data on the building and machines, as well as vibration measurements performed by the Bureau of Engraving and Printing, and marked the locations for vibration measurements and Schmidt Hammer testing. Mr. Erik Anderson of the Structures Division of the Center for Building Technology performed and interpreted the Schmidt Hammer tests. Mr. Beverly F. Payne of Mechanical Production, Metrology Division, of the Center for Manufacturing Engineering checked the vibration analyzer of the Bureau of Engraving and Printing and calibrated the accelerometers used in the NBS tests.

## 8. References


[1] Rudder, F. F., "Engineering Guidelines for the Analysis of Traffic-Induced Vibration," Federal Highway Administration Report FHWA-RD-78-166, Washington, D.C., February, 1978.

[2] ACI Committee 215, Consideration for Design of Concrete Structures Subjected to Fatigue Loading, Journal of the American Concrete Institute, March, 1974.

[3] Blakeley, George H., "Dimensions, Weights and Properties of Special and Standard Structural Steel Shapes Manufactured by Bethlehem Steel Company," Dando Printing and Publishing Co., Philadelphia, PA, 1907.

Table 1: Measured Accelerations and Estimated Velocities and Displacements for the North Floor (Fig. 3) Response at 14.07 Hertz with Machine Web Speed of Approximately 125 feet/minute.

| Grid Point Location (Row, Column) | Phase Shift * (Degrees) | RMS Acceleration (g's) | RMS Velocity (inches/sec) | RMS Displacement (inches) |
|---|---|---|---|---|
| 4, 7 | -19 | .007 | .029 | $.33 \times 10^{-3}$ |
| 5, 7 | -10 | .007 | .031 | $.35 \times 10^{-3}$ |
| 6, 3 | - 5 | .009 | .039 | $.44 \times 10^{-3}$ |
| 6, 5 | 0 | .014 | .061 | $.69 \times 10^{-3}$ |
| 7, 7 | 3 | .009 | .040 | $.46 \times 10^{-3}$ |
| 8, 5 | 5 | .012 | .051 | $.58 \times 10^{-3}$ |
| 9, 2 | 0 | .004 | .018 | $.20 \times 10^{-3}$ |
| 9, 6 | 3 | .007 | .030 | $.34 \times 10^{-3}$ |
| 9, 7 | 3 | .004 | .019 | $.22 \times 10^{-3}$ |
| 10, 5 | - 5 | .005 | .020 | $.23 \times 10^{-3}$ |
| 11, 6 | -14 | .003 | .014 | $.16 \times 10^{-3}$ |
| 12, 5 | -25 | .002 | .009 | $.11 \times 10^{-3}$ |

* Relative to reference accelerometer location 6, 5.

Table 2: Measured Accelerations and Estimated Velocities and Displacements for the North Floor (Fig. 4) Response at 17.97 Hertz with Machine Web Speed of Approximately 155 feet/minute.

| Grid Point Location (Row, Column) | Phase Shift * (Degrees) | RMS Acceleration (g's) | RMS Velocity (inches/sec) | RMS Displacement (inches) |
|---|---|---|---|---|
| 6, 3 | -15 | .005 | .018 | $.16 \times 10^{-3}$ |
| 6, 5 | 0 | .007 | .025 | $.22 \times 10^{-3}$ |
| 7, 5 | 2 | .012 | .041 | $.36 \times 10^{-3}$ |
| 8, 3 | -20 | .010 | .033 | $.29 \times 10^{-3}$ |
| 8, 5 | -13 | .014 | .049 | $.43 \times 10^{-3}$ |
| 9, 2 | -31 | .009 | .032 | $.28 \times 10^{-3}$ |
| 9, 5 | -27 | .016 | .053 | $.47 \times 10^{-3}$ |
| 9, 6 | -27 | .013 | .045 | $.40 \times 10^{-3}$ |
| 10, 3 | -43 | .013 | .045 | $.40 \times 10^{-3}$ |
| 10, 5 | -41 | .018 | .061 | $.54 \times 10^{-3}$ |
| 10, 6 | -42 | .015 | .052 | $.46 \times 10^{-3}$ |
| 10, 7 | -45 | .010 | .035 | $.31 \times 10^{-3}$ |
| 12, 3 | -55 | .010 | .034 | $.30 \times 10^{-3}$ |
| 12, 5 | -55 | .013 | .045 | $.40 \times 10^{-3}$ |
| 13, 5 | -69 | .009 | .030 | $.26 \times 10^{-3}$ |

* Relative to reference accelerometer location 6, 5.

Table 3a: Measured Accelerations and Estimated Velocities and Displacements for the South Floor (Fig. 4) Response at 13.28 Hertz with Machine Speed of Approximately 117 feet/minute.

| Grid Point Location (Row, Column) | Phase Shift * (Degrees) | RMS Acceleration ** (g's) | RMS Velocity (inches/sec) | RMS Displacement (inches) |
|---|---|---|---|---|
| 2, 4 | -31 | .012 | .056 | $.67 \times 10^{-3}$ |
| 3, 4 | -27 | .016 | .073 | $.87 \times 10^{-3}$ |
| 4, 4 | -17 | .019 | .088 | $1.06 \times 10^{-3}$ |
| 5, 6 | -12 | .016 | .073 | $.88 \times 10^{-3}$ |
| 5, 2 | - 6 | .012 | .056 | $.67 \times 10^{-3}$ |
| 7, 6 | - 7 | .021 | .096 | $1.16 \times 10^{-3}$ |
| 7, 5 | - 5 | .028 | .127 | $1.53 \times 10^{-3}$ |
| 7, 4 | 0 | .033 | .153 | $1.83 \times 10^{-3}$ |
| 7, 2 | - 1 | .016 | .076 | $.91 \times 10^{-3}$ |
| 8, 4 | - 5 | .030 | .138 | $1.65 \times 10^{-3}$ |
| 9, 7 | -13 | .011 | .051 | $.61 \times 10^{-3}$ |
| 9, 5 | -10 | .021 | .098 | $1.17 \times 10^{-3}$ |
| 9, 4 | - 8 | .024 | .112 | $1.35 \times 10^{-3}$ |
| 9, 3 | - 8 | .018 | .082 | $.98 \times 10^{-3}$ |
| 9, 2 | - 8 | .011 | .051 | $.61 \times 10^{-3}$ |
| 10, 4 | -13 | .021 | .098 | $1.18 \times 10^{-3}$ |
| 11, 6 | -19 | .015 | .068 | $.82 \times 10^{-3}$ |
| 11, 5 | -19 | .019 | .086 | $1.03 \times 10^{-3}$ |
| 11, 4 | -18 | .019 | .088 | $1.06 \times 10^{-3}$ |
| 11, 3 | -17 | .015 | .067 | $.80 \times 10^{-3}$ |
| 11, 2 | -19 | .008 | .038 | $.46 \times 10^{-3}$ |
| 12, 4 | -23 | .014 | .067 | $.80 \times 10^{-3}$ |
| 13, 6 | -32 | .009 | .040 | $.48 \times 10^{-3}$ |
| 13, 4 | -29 | .011 | .051 | $.62 \times 10^{-3}$ |

* Relative to reference accelerometer location 7, 4.

** Significant differences were observed between accelerations measured at the reference accelerometer - probably due to small changes in machine speed due to frequent stops and restarts of machine - corrections are applied in Table 3b to maintain constant acceleration levels at the reference accelerometer.

Table 3b: Corrected Accelerations and Corrected Estimates of Velocities and Displacements for the South Floor (Fig. 4) Response at 13.28 Hertz with Machine Speed of Approximately 117 feet/minute.

| Grid Point Location (Row, Column) | Phase Shift * (Degrees) | RMS Acceleration (g's) | RMS Velocity (inches/sec) | RMS Displacement (inches) |
|---|---|---|---|---|
| 2, 4 | -31 | .015 | .071 | $.85 \times 10^{-3}$ |
| 3, 4 | -27 | .020 | .093 | $1.11 \times 10^{-3}$ |
| 4, 4 | -17 | .025 | .114 | $1.36 \times 10^{-3}$ |
| 5, 6 | -12 | .020 | .094 | $1.13 \times 10^{-3}$ |
| 5, 2 | - 6 | .013 | .062 | $.74 \times 10^{-3}$ |
| 7, 6 | - 7 | .025 | .115 | $1.38 \times 10^{-3}$ |
| 7, 5 | - 5 | .031 | .141 | $1.69 \times 10^{-3}$ |
| 7, 4 | 0 | .033 | .153 | $1.83 \times 10^{-3}$ |
| 7, 2 | - 1 | .018 | .084 | $1.00 \times 10^{-3}$ |
| 8, 4 | - 5 | .031 | .143 | $1.73 \times 10^{-3}$ |
| 9, 7 | -13 | .012 | .058 | $.69 \times 10^{-3}$ |
| 9, 5 | -10 | .024 | .109 | $1.31 \times 10^{-3}$ |
| 9, 4 | - 8 | .024 | .112 | $1.35 \times 10^{-3}$ |
| 9, 3 | - 8 | .020 | .094 | $1.12 \times 10^{-3}$ |
| 9, 2 | - 8 | .012 | .057 | $.69 \times 10^{-3}$ |
| 10, 4 | -13 | .022 | .102 | $1.22 \times 10^{-3}$ |
| 11, 6 | -19 | .016 | .075 | $.90 \times 10^{-3}$ |
| 11, 5 | -19 | .021 | .095 | $1.11 \times 10^{-3}$ |
| 11, 4 | -18 | .020 | .092 | $1.10 \times 10^{-3}$ |
| 11, 3 | -17 | .016 | .075 | $.89 \times 10^{-3}$ |
| 11, 2 | -19 | .009 | .043 | $.51 \times 10^{-3}$ |
| 12, 4 | -23 | .015 | .072 | $.86 \times 10^{-3}$ |
| 13, 6 | -32 | .009 | .042 | $.51 \times 10^{-3}$ |
| 13, 4 | -29 | .012 | .054 | $.65 \times 10^{-3}$ |

* Relative to reference accelerometer location 7, 4.

Table 4: Measured Accelerations and Estimated Velocities and Displacements for the South Floor (Fig. 5) Response at 18.75 Hertz with Machine Web Speed of Approximately 160 feet/minute.

| Grid Point Location (Row, Column) | Phase Shift * (Degrees) | RMS Acceleration (g's) | RMS Velocity (inches/sec) | RMS Displacement (inches) |
|---|---|---|---|---|
| 4, 4 | -62 | .004 | .015 | $.12 \times 10^{-3}$ |
| 7, 4 | 0 | .011 | .037 | $.32 \times 10^{-3}$ |
| 9, 4 | -35 | .014 | .046 | $.39 \times 10^{-3}$ |
| 11, 4 | -78 | .013 | .043 | $.36 \times 10^{-3}$ |
| 13, 4 | -156 | .010 | .034 | $.29 \times 10^{-3}$ |

* Relative to reference accelerometer location 7, 4.

Table 5: Maximum Values of Accelerations, Velocities and Displacements.

| FLOOR | Machine Web Speed (Feet/Minute) | Natural Freq. of Floor Vib. (Hertz) | Maximum RMS Acceleration (g's) | Maximum RMS Velocity (Inches/Sec) | Maximum RMS Displacement (Inches) |
|---|---|---|---|---|---|
| North | 125 | 14.07 | .014 | .061 | $.69 \times 10^{-3}$ |
| North | 155 | 17.97 | .018 | .061 | $.54 \times 10^{-3}$ |
| South | 117 | 13.28 | .033 | .153 | $1.83 \times 10^{-3}$ |
| South | 160 | 18.75 | .014 | .046 | $.39 \times 10^{-3}$ |

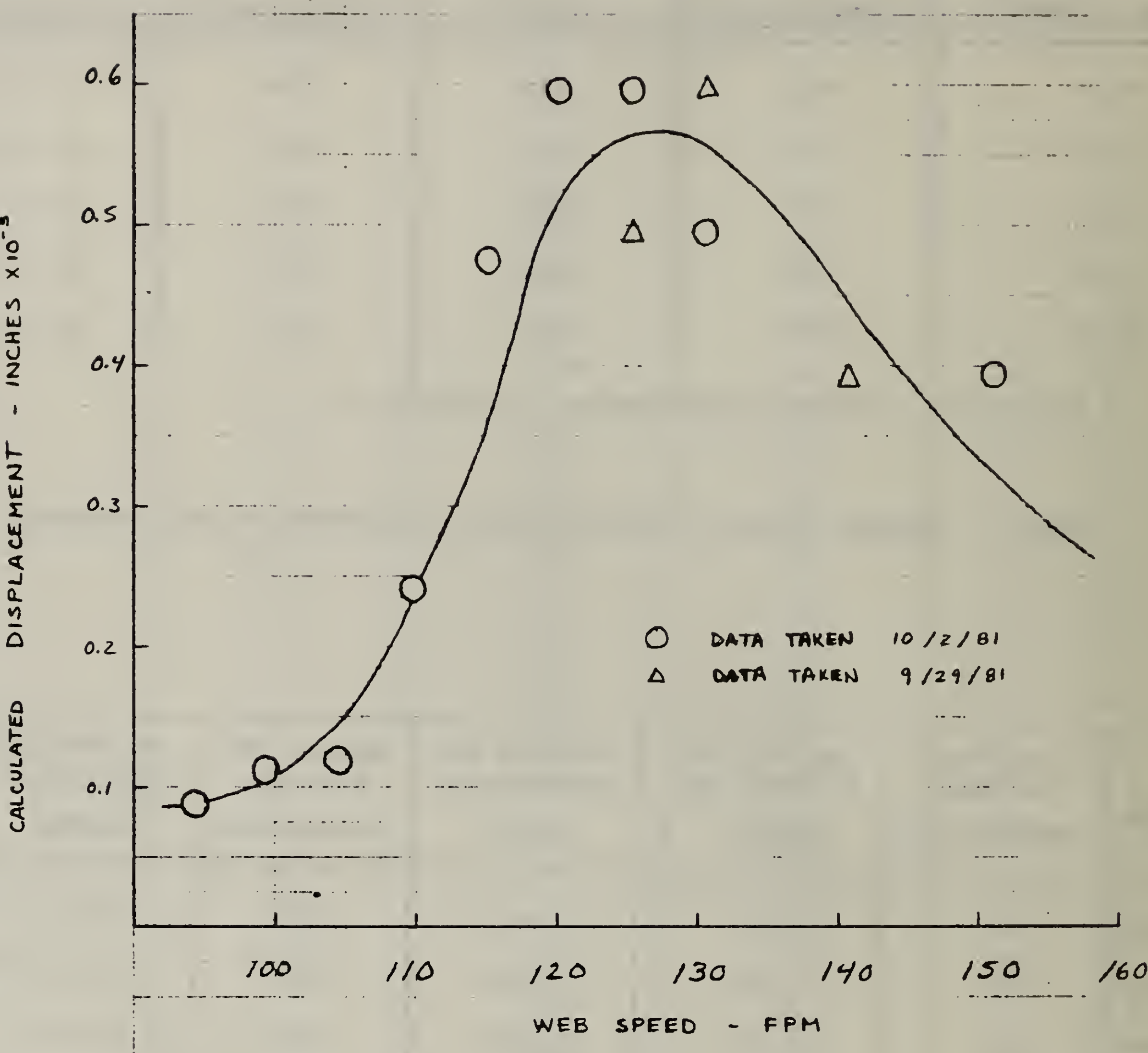



FIG. 1a: Estimated Vertical Floor Displacements of #1 Coiler/Perforator (North Machine) Provided by Bureau of Engraving and Printing Personnel.

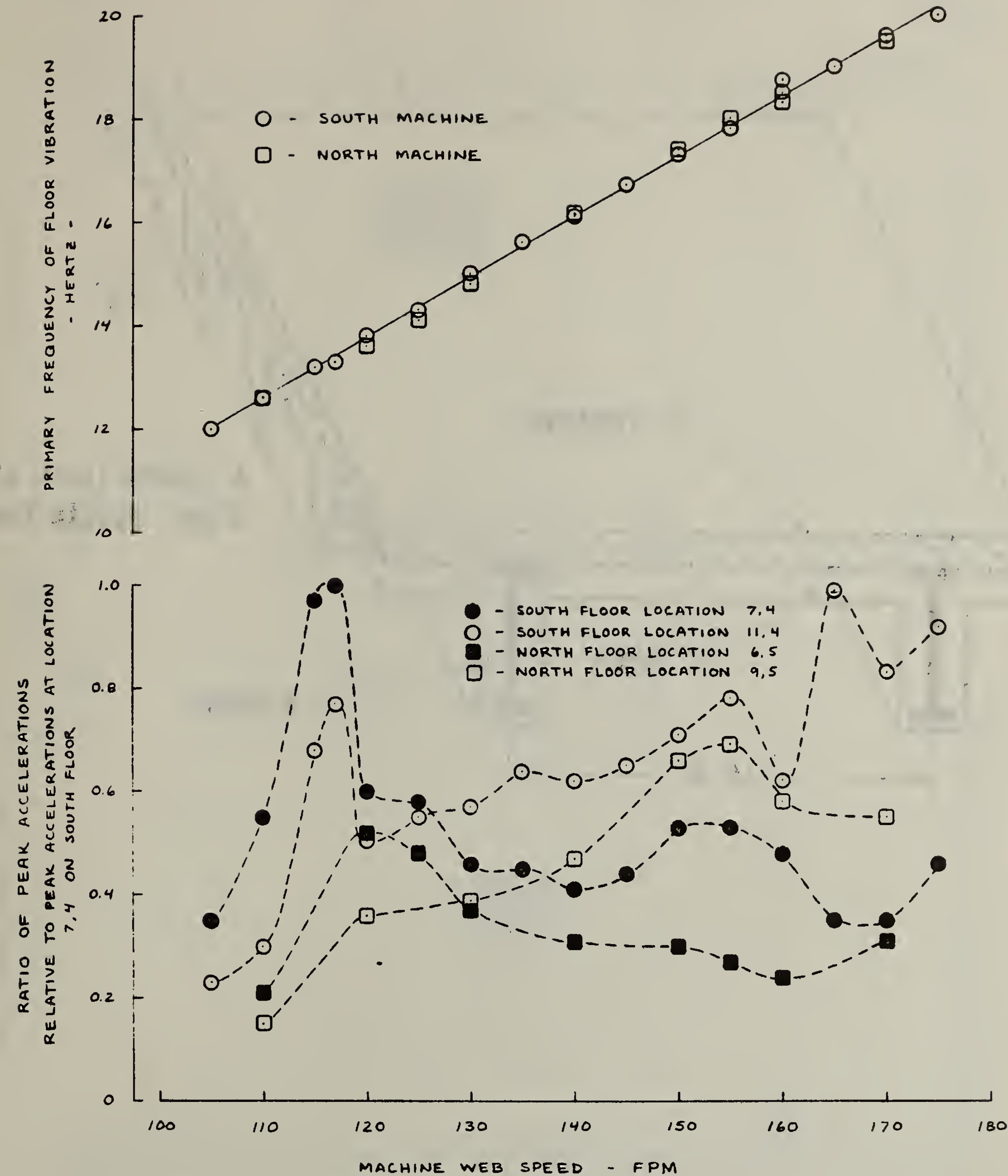



FIG. 1b: Relative Peak Accelerations of Primary Frequency of Floor Vibrations and Primary Frequency as a Function of Machine Web Speed.

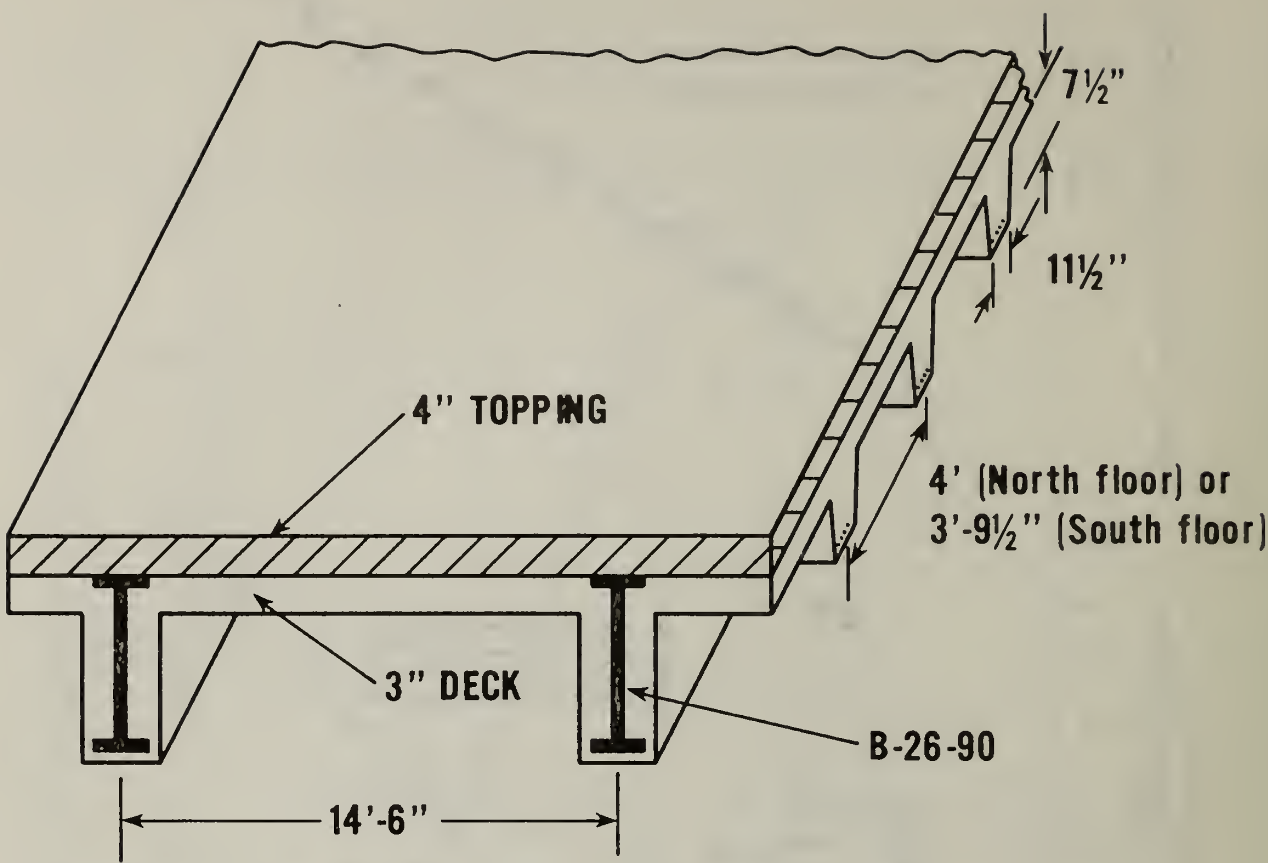



FIG. 2: Schematic Drawing of Typical
Floor System Segment.

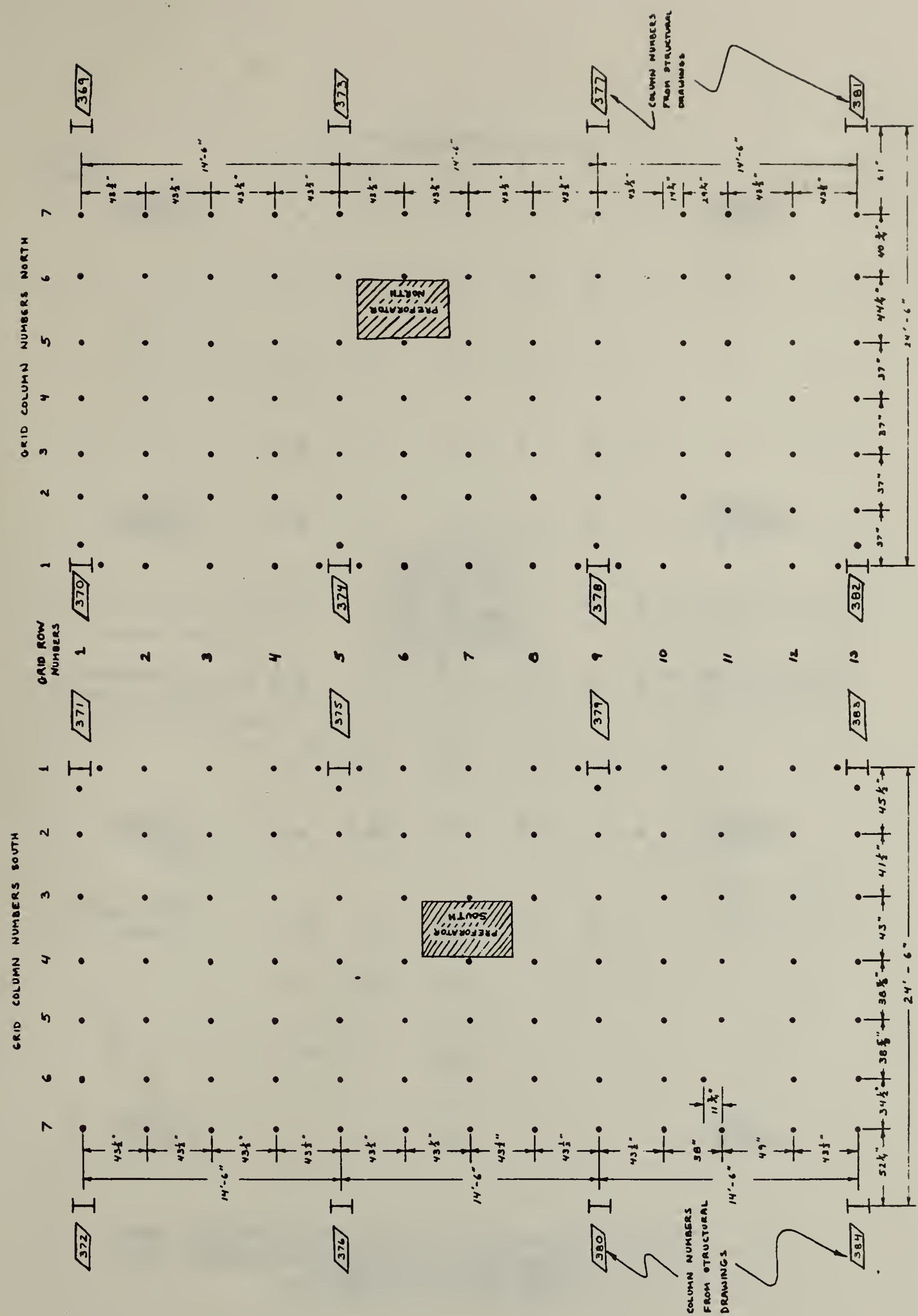



FIG. 3: Grid of Test Points (Dots indicate grid points).

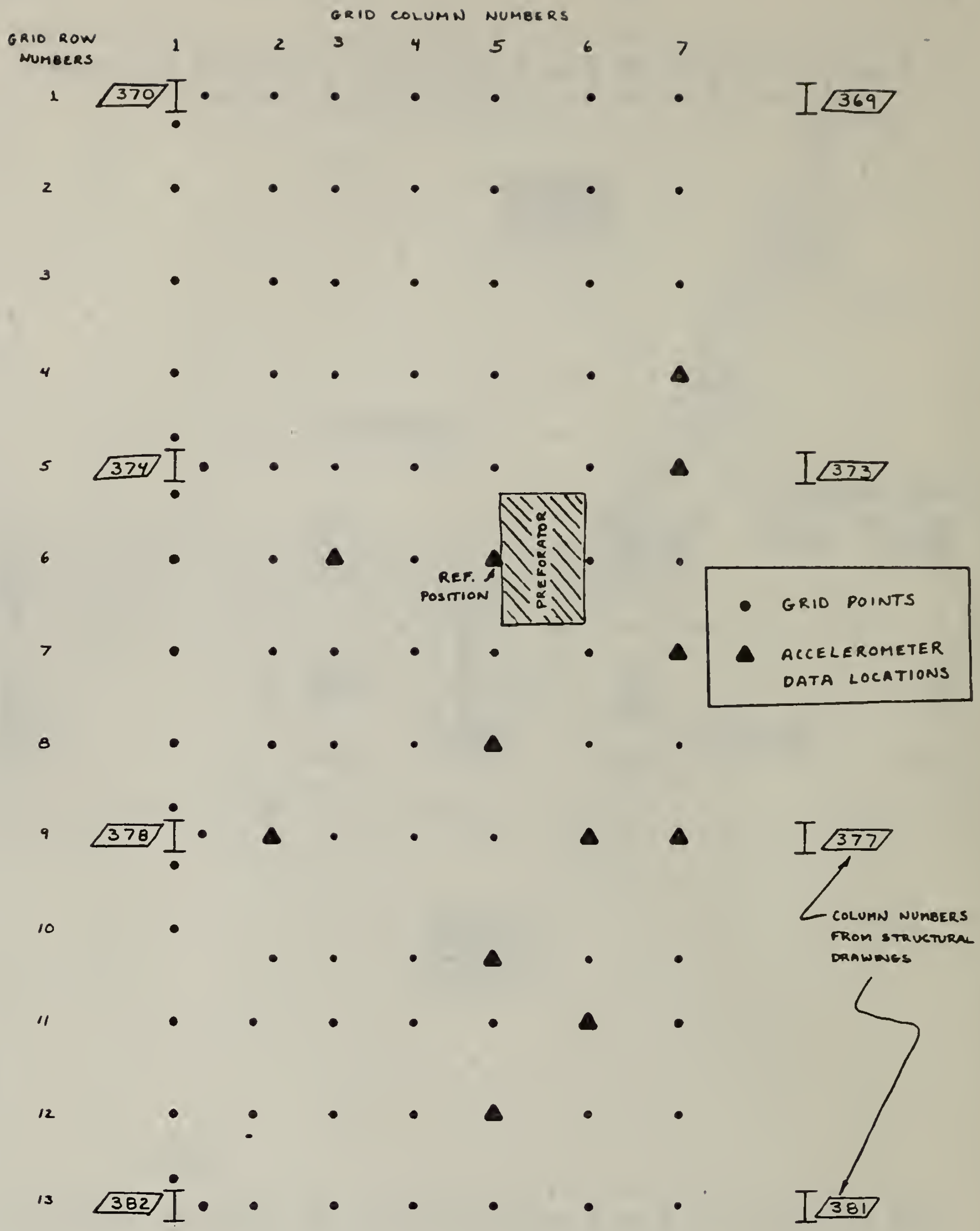



FIG. 4: Locations at which Vibration Data were Taken on North Floor with Machine Web Speed of 125 Feet/Minute.

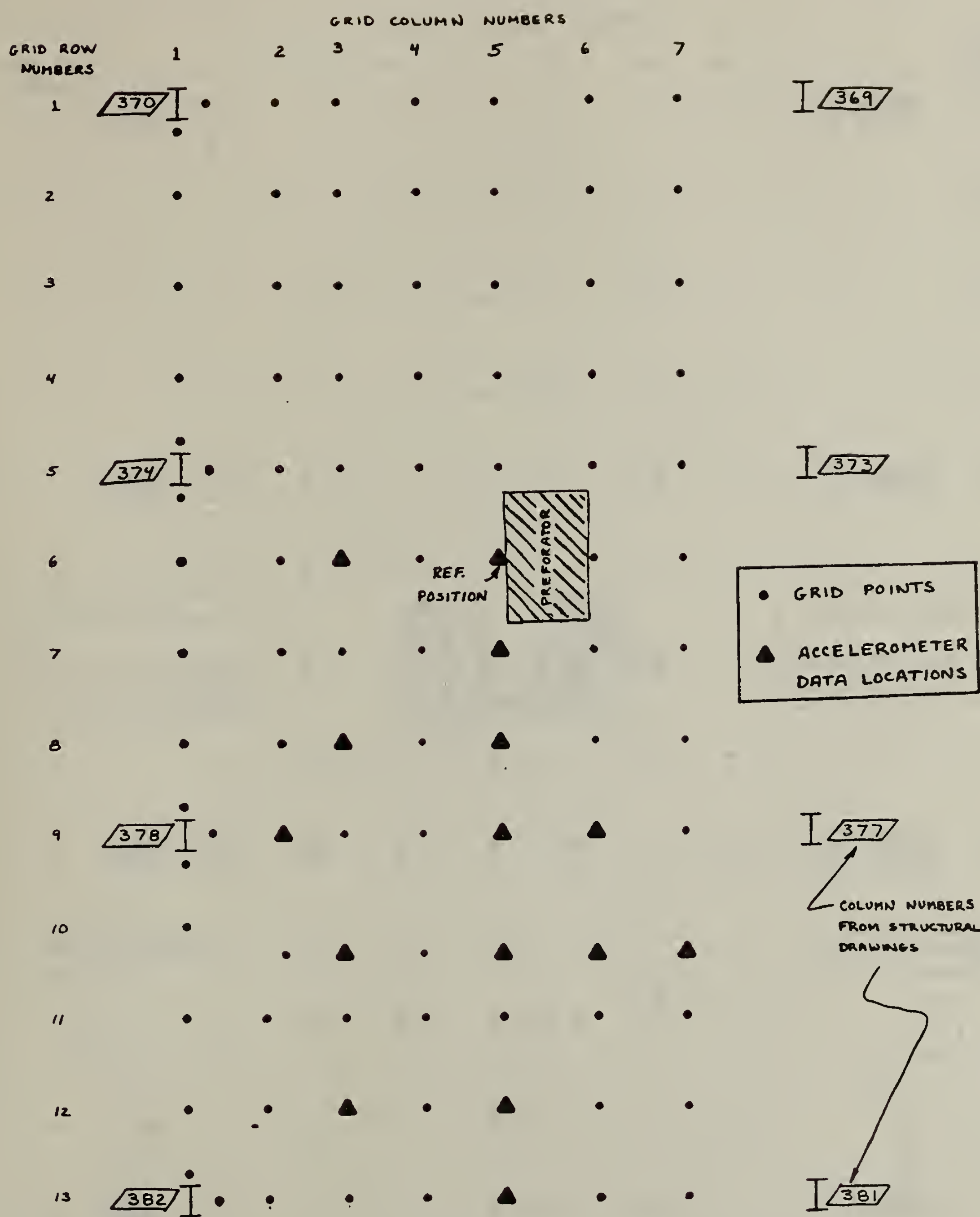



FIG. 5: Locations at which Vibration Data were Taken on North Floor with Machine Web Speed of 155 Feet/Minute.

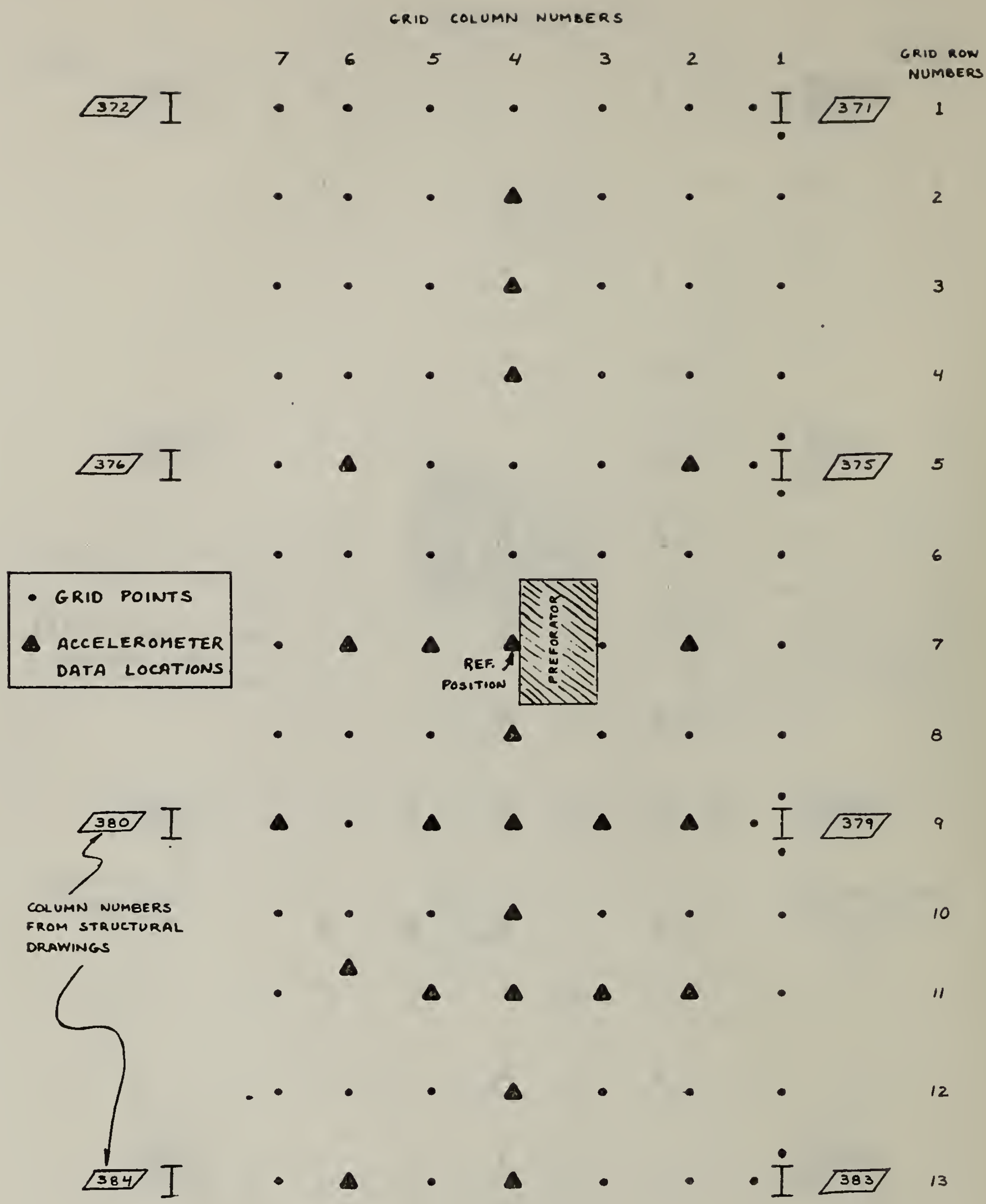



FIG. 6: Locations at which Vibration Data were Taken on South Floor with Machine Web Speed of 117 Feet/Minute.

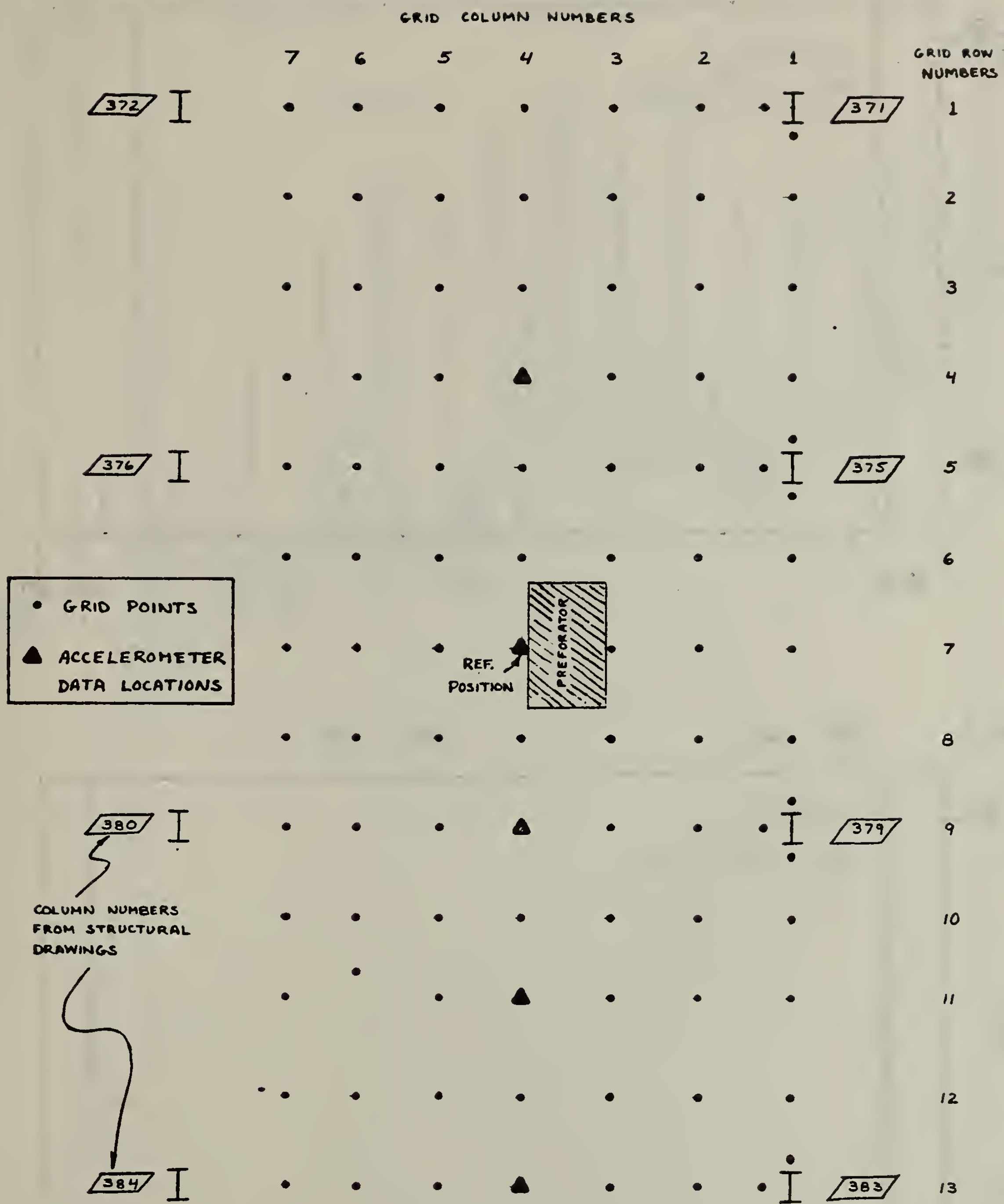
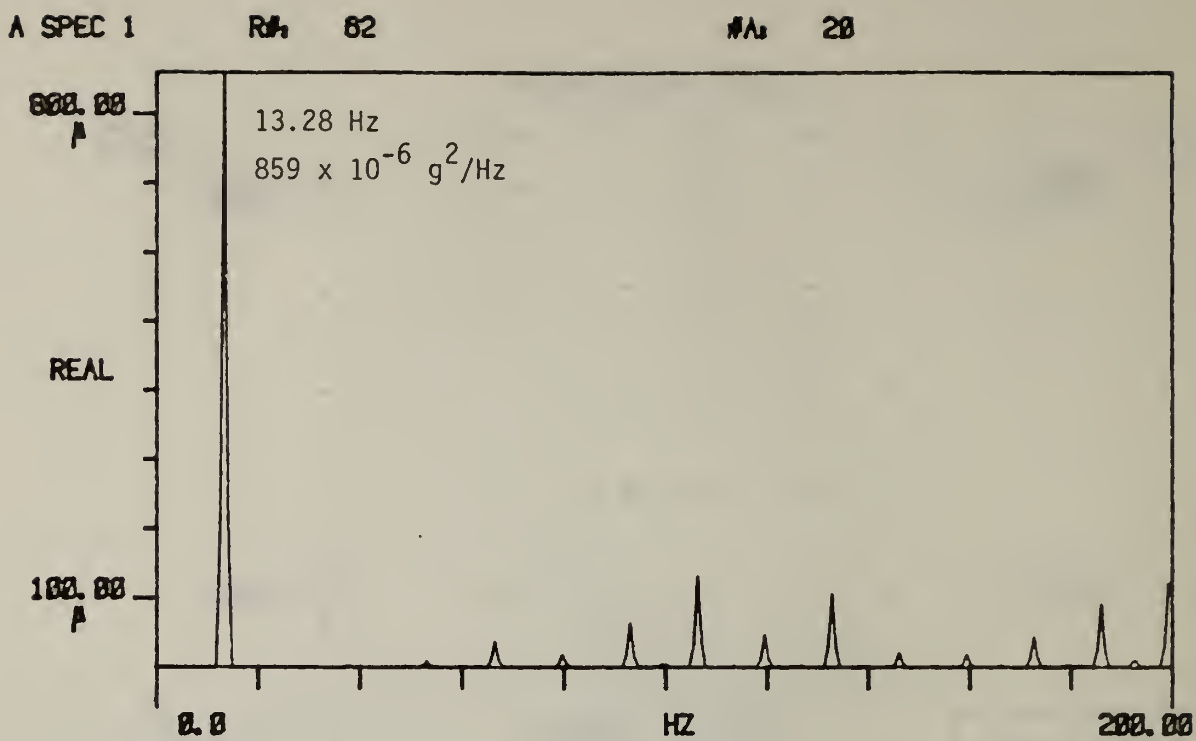



FIG. 7: Locations at which Vibration Data were Taken on South Floor with Machine Web Speed of 160 Feet/Minute.



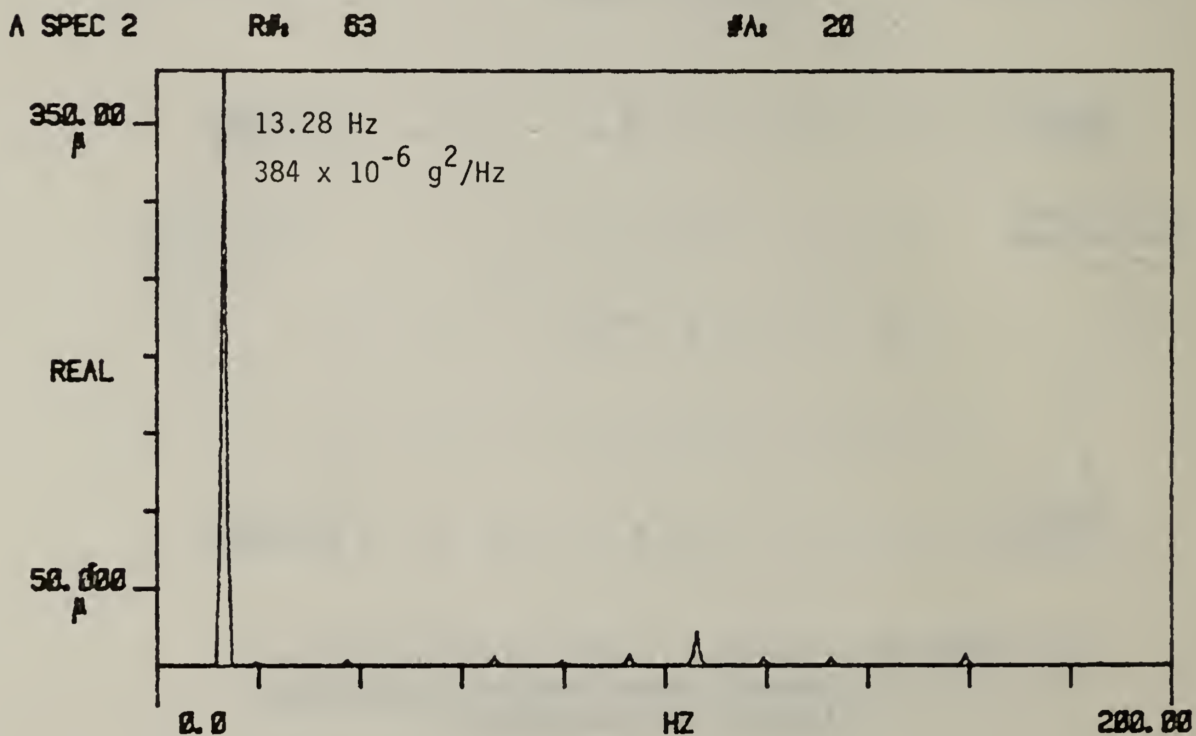




FIG. 8: Typical Power Spectra at Two Points Indicating Relative Magnitudes of Accelerations.

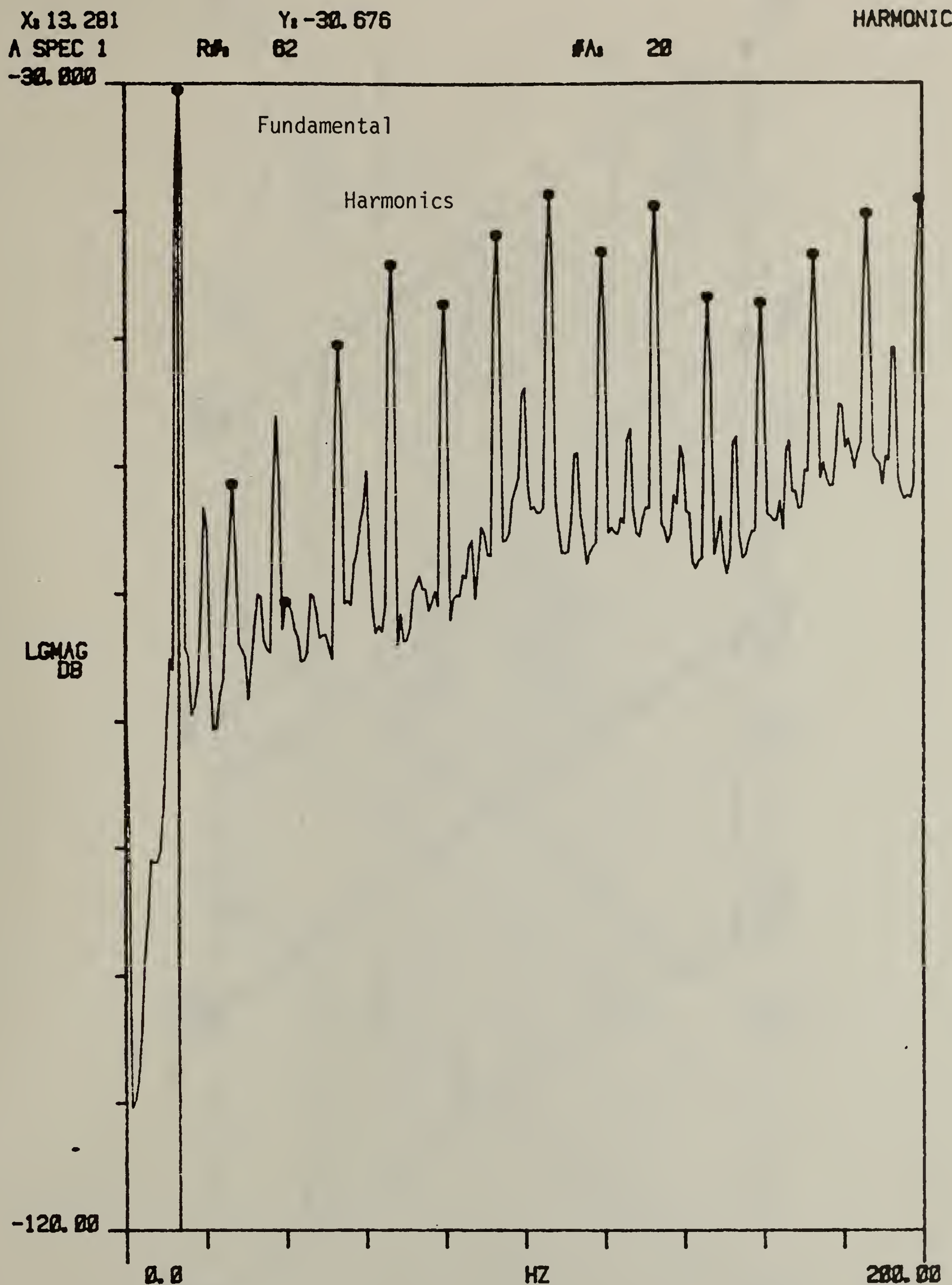



FIG. 9: Log-Plot of Typical Auto Spectrum with Resonant Frequency and Harmonics Identified.

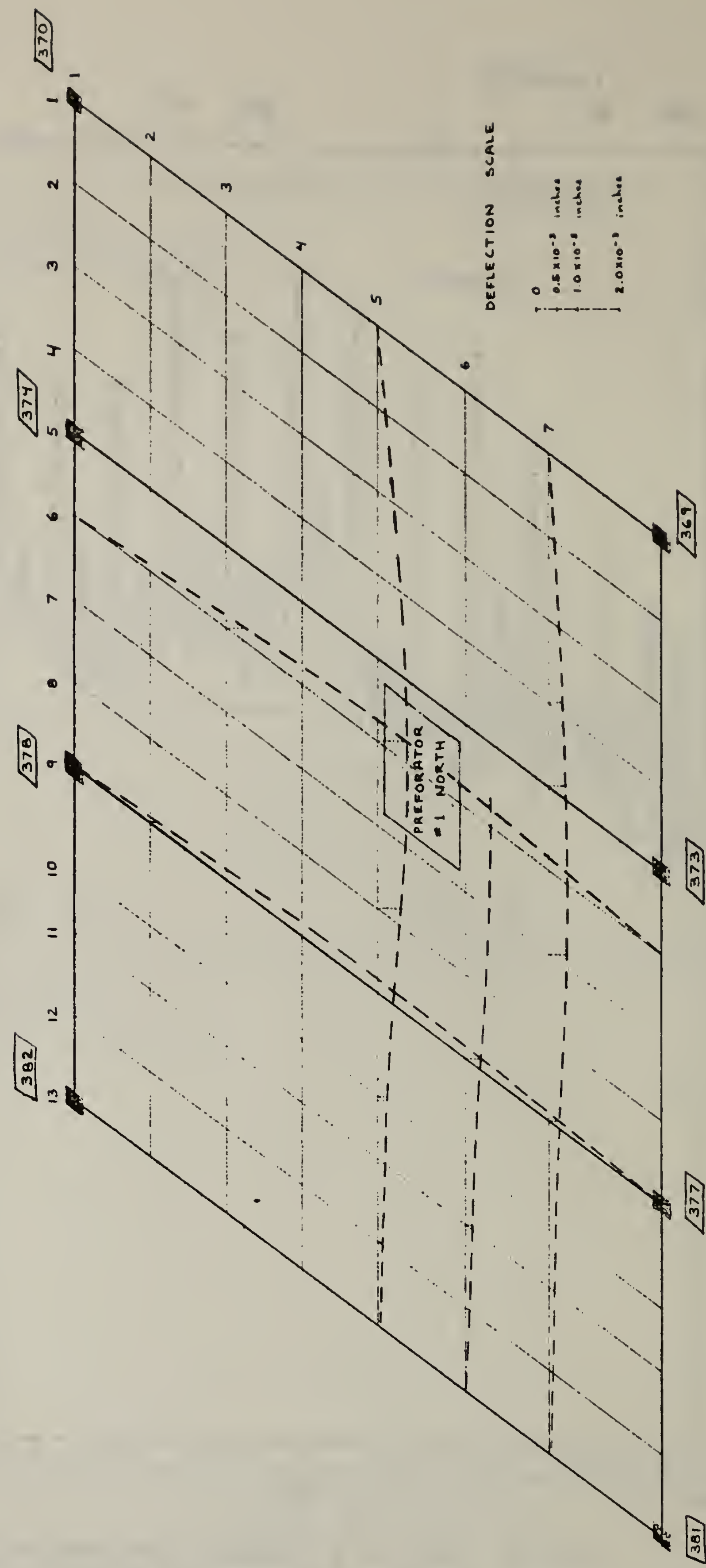



FIG.10: Mode Shape of North Floor Vibration at 14.07 Hertz with Machine Web Speed of 125 Feet/Minute.

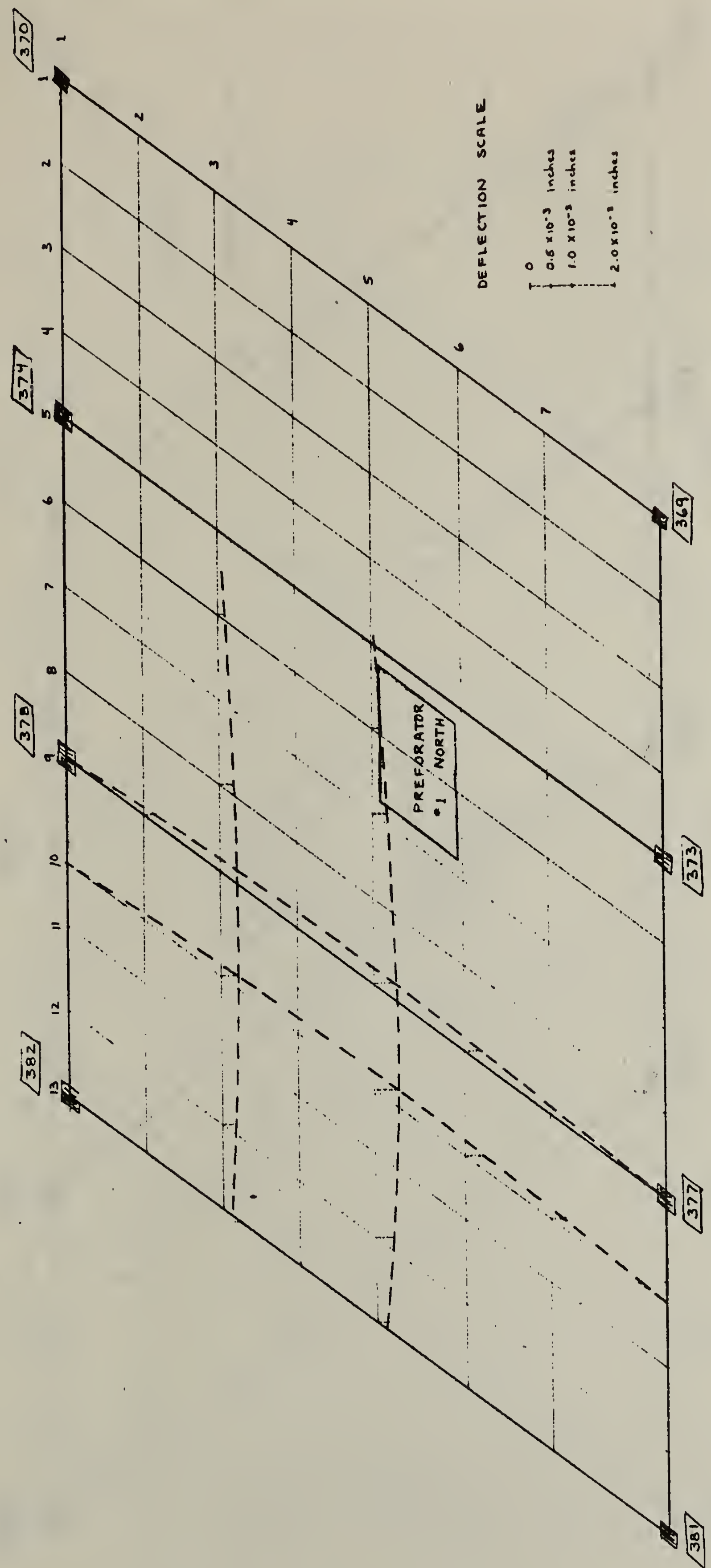



FIG. 11: Mode Shape of North Floor Vibration at 17.97 Hertz with Machine Web Speed of 155 Feet/Minute.

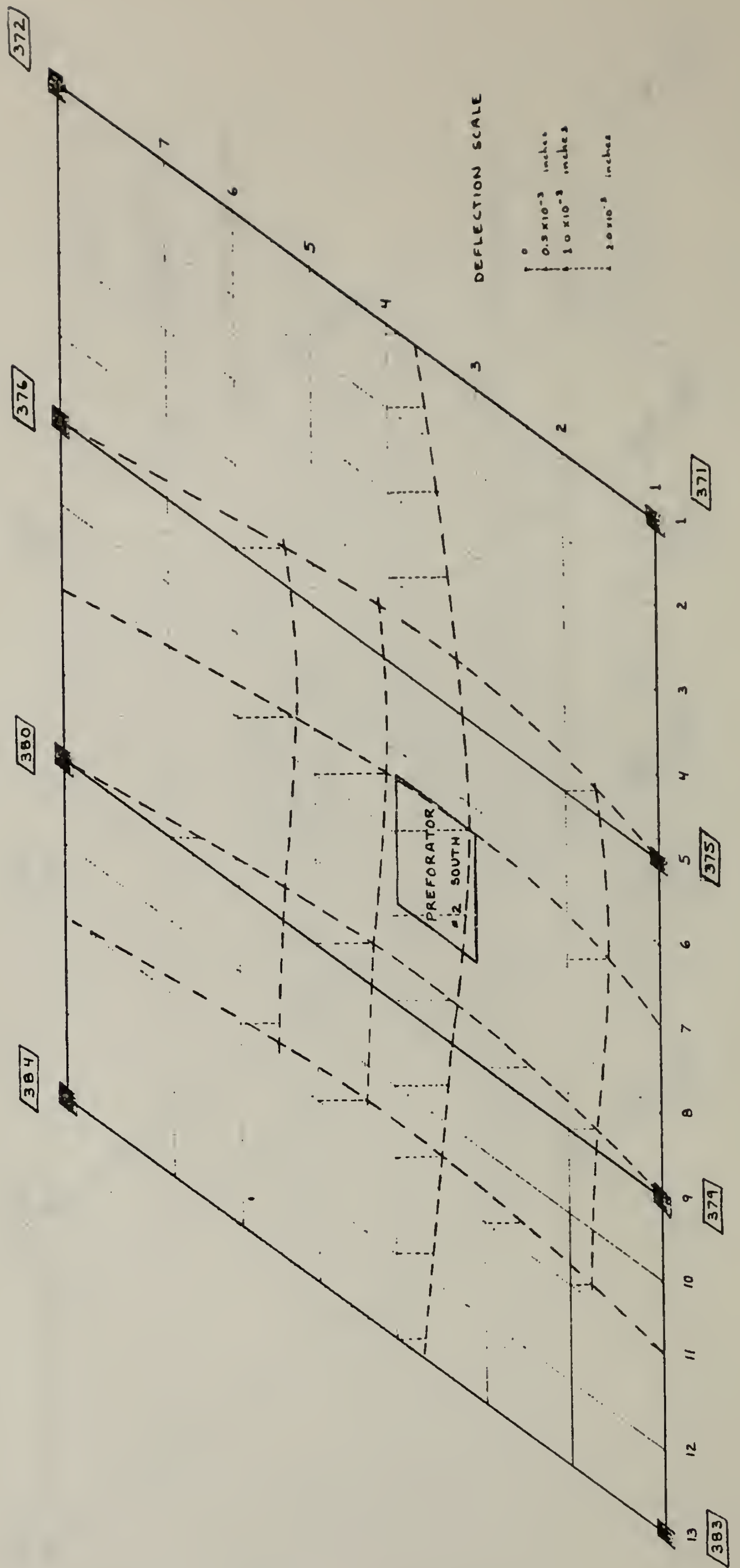



FIG. 12: Mode Shape of South Floor Vibration at 13.28 Hertz with Machine Web Speed of 117 Feet/Minute.

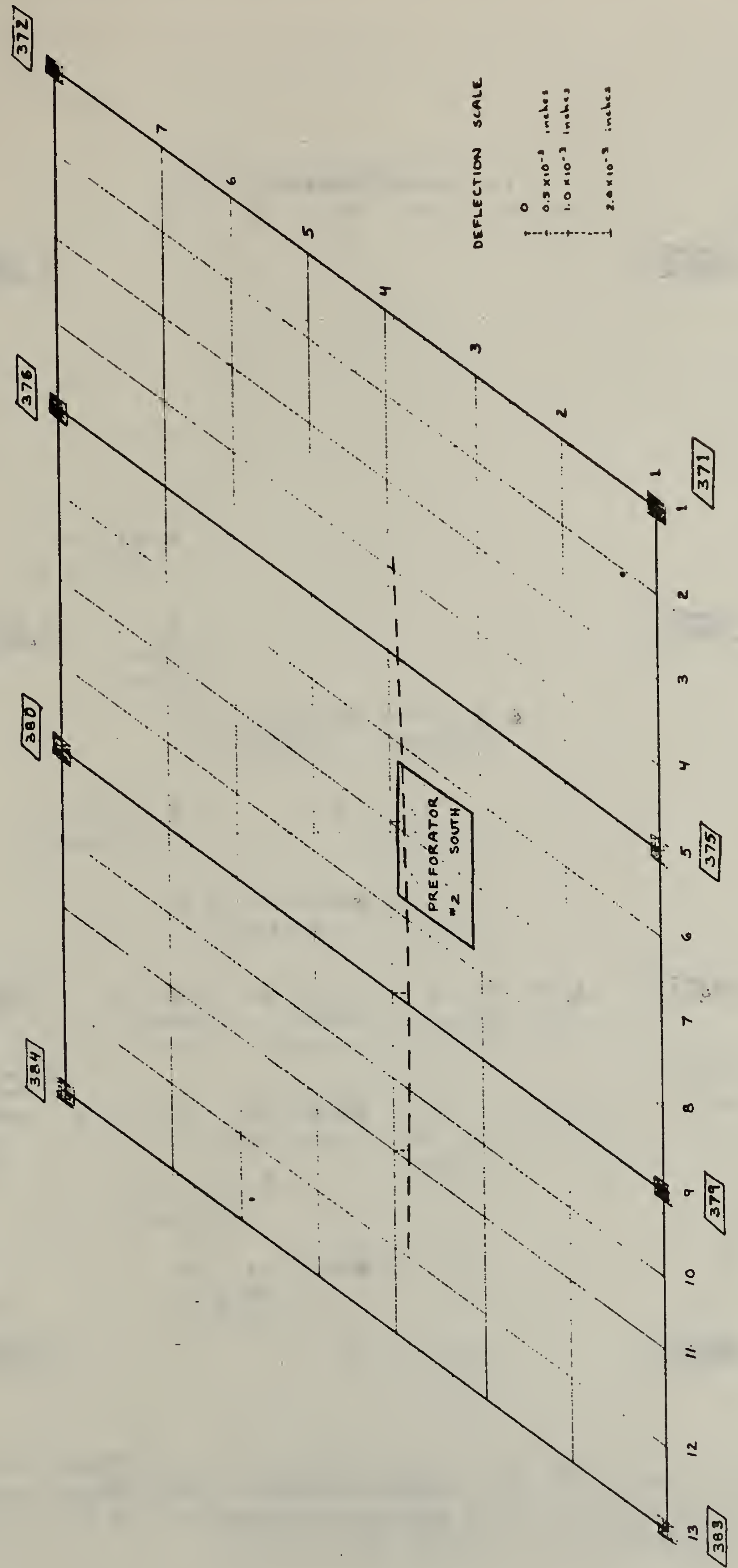



FIG. 13: Mode Shape of South Floor Vibration at 18.75 Hertz with Machine Web Speed of 160 Feet/Minute.

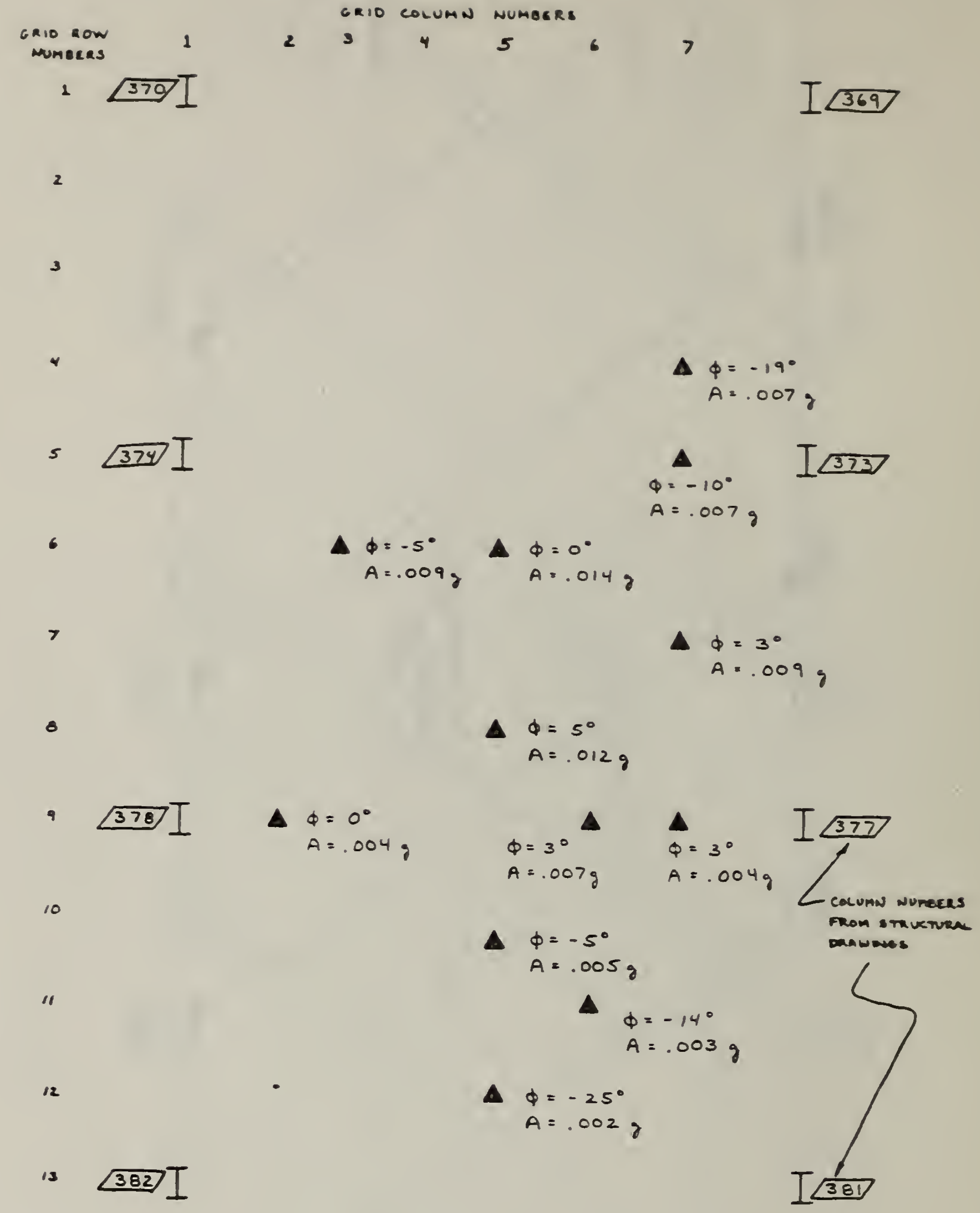



FIG. 14: Acceleration Data and Phase Relationships for North Floor Vibrations with Machine Web Speed of 125 Feet/Minute.

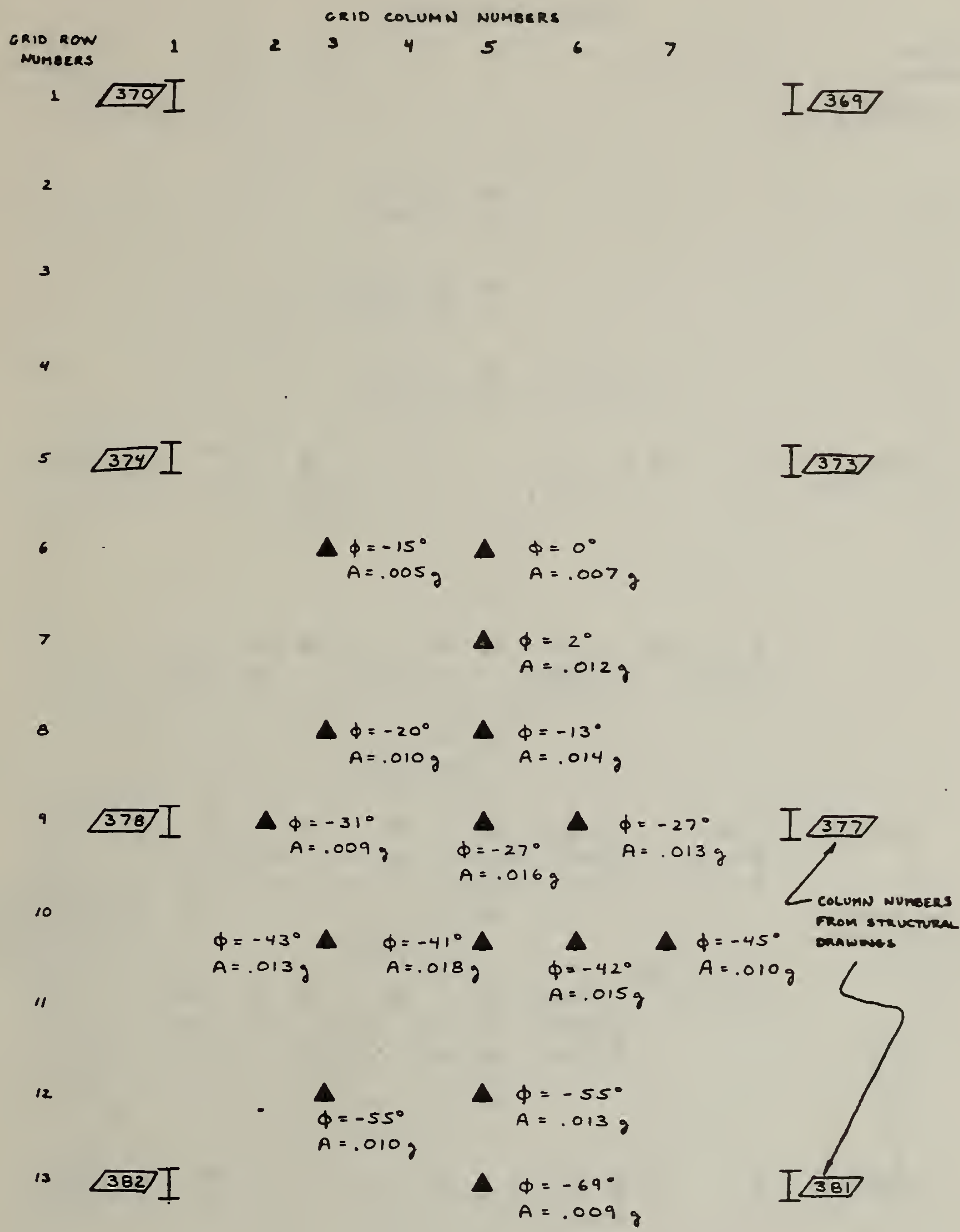



FIG. 15: Acceleration Data and Phase Relationships for North Floor Vibrations with Machine Web Speed of 155 Feet/Minute.

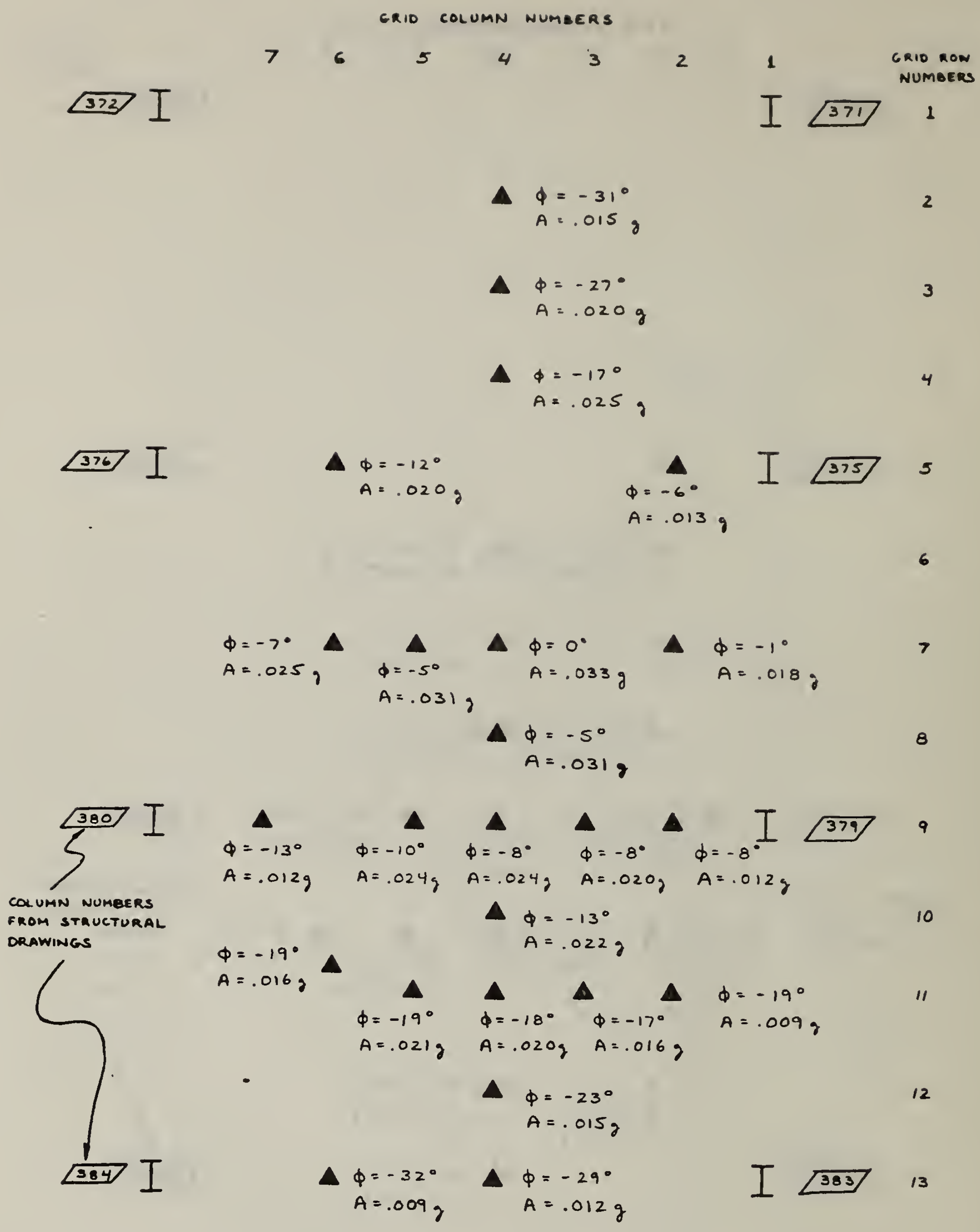



FIG. 16: Corrected Acceleration Data and Phase Relationships for South Floor Vibrations with Machine Web Speed of 117 Feet/Minute.

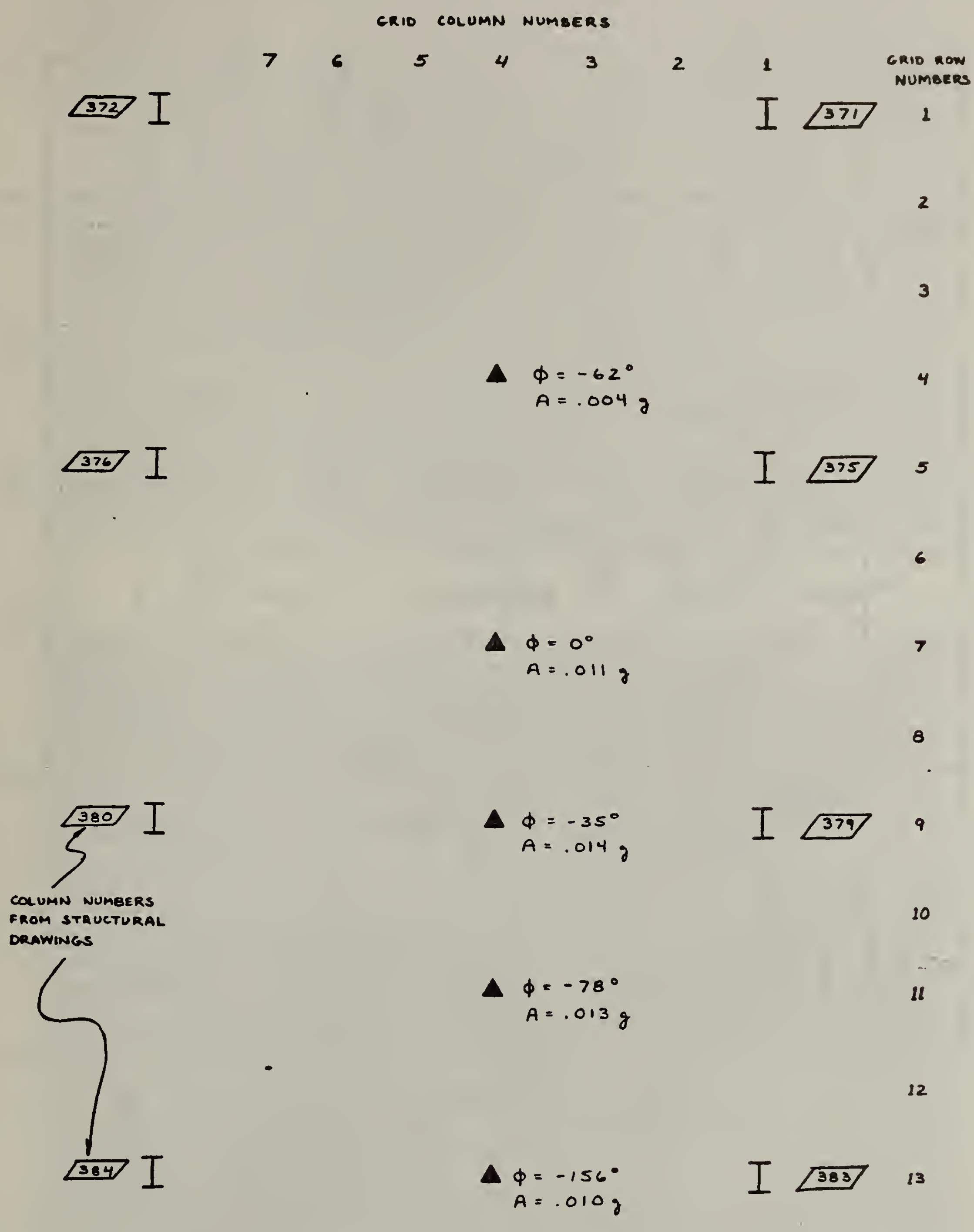



FIG. 17: Acceleration Data and Phase Relationships for South Floor Vibrations with Machine Web Speed of 160 Feet/Minute.

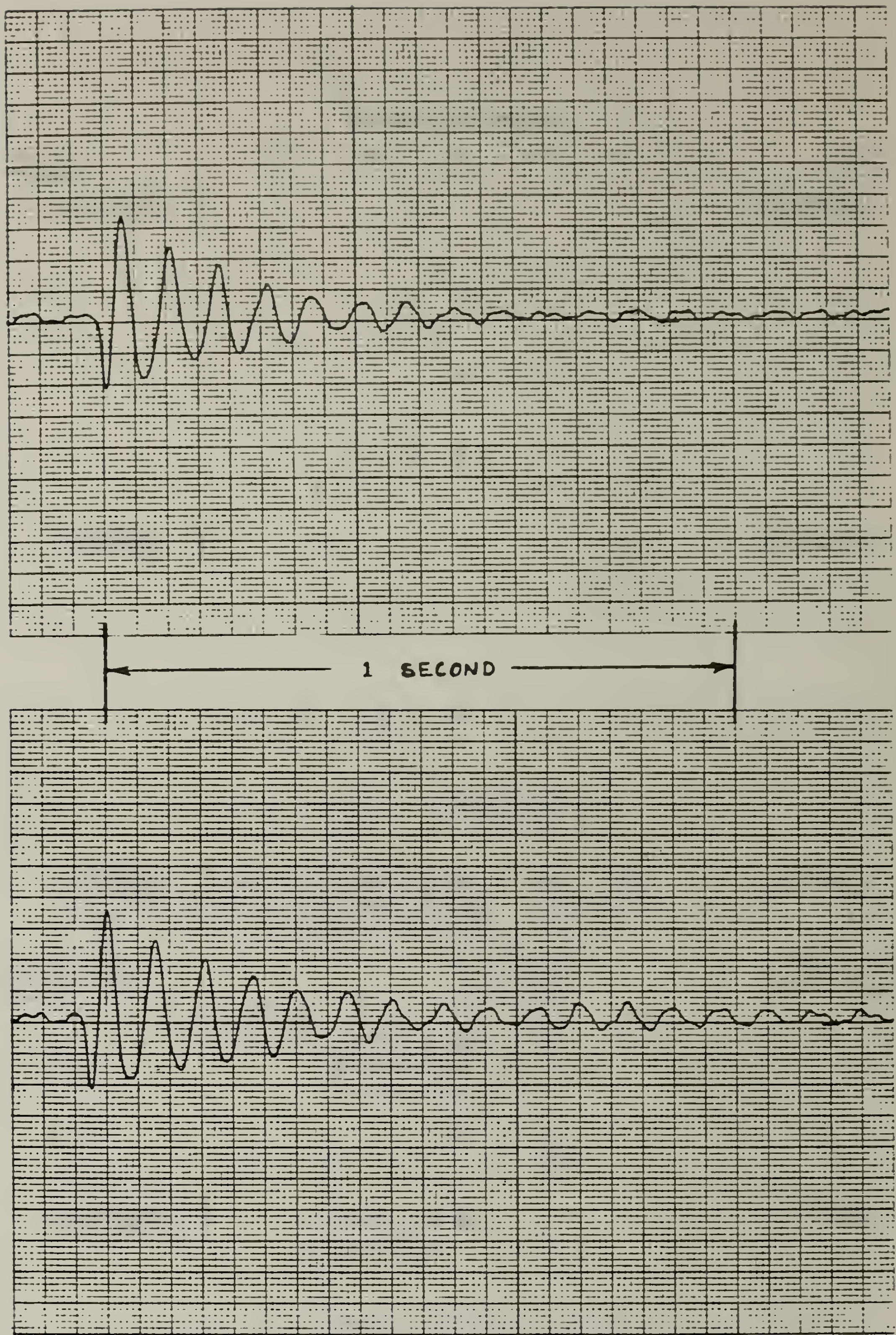



FIG. 18: Strip Chart Records of Acceleration Traces From Impact Tests at Locations 7, 4.

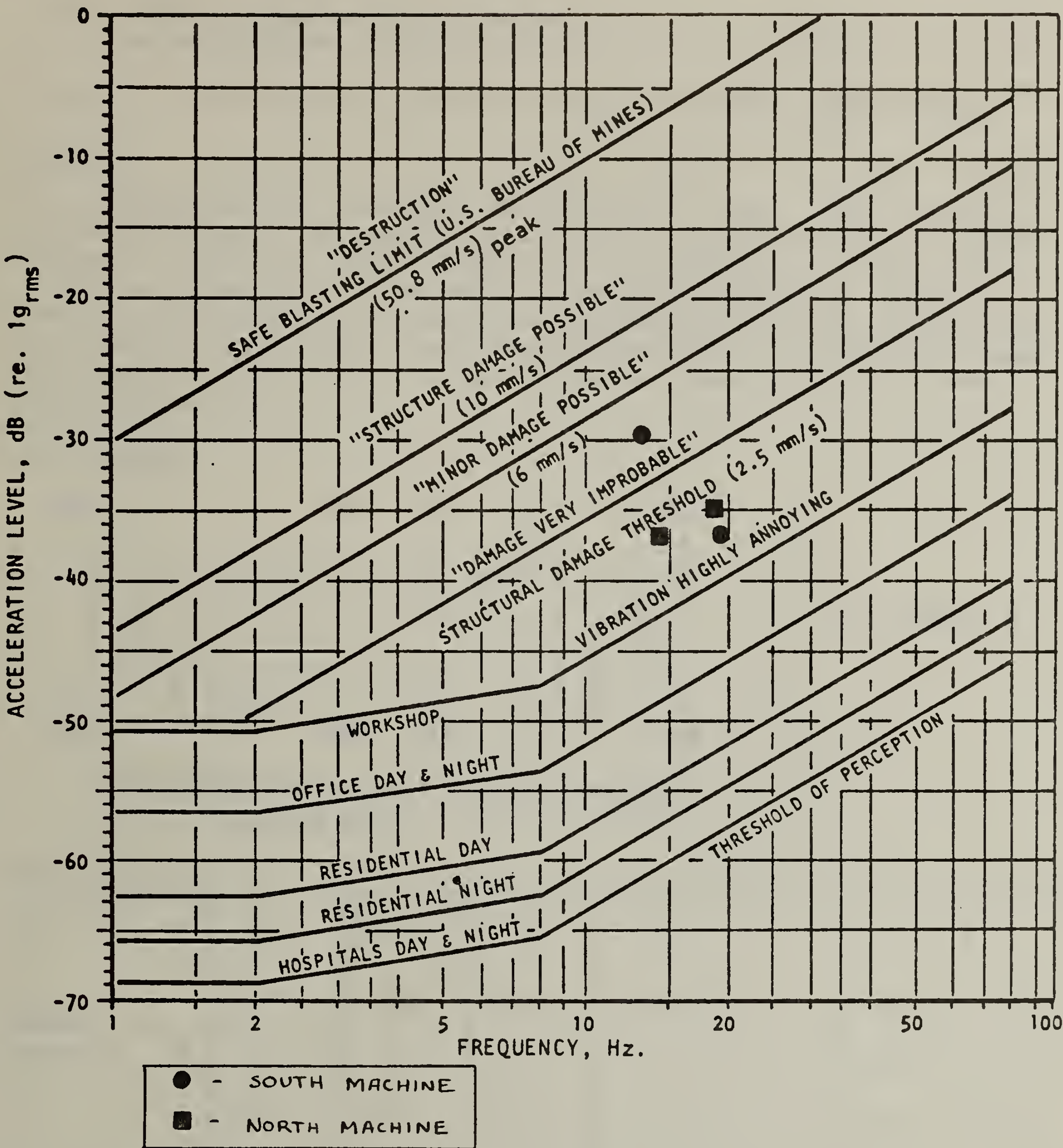



FIG. 19: Comparison of Maximum Measured Accelerations Against Empirical Criteria for Structural Vibrations Suggested in Reference 1.

MEMORANDUM FOR THE RECORDS OF THE INVESTIGATION OF MACHINE VIBRATIONS AT THE BUREAU OF ENGRAVING AND PRINTING

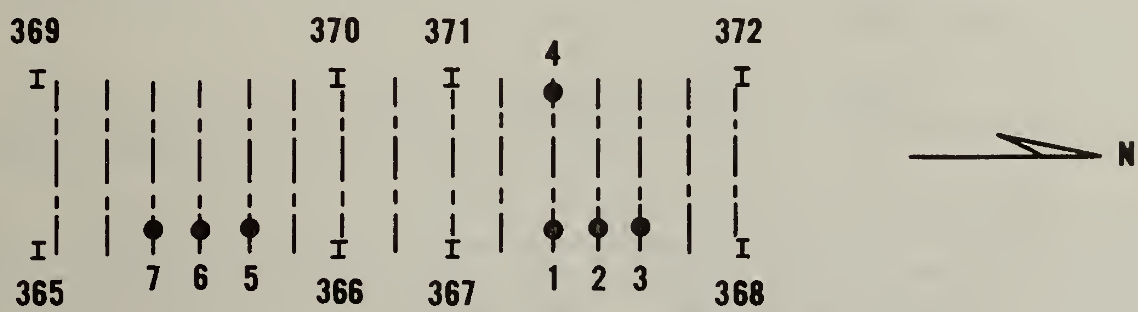
From: Felix Y. Yokel and Erik Anderson
Geotechnical Engineering Group, 741.05

Subject: Investigation of Concrete Strength by Schmidt Rebound Hammer

General:

The investigation was carried out on December 17, 1981. Tests were made on the underside of the concrete joist of the first floor near the joist supports. Test locations are shown in the attached sketch. The test locations are identified in the sketch by numbers 1 through 7. Column locations are identified by their reference numbers in the construction plans. The concrete surfaces where tests were conducted were cleaned by the Bureau of Engraving and Printing personnel with a wire brush in order to remove whitewash and dirt.

Test Results:




**Note: Numbers denote column locations designated in the building plans.**

| Test Location | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Hammer Readings | 39 | 47 | 36 | 38 | 39 | 45 | 53 |
| | 39 | 40 | 25 | 38 | 42 | 45 | 48 |
| | 39 | 37 | 25 | 38 | 40 | 46 | 44 |
| | 39 | 45 | 33 | 36 | 40 | 36 | 42 |
| | 39 | 39 | 31 | 41 | 40 | 42 | 38 |
| | 40 | | 24 | 35 | 37 | 42 | 43 |
| Avg. Reading | 39 | 42 | 29 | 38 | 40 | 43 | 45 |

Approximate Concrete Strength, PSI

| Test Location | Approximately $f'_c$, psi 1/ |
|---|---|
| 1 | 3,800 ± |
| 2 | 4,200 ± |
| 3 | 1,260 ± |
| 4 | 3,300 ± |
| 5 | 3,900 ± |
| 6 | 4,500 ± |
| 7 | 5,100 ± |

Approximate Concrete Strength for the Average of All 41 Readings:

$f'_c = 3,800$

---

1/ Strengths were calculated in accordance with calibration curves of the manufacturer.

2/ Even though numerous investigations have shown that there is a correlation between compressive strength of concrete and rebound readings, there is considerable disagreement on the accuracy of prediction (refer to NBSIR 80-2163, "Nondestructive Evaluation Methods for Quality Acceptance of Hardened Concrete in Structures," by James R. Clifton and Erik D. Anderson). Mitchel and Hoagland (Highway Research Bulletin 305, 1961) found that the difference between estimated strengths based on rebound readings and measured concrete strengths averaged 18.8% under controlled conditions. Hammer readings are affected by smoothness of surface, moisture content of concrete, type of coarse aggregate, rigidity of specimen, and carbonation of the concrete surface.

NBS-114A (REV. 2-80)

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|---|---|---|---|

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**5. AUTHOR(S)**

T. A. Reinhold, F. Y. Yokel and F. F. Rudder

**6. PERFORMING ORGANIZATION** *(If joint or other than NBS, see instructions)*

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Washington, D.C. 20234

**10. SUPPLEMENTARY NOTES**

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

**11. ABSTRACT** *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

Floor vibrations induced in a Bureau of Engraving and Printing building by a recently-installed perforator were investigated by measuring relative acceleration amplitudes and phase relationships between a reference position and points on a grid laid out on the affected floor. From these measurements, it was possible to determine mode shapes, resonant frequencies and displacement amplitudes. On the basis of the displacement amplitudes, anticipated cyclic stresses in the structural system were estimated. The results of the measurements and analysis were compared with existing data on vibration-induced structural damage and fatigue strength of steel and reinforced concrete. Damping ratios were also determined in a separate test, in order to ascertain at later dates whether any structural deterioration is taking place.

**12. KEY WORDS** *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

cyclic strength; fatigue; floor vibrations; machine foundations; reinforced concrete; steel; structural engineering

**13. AVAILABILITY**

☒ Unlimited
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