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# A NEW METHOD FOR THE MEASUREMENT OF THE NATURAL PERIODS OF BUILDINGS

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## ABSTRACT

It is shown that the inertia force obtained by a man moving his body back and forth in synchronism with the natural period of vibration of a large structure is sufficient to build up a measurable amplitude of motion. By recording such structural vibrations versus time, the natural period and damping of several of the lower modes of vibration can be determined. The amplitudes of motion set up in this way are for many structures significantly larger than can be obtained from wind excitation, which has been used in the past for the measurement of the period of the fundamental mode.

## Introduction

The natural periods of vibration of a structure are perhaps the most significant dynamic parameters involved in response analysis. Not only are the numerical values needed for computations, but a comparison between experimentally determined values and calculated values is an important check on the validity of the simplified mathematical models which must of necessity be used in the analysis (Housner, 1962).

The importance of the fundamental natural period as an indication of the dynamic behavior of structures is emphasized by the introduction of this parameter into some modern earthquake-resistant building codes. The "Recommended Lateral Force Requirements" of the Structural Engineers Association of California (1960), for example, fixes the basic lateral force coefficient to be used in design by a formula involving the fundamental natural period.

An additional reason for an interest in these natural periods is the belief that concealed structural damage such as might occur during a strong earthquake might significantly alter the fundamental period, and hence period measurements before and after an earthquake might reveal such hidden damage. Although there is some evidence from past measurements that significant period shifts have been caused by earthquakes, the presently available data are not sufficient to arrive at any definite conclusion. It is important that period measurements be made on existing structures so that, should an earthquake occur, the basic data will be available for comparison. At present, accurate period data is at hand for only a very few buildings.

## Experimental Methods

The experimental methods that have been used for period measurements of full-scale structures are: (1) resonance testing, using a variable frequency sinusoidal vibration generator; (2) free vibration decay tests, excited by initial displacements or velocities; (3) wind-excited forced vibration tests, using the very small amplitudes set up by natural gusts.

The first two types of tests require relatively elaborate equipment, and in practice it is seldom possible to secure permission to make such tests in buildings. The wind-excited tests can be quickly carried out without the installation of any equipment in the building, it being only required to temporarily place a portable seismograph in an upper story position.

The difficulties with the wind-excited tests are: (1) suitable natural gusts may not always be available; (2) very low amplitude levels are set up, and thus some structural elements may not be brought into action in a typical way; (3) since the form of the exciting force is not known, no information on structural damping can be deduced from the record; and (4) usually only the fundamental mode of vibration will have an appreciable motion, and thus no information on the higher modes is obtained. In spite of these defects, the simplicity of the test, and the fact that it is the only possibility for most buildings, has given it an important place in structural dynamic investigations. A considerable amount of such data was collected in the early 1930's by the United States Coast and Geodetic Survey and reported in the publication "Earthquake Investigations in California" (1936). At the present time the United States Coast and Geodetic Survey is reactivating and enlarging this period measuring program with improved instrumentation.

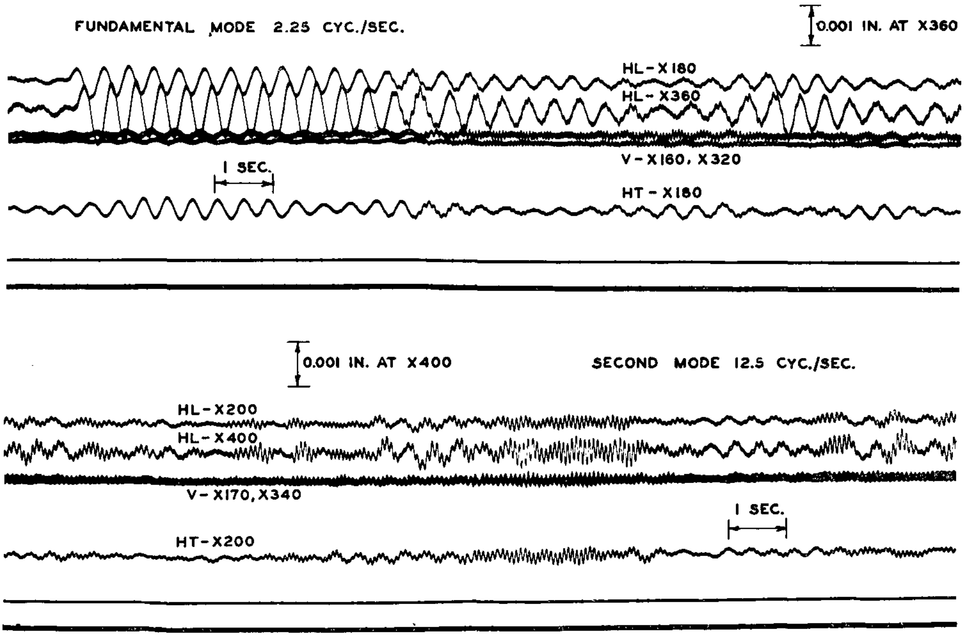


FIG. 1. Sample records of wind-excited tower vibrations.

As an example of the results that can be obtained with such wind-excited tests, figure 1 shows measurements made on a 100 ft high concrete intake tower of a dam. (Keightley, Housner, and Hudson, 1961). This test was unusual in that a second mode of vibration was also clearly excited during part of the record, and hence the first two periods of vibration could be determined. The records of figure 1 were obtained on a photographically recording portable seismograph having a natural period of about 2 seconds and a magnification of approximately 400.

There is a possibility that some information on structural damping could be extracted from a wind-excited vibration record such as fig. 1 if some data on the input force could be obtained. If, for example, the exciting force power spectrum could be simultaneously measured, something might then be deduced about the damping. This does not seem to be feasible in practice, however, because of the large size of the structures involved, which would require that the input wind forces be simultaneously measured at a number of points to arrive at the integrated exciting force.

## A New Method of Excitation

During some wind-excited tests of a 150 ft high concrete intake tower, it was noted that a considerable deflection of the seismograph recorder could be set up by the operator jumping laterally at the top of the tower. This suggested that the small inertia force generated by the operator himself, if it were properly synchronized with the natural period of the tower, might be sufficient to build up a measurable resonant vibration. With a little practice it was found that this was indeed the case. By keeping one eye on the seismograph recorder to observe the way the vibrations were building up, an operator with an ordinary sense of rhythm could by periodic motions of his body produce considerably larger amplitudes of motion at the fundamental period than had been produced by the wind. Figure 2 shows the record obtained in this way on the 150 ft high concrete intake tower using the same seismograph that was used for figure 1.

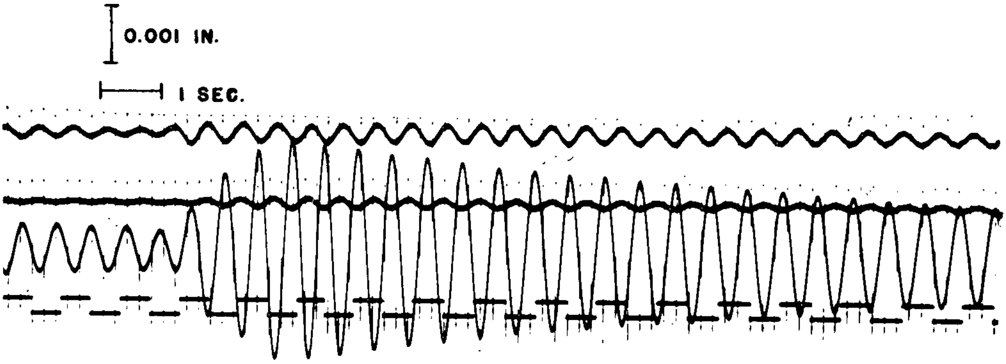


FIG. 2. "Man-excited" vibrations of 150 ft. high concrete intake tower of dam.

It was immediately evident that this method of excitation had three important advantages over the wind-excited force: (1) larger amplitudes of motion could be built up at a definite period; (2) the test could be carried out at any time, in the presence or absence of wind; and (3) in the absence of wind, by stopping the exciting force after an appreciable motion had been built up, the decay of free vibrations could be recorded, and hence damping could be measured.

A vibration of the above kind is in one sense a "self-excited" vibration. Since this phrase, "self-excited", is already used in mechanics for a rather different phenomenon in which the forces sustaining the motion are derived from the motion itself, it might be better to refer to this particular type of forced vibration as a "man-excited" motion. This method of excitation naturally recalls the old stories often mentioned in mechanics lectures of bridges destroyed by marching armies, and the supposedly common rule that soldiers should break step when crossing a bridge.

At first thought it seemed unlikely that a sufficient exciting force could be obtained in this very simple way to be useful for large structures such as multistory buildings. However, it turns out that it is just for such large structures with their relatively low natural frequencies that the method is most useful. As will be shown by some specific examples, it is often possible in multistory buildings to achieve an amplitude far exceeding that obtained from the wind.

The essential feature in producing a significant "man-excited" vibration is to insure that the center of mass of the body moves with as large as possible amplitude at a reasonably constant frequency. One effective technique is to stand facing perpendicular to the direction of excitation and then to sway the body sideways, shifting the weight from one leg to the other. Another technique is to hold a column or door-jamb, and then move the body backward and forward, transmitting the force to the structure through the arms and legs. Other interesting possibilities, perhaps involving the synchronized efforts of several people, will suggest themselves.

An idea as to the magnitude of the force generated in this way can be gained by supposing that the center of mass of a 150 lb man is moved sinusoidally through a double amplitude of 6 in. at a frequency of 1 cps. This would produce an inertia force magnitude of 46 lb. Considering that a structure having 1 % of critical damping has a dynamic amplification factor at resonance of 50, such force magnitudes can easily produce measurable displacements.

Returning to fig. 2, it is of interest to note how quickly the vibration amplitudes build up at resonance. Only four cycles of motion were required to bring the amplitude to a large value, from which a clear free vibration decay record was obtained. From this decay curve, the damping can be calculated to be less than 1 per cent of critical. The values of period and damping obtained in this way were subsequently found to be in good agreement with those calculated from resonance curves determined with a sinusoidal vibration generator installed at the top of the tower.

At this stage in the investigations, a new portable seismograph became available which proved to be particularly well suited to such tests. Through the courtesy of the Seismological Laboratory of the California Institute of Technology, an experimental model of the "lunar seismometer" (Lehner *et al.*, 1962), along with a compact recording drum and pen recorder system, was borrowed for a number of building period tests. This lunar seismometer is a permanent magnet-moving coil type adjusted to a natural period of about 1 second. By means of a simple transistor amplifier, a 5 in. ink-recording pen can be driven at a maximum magnification of about 10,000 at 4 cps and about 1000 at 1 cps. A small recording drum of $3\frac{3}{4}$ in. diameter is operated at a recording speed of 1 cm/sec. The combination of large output, high gain variable over a large range, compactness, and ruggedness, makes this instrument very suitable for building period tests. Another important advantage is the pen-recorder, which not only gives an immediately visible record, but which has a relatively large mechanical moving element to watch, which assists in synchronizing the applied inertia force and the resonant vibrations.

## TESTS ON BUILDING FRAMES

The first tests with the lunar seismograph were made on a five-story reinforced concrete frame building in course of construction. Figure 3 shows typical records from which both the fundamental natural period and the damping can be obtained as given. These values were later checked against resonance curve calculations from steady state sinusoidal vibration generator tests with a satisfactory agreement.

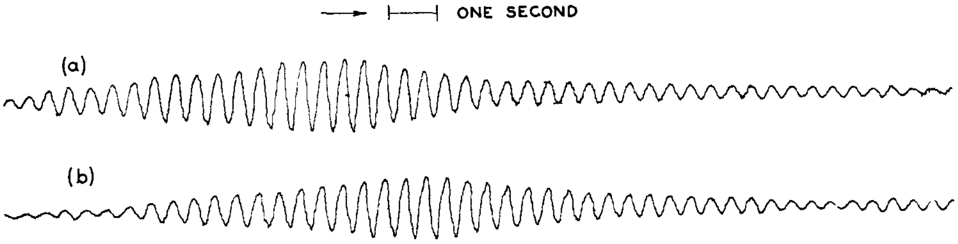


FIG. 3. "Man-excited" vibration of five-story reinforced concrete frame building. Fundamental mode 2.36 CPS; damping ≈ 1.8% critical.

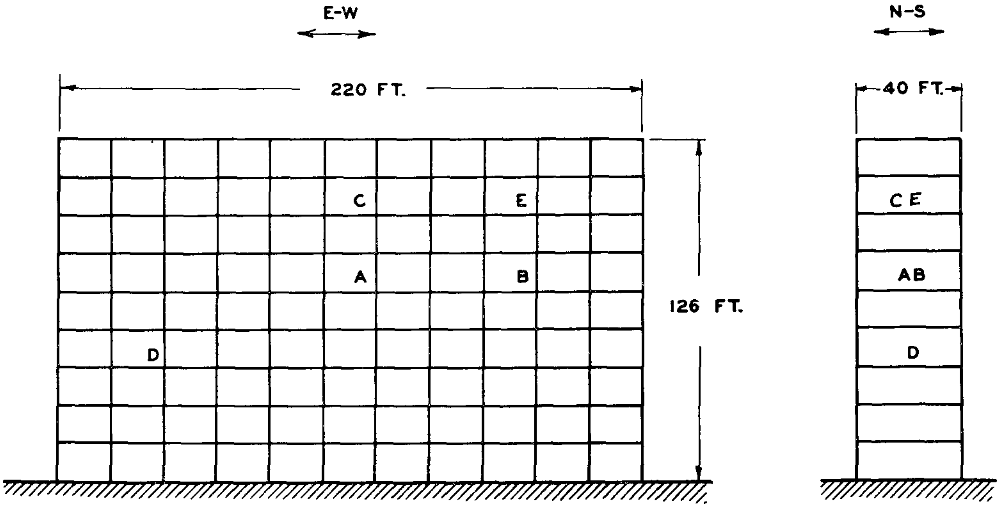
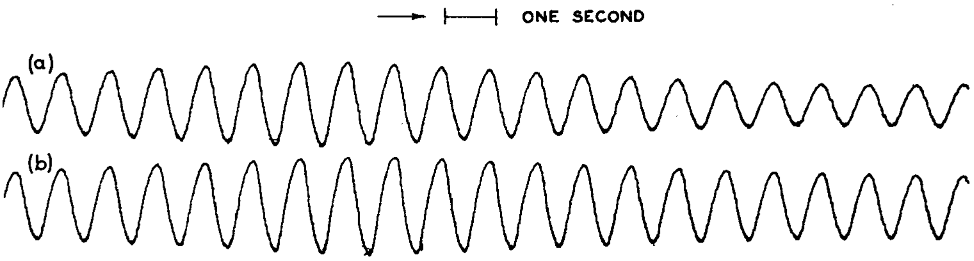


FIG. 4. Nine-story steel-frame building used for "man-excited" vibration tests. Letters mark points of excitation and measurement.

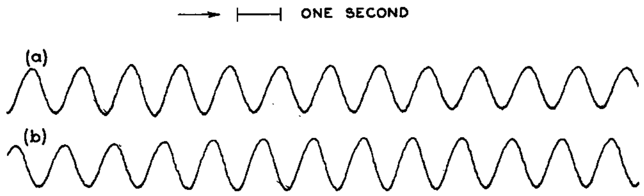
A second test of the method was made on the frame of a nine-story steel-frame building under construction. In this case it was possible to clearly distinguish between 8 different modes of vibration, as shown in figures 5, 6, and 7. Figure 4 shows the general configuration of the building, and indicates the locations of the points of excitation. These points of excitation should be selected to emphasize the mode desired, and to suppress other modes. For example, by applying the exciting force at a node for the 2nd mode of vibration, the 3rd mode can be more easily recognized. Although these mode shapes will, of course, not be accurately known for actual structures, it will be possible to make a sufficiently accurate estimate from the general configuration of the structure.



FUNDAMENTAL E-W TRANSLATION, 1.04 CPS
(POINT A IN FIG. 4)

SECOND MODE E-W TRANSLATION, 3.0 CPS
(POINT A IN FIG. 4)

Fig. 5. "Man-excited" vibrations of nine-story steel-frame building. E-W lateral translation modes.



FUNDAMENTAL N-S TRANSLATION, 0.86 CPS
(POINT A IN FIG. 4)

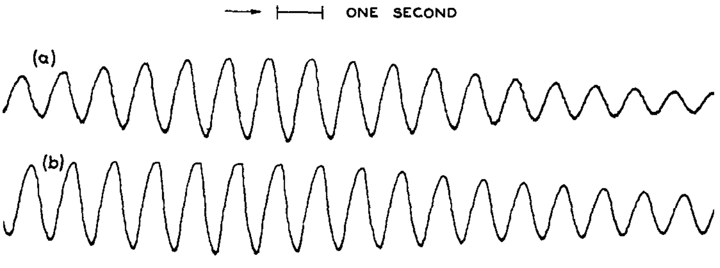
SECOND MODE N-S TRANSLATION, 2.8 CPS
(POINT A IN FIG. 4)

THIRD MODE N-S TRANSLATION, 5.0 CPS
(POINT D IN FIG. 4)

Fig. 6. "Man-excited" vibrations of nine-story steel-frame building. N-S lateral translation modes.

Figure 5 shows two lateral translation modes in the long E–W direction of the building. The damping in the fundamental mode is about 1 per cent of critical, definitely less than that of the reinforced concrete frame of figure 3.

Figure 6 shows three lateral translation modes in the short N–S direction of the building. The damping of the fundamental mode is considerably less than in the other direction; in fact, the decrease in the successive amplitudes is so small as to be scarcely measurable. In this case an approximate value of damping of the second mode could also be obtained.



FUNDAMENTAL TORSION MODE, 1.08 CPS
(POINT B IN FIG. 4)

SECOND TORSION MODE, 3.5 CPS
(POINT B IN FIG. 4)

THIRD TORSION MODE, 7.2 CPS
(POINT E IN FIG. 4)

FIG. 7. "Man-excited" vibrations of nine-story steel-frame building. Torsional modes.

Figure 7 shows three torsional modes excited by transverse inertia forces at the end of the building. The damping of the fundamental mode in torsion is appreciably greater than the lateral modes, and is about 2 per cent critical. The value of the fundamental torsional frequency, 1.08 cps, is very close to the lateral E–W frequency of 1.04 cps. It should be noted, however, that the direction of the exciting force for the torsional mode is perpendicular to that which would excite this E–W frequency, and hence the two modes can be separated even though their freqeuncies are so close together.

Complete vibration generator tests were made on this building as a part of the same investigation, and the data obtained from accurate resonance curves substantiated the information derived from the above simple "man-excited" tests.

As an additional means of studying the dynamic properties of structures, period tests with the lunar seismograph were made at intervals during construction of the nine-story building. By noting the way in which the periods change as various structural elements are added, considerable detail concerning the dynamic action of these structural elements can be obtained. In this case, period measurements were made at some twelve different stages of construction, during which the fundamental lateral translational period of vibration increased from 0.8 to 1.2 seconds.

## EARTHQUAKE RESPONSE OF A STEEL FRAME BUILDING

In the course of the period measurements on the nine-story steel-frame building an extra premium was obtained in the form of a natural earthquake which excited a building motion considerably greater than had been involved in the period tests.

During adjustment of the lunar seismograph prior to a period test, a large signal appeared which was at first believed to be an instrument malfunction. Fortunately the recorder was kept running for a time, for the cause of the motion turned out to be a magnitude 5.0 earthquake with an epicenter about 70 miles from the building.

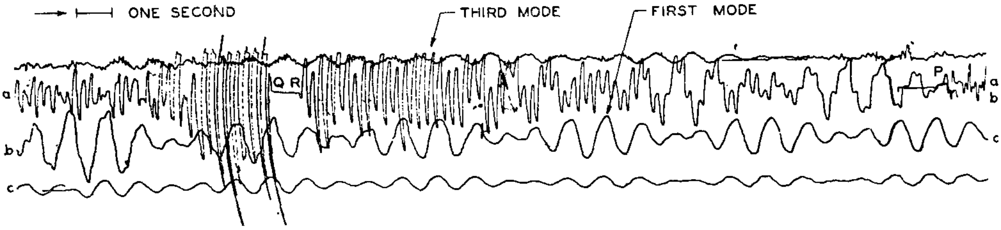


FIG. 8. Earthquake response recorded by Lunar seismograph in nine-story steel-frame building N-S.

(28 February 1963; 4:25:58 PST; 34°56′N, 118°59′W). Figure 8 shows the N-S lateral response of the building to this earthquake. The strong motion begins at $P$ and continues for several widths of the record as indicated. During the short time interval $Q$-$R$ the recorder was turned off while the gain was reduced for the remainder of the record. The initial strong motion of the building quickly passes into an almost pure 3rd mode of lateral translation, which then gradually passes into a motion which is almost entirely the fundamental mode. The 3rd mode frequency is very close to 5 times the fundamental frequency, which would be the exact ratio for a uniform shear type structure. The 2nd mode of lateral translation is not prominent on the record because the seismograph was located on the 8th floor, near a node for the 2nd mode of vibration. The frequencies excited by the earthquake of fig. 8 cannot be compared numerically with the "man-excited" frequencies of fig. 6 because the structure of the building frame was altered between the two tests by the addition of fire-proofing material to the columns.

Records of actual earthquake induced motions in multistory buildings are, of course, very rare, and the above extremely fortuitous record gives important direct information on the way in which the higher modes of vibration are set up in such structures.

## CONCLUSIONS

It is believed that the simple means of building excitation described above will make it possible to considerably improve the data hitherto obtained from many buildings by wind-excited tests. Although the amplitude levels of such tests are very small, the data may be useful for design purposes. Several instances have already occurred in which wide differences between building periods as measured by the above means and calculations based on the design model have led to a re-evaluation of the design procedures, and a clarification of the way in which the structural members were behaving.

Since tests of the above type may be the only feasible way of acquiring data on most actual buildings, possibilities of improvements in instruments and techniques should be carefully studied.

## ACKNOWLEDGMENTS

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