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U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Electro-Optical Deflection Measuring Device

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Electro-Optical Deflection Measuring Device

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ABSTRACT

The development and testing of an electro-optical device for the direct measurement of lateral deflections of tall structures are described. The device utilizes a tracking telescope mounted on a fixed reference and a light source attached to the structure at the level for which lateral deflections are to be measured. Operating characteristics of the system are based on the results of tests carried out over a period of several months in one of the elevator shafts of a 12-story building.

Key Words: Buildings; deflections; instrumentation; structural response; wind loads.

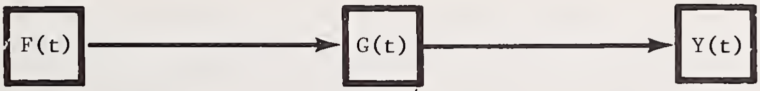
Electro-Optical Deflection Measuring Device

1. Introduction

With the continuing trend toward taller and more flexible buildings, lateral deflections and oscillations caused by wind, ground motions and solar heating are assuming a significant role in the design process. If this trend continues, and it most likely will, new criteria must be developed to ensure satisfactory performance at acceptable levels of risk and cost.

There is an interaction between dynamic structural deflections, the human occupants (human response), and the building subsystems. The sensitivity of humans to building motion depends upon a number of parameters, including acceleration, velocity, frequency, damping, and duration of exposure. Although human response is necessarily subjective in nature, the response of a structure and its subsystems is objective and may be quantified through the use of appropriate instrumentation.

Analysis leading to design involves a designated forcing function and a calculated transfer function to determine the system response. This can be expressed in block diagram form as



Measurements of system response (deflection of a structure in service) allow a reverse process. The structural characteristics can be determined if the forcing function is known or the forcing function can be inferred if the structural characteristics are known. Thus, proper understanding of response leads to the solution of the interaction problem and ultimately to allowable deflections as they relate to both building subsystem response and human response.

With recent emphasis on serviceability, the direct measurement of structural response in full scale with which to compare both theoretical predictions and model results has become increasingly important. The lack of such data in the past has been primarily due to the fact that satisfactory instrumentation and measuring techniques have not been available. In the following sections, the development and testing of an electro-optical system for the direct measurement of structural deflections and oscillations are discussed. Finally, comparisons are made between calculated and measured dynamic characteristics of a 12-story reinforced concrete flat-plate structure.

2. Background

Early attempts to measure lateral deflections of tall structures relied on pendulums whose natural period was much longer than that of the building (1,2). In fact, most measurements of lateral deflections reported to date have been made with inertial transducers of one form or another (3,4).

Ideally, a complete time history of structural motion is desired. This includes both mean and fluctuating components over periods of several months and at frequencies up to 10 Hz. Amplitudes of interest may range from 0.025 mm (0.001 in) to several millimeters. In theory, most of these requirements are within the range of existing inertial transducers, but practical considerations severely limit their application. Deflections are usually accompanied by rotations and it is extremely difficult to separate these effects over a reasonably wide bandwidth. That is to say, an inertial transducer will respond to both forms of motion if the range of frequencies is sufficiently wide (5). It is therefore necessary to rely on more than one type of transducer to completely define time histories of motion. Other approaches can be used which are not restricted by limitations of frequency response. The measurement of column strains is one technique. However, this is not a direct measurement of lateral deflection and this approach requires certain assumptions to arrive at deflections. The uncertainties involved often limit the value of these measurements. The same may be said of deflections determined from the double integration of acceleration measurements.

The use of a theodolite, while entirely satisfactory for long-term static observations, does not lend itself to the measurement of fluctuating components. In evaluating various techniques for the direct and continuous measurement of lateral deflections, it was concluded that optical devices, coupled with suitable electronics, offered the most promising approach.

3. Optical Techniques

A number of possible schemes to measure structural deflections by optical techniques have been discussed by Ward (6). Some of these schemes have been developed into working systems, all of them utilizing a laser source projecting a beam vertically upward from a fixed datum to a position sensing device. Sensing devices that have been used successfully include: a null-seeking array of photoelectric cells mounted on an x-y plotter (6), a matrix of photodiodes and associated scanning system (7), and a photoelectric cell in combination with an objective lens and an optical plate having a linear variation in transmittance (8).

A serious disadvantage of the x-y plotter approach, in addition to requiring active mechanical components, is that the laser beam must be "captured" by the photocell array. A momentary loss of power would generally require operator response or manual intervention. The use of a diode matrix limits resolution (fixed by minimum diode size) and system cost increases roughly as the square of the required dynamic range. Finally, the photocell-optical plate technique requires optics whose physical size varies directly with the dynamic range and requires expensive accessory equipment.

In addition to the above, several other laser beam techniques were considered during the early stages of the development program. Some of them were as follows:

1. Two overlapping, motor-driven arms with a photoelectric cell extending along the bottom side of each arm. By mounting potentiometers or shaft encoders on the motor shafts and by using the peak photocell output to trigger a sample-and-hold amplifier, it would be possible to obtain the angle at which each are intercepted the beam. Knowing the distance between centers of rotation, one could then calculate x-y coordinates of the beam position. An advantage of this approach is that deflections at several levels could be measured simultaneously with one laser source.

2. A vidicon tube focused on the top surface of a translucent screen mounted at the top of an elevator shaft. Resolution would be 600 lines in one direction and practically infinite in the other direction. Though not developed beyond the conceptual stage, this technique has considerable potential.

3. A fixed array of photocells in combination with servo-controlled deflecting mirrors in the optical path. Deflection measurements of the Tagus River Bridge were obtained using a similar system (9). A working model was constructed as part of the NBS project and successfully used, but was abandoned in favor of a purely electronic sensing device.

4. The Electro-Optical Tracking System

The approach finally adopted and developed into a working instrument is shown in Fig. 1. A light source is attached to the structure at the level for which lateral deflections are to be measured. A collimating lens projects the light beam down to the tracking telescope where a real image is formed on the surface of a position detector by the objective lens. The objective lens is followed by a diverging or negative lens which increases the focal length of the telescope and facilitates focusing on the sensor. The light path in the telescope box is folded by two mirrors at 45 degrees to keep the physical size [406 mm high x 254 mm wide x 102 mm deep (16 x 10 x 4 in)] of the box reasonably small. A separate lens is mounted on the side of the telescope box to simplify coarse adjustment by focusing the source image on a target engraved on the telescope base plate.

The sensor is a silicon photovoltaic cell having an output terminal at each side of the 10 mm (0.395 in) square active surface. This is reduced to an effective area of approximately 8.5 mm (0.335 in) square because of the finite image size. The sensor can be rotated in its mount to align the electrical axes with the geometric axes of the telescope. The dynamic range of the system is governed by the diameter of the collimating lens, the optical path length, the focal length of the telescope, and the surface area of the detector. A motor-mounted optical flat can be rotated into the light path just ahead of the sensor to displace the image for system calibration in amplitude.

The electronics consist of two differential amplifiers which convert the two pairs of currents generated by the sensor into voltages. Since these voltages are a function of both image position and light intensity, an automatic gain control is provided to compensate for fluctuations in the source intensity and accumulation of dust on the objective lens. The low impedance output makes the system compatible with a wide range of recorders and display devices.

It should be pointed out that practically any light source is acceptable if the objective lens is illuminated and the image at the surface of the sensor is of sufficient intensity. A 12-volt spiral filament bulb is currently being used and is operated at 8 volts to give extended bulb life (approximately one year). It is also important to note that the system responds only to translations of the light source since rotations of a point are not detected. The tracking telescope must, of course, be supported by a fixed reference.

5. Calibration

Prior to installation in an actual service situation, a prototype instrument was operated on a horizontal test range over distances of 30 and 91 m (100 and 300 feet). The light source was mounted on a cross-slide milling table which was supported by a concrete pier. This allowed the source to be positioned within ± 0.025 mm (± 0.001 inch) over a range of ± 50 mm (± 2 in) for each axis. The tracking telescope was also mounted on a concrete pier. The telescope was aligned with the light beam by means of three fine-thread adjusting screws in the base plate. Once the box was properly aligned, the optical components were positioned and focused. Finally, the sensor was translated and rotated to align the electrical zero and axes with the telescope box.

A typical plot of actual and indicated source displacements is shown in Fig. 2. This plot covers the full range of the system for an optical path length of 30 m (100 ft). Skewness of the axes is inherent in the sensor and can be reduced only by careful selection of sensors. Nonlinearities at large displacements are due to both the detector and amplifier characteristics. The system has a nominal sensitivity of 200 mv per mm (5 volts per in) of source displacement and a resolution of approximately 0.13 mm (0.005 in) for a path length of 30 m (100 ft), i.e., 1 part in 240,000. In the several months that the instrument was operated on the test range, long-term electrical drift was found to be negligible. No dynamic response studies were conducted on the test range. However, the device would be expected to exhibit satisfactory response well above 100 Hz since it is purely an electro-optical system. The current configuration uses a 50 Hz low-pass filter on the output stage.

6. Performance of the Operational System

It was recognized early in the development program that the system, basically constituting an angle measuring device, could be adversely affected by thermal gradients producing changes in the index of refraction. Thermal gradients in the direction of the optical path (thermal stratification when operated in a vertical configuration) would have no effect while those normal to the path (convection columns for example) would have the greatest effect at the objective lens (tracking telescope) and no effect at the collimating lens (light source). Thus, the operating environment must be considered when using this optical device and a detailed study of system performance under typical operating conditions was therefore undertaken. Other operating functions that were evaluated included the physical alignment, ease of placement, effect of stray light sources, and the instrument's ability to reliably track the motion of the structure.

7. The Test Building

Performance tests were conducted over a period of several months on two units in an elevator shaft of the Administration Building on the NBS campus at Gaithersburg, Maryland. This building is a 12-story reinforced concrete, flat-plate structure with plan dimensions of 15 x 67 m (49 x 220 feet). It has a reasonably clear exposure to the prevailing NW winds and the surrounding terrain may be classified as "gently rolling" with a power law exponent of approximately 0.25. The building and surrounding structures are shown schematically in Fig. 3.

The building has two basement levels, resulting in a clear shaft height of 51 m (166 feet), (Fig. 4). There are two rectangular shafts, each containing two cars. The shafts were constructed monolithically and are framed into the floor system. The south side of each shaft forms part of the outside wall and the remaining shaft walls are surrounded by air-conditioned office space.

The Administration Building was selected because it was readily accessible, but more important it was estimated that the structure would provide a severe performance test of the electro-optical deflection measurement system. Motions of this structure are small, frequencies are relatively high, and the elevator shafts have the potential of containing significant thermal gradients in the shaft because of the directly exposed exterior wall. Also, data transmission lines from the system amplifiers to the tape recorders were longer than would normally be anticipated [approximately 820 m (2700 feet)], thus providing additional electronic problems to be evaluated.

8. Equipment Installation

Light sources were mounted in adjustable brackets which were bolted to existing hanger slots in the shaft wall. The light sources could be rotated about two perpendicular axes, allowing the light beams to be aimed directly at the tracking telescopes on the shaft floor. Access to the positions of the light sources was gained by climbing onto the roof of the elevator car and running it to the top of the shaft under manual control. A variable transformer located in the hoist room directly above the shaft allowed the bulb voltage to be adjusted for proper image intensity.

Light source locations in the east shaft are shown in Fig. 4. The resulting optical path length was 50 m (163 feet). The tracking telescopes were connected by cables to the system electronics located outside the shaft [approximately 6 m (20 feet)] which allowed adjustment without interrupting elevator service.

The procedure used in the installation and adjustment of instrumentation was as follows:

The light source was focused on the approximate position to be occupied by the tracking telescope. The telescope was then positioned and roughly aligned using the aiming lens on the side of the box. Once the image was acquired by the position detector, the objective lens was capped and the balance potentiometers nulled. The cap was then removed and the three adjusting screws in the base plate were used to bring the image onto the electrical-zero position of the detector. The collimating lens on the light source was next adjusted to produce maximum intensity on the detector and the bulb voltage was regulated to produce a detector current of approximately 5 microamperes. Typically, these adjustments can be made in approximately 15 minutes.

In addition to the two electro-optical tracking systems, an accelerometer was installed to measure accelerations in the N-S direction. The accelerometer was placed directly on the concrete floor at roof level and adjacent to an E-W column line (Fig. 4). The accelerometer is a force-balance device with a sensitivity range of 10^{-2} to 10^{-6} g's. The frequency bandwidth selected for these acceleration observations was 0.1 to 9 Hz (-3 dB point).

9. Data Transmission and Recording

At the time this study was undertaken, research into wind pressures on Building 226 (Fig. 3) was in progress. Instrumentation associated with this program included, among other items, a 20-m (66-ft) meteorological tower with several fast-response anemometers and a sophisticated data acquisition system. It was therefore decided to transmit data from the Administration Building to the recording center in Building 226, a distance of approximately 820 m (2700 ft), via telephone lines.

Instrumentation amplifiers with a gain of X10 were installed at the outputs of the two tracking telescope systems in the Administration Building. This resulted in a very satisfactory signal-to-noise ratio and capacitance of the signal lines was found to be acceptable over the frequency range of interest. Data lines from the meteorological tower [located 60 m (200 ft) directly north of Building 226] were already in operation.

Calibration drive motors for the tracking telescopes were activated from Building 226 by means of a battery and a momentary-on switch. This activated a high impedance relay in the Administration Building which in turn activated a latching relay in the motor circuits. To initiate and terminate calibration, it was necessary to temporarily use the common side of the data lines in the relay circuit as only three line pairs to the elevator shaft were available.

Data were recorded on digital, analog and stripchart recorders. Continuous records of N-S motion and wind speed were recorded on paper stripcharts. A computer-controlled digital and analog system was used to record data under strong wind conditions. The computer was programmed to initiate recording at a certain wind speed [usually 17 m/s (35 mph)] and record lengths were 15 minutes. Records were separated by a 30-minute hold period. For typical runs, variables recorded included N-S and E-W components of wind velocity, total wind speed, N-S and E-W deflection measured by each tracking system, acceleration, ambient air temperature and barometric pressure. Solar radiation will be monitored in future experiments. A detailed description of the data acquisition system can be found in Ref. (10).

10. Experimental Results

A typical 10-minute record is shown in Fig. 5. The variables are acceleration of the building in the N-S direction, deflection of the building in the N-S direction, and the total wind speed at 10 meters (33 feet) above ground. The analysis of these records is considered in the following sections.

As seen in Fig. 5, the wind speed varied from 5 to 14 m/s (11 to 32 mph), peak-to-peak acceleration was 0.34×10^{-3} g's and the peak deflection was 0.69 mm (0.027 in). Mean wind direction for this record was WNW.

11. Data Analysis

The records that were considered in the analysis were the N-S deflection and the N-S acceleration of the building. In addition, mean values and spectral densities of wind velocity were determined. These records were digitized at a rate of 20 samples per second. The length of record considered was 7.5 minutes, resulting in 9000 data points for each record. Autocorrelation and spectral density functions were calculated for the acceleration and deflection records. Spectral density functions were obtained as Fourier transforms of the autocorrelation functions (11). In calculating autocorrelation functions, 200 lags were used.

The autocorrelation and spectral density functions for the building deflection and acceleration due to a wind with a mean speed of 10.5 m/s (23.5 mph) in the west to east direction and 2.3 m/s (5.1 mph) in the south to north direction, measured at the 20-m (66-ft) height, are shown in Figs. 6 and 7. Variable DY1 represents the N-S deflection of the building and variable AY1 represents the N-S acceleration. The rms levels for the deflection and acceleration records were 0.12 mm (0.0048 in) and 0.187 x 10^{-3} g's, respectively. As seen in Figs. 6 and 7, both analyses yield a value of about 1.0 Hz for the predominant natural frequency of the building with some indications of the higher frequencies on the power spectrum for acceleration. This value compares favorably with that obtained from a theoretical study of the structure which is discussed subsequently.

In view of the direction of the wind, which was predominantly along the strong axis of the building, the results shown in Figs. 6 and 7 are due essentially to building motion normal to the direction of the wind, i.e., cross-wind response. To examine the effects of the change in direction of the wind relative to the weak axis of the building, records were also analyzed for a wind with a mean speed of 6.3 m/s (14.0 mph) in the west to east direction and 1.9 m/s (4.2 mph) in the north to south direction, measured at the 20-m (66-ft) height. The rms deflection was 0.11 mm (0.0044 in) and the resulting spectrum is shown by the dashed line in Fig. 6. It is seen that there is negligible definition of the predominant natural frequency in the deflection record. Damping of the structure was estimated from the rate of decay of the autocorrelation functions. The results are shown in Fig. 8. Damping was estimated to vary from 1.3 to 1.8 percent of critical damping.

12. Theoretical Study of the Structure

In order to compare measurement against theory, the natural frequency of the entire structure was calculated using current state-of-the-art references and techniques. Two methods were used: a simple calculation using building code equations, and a frequency analysis using a general structural analysis computer program. The recommended method for estimating the longest natural period according to UBC (12) and ANSI A58.1 (13) for building structures is given as

$$T = \frac{0.05h_n}{\sqrt{D}} \qquad (1)$$

where h_n is the height of the building in feet and D is the width in feet of the building in the direction under consideration, or for moment resisting space frames which resist 100% of the lateral force,

$$T = 0.10N \qquad (2)$$

where N is the total number of stories above exterior grade. For the type of structure being considered here, the lowest natural frequency would be estimated to lie between the values obtained from equations (1) and (2).

The Administration Building is a reinforced concrete structure with flat-plate floors and square, rectangular-tied columns. In rectangular plan dimensions it is 15 m (49 ft) by 67 m (220 ft) and from subbasement to the roof of the penthouse it is 55 m (181 ft). The building is asymmetric about both axes due to irregular spacing of columns and two elevator shafts near one end of the structure (Fig. 4). A typical structural bay through the narrow width of the building consists of 254 mm (10 in) floors and variable column size and spacing. The two elevator shafts are rectangular in plan with 203 mm (8 in) walls extending approximately the full height of the structure. Interior finishings are typically movable fiberglass metal clad partitions and the majority of floors are office occupancy with relatively sedentary activity. The heating, ventilating and air conditioning systems are located on the second floor. Exterior finishing on the broad faces of the structure is glass and light metal cladding between stainless steel mullions running full height of the structure which isolate the majority of the structural system from direct exterior exposure. The elevator shafts are directly exposed to the exterior for their full height on one narrow wall (Fig. 4). Each end of the structure has a solid brick masonry wall over the full width and height. The walls are attached to spandrel beams at each floor level. The structure is relatively stiff and experiences no undesirable performance.

Table I summarizes the calculation of the lowest natural frequency ($f = 1/T$) from equations (1) and (2) for the direction parallel to the narrow dimension of the structure. Equation (1), which applies more to the stiffer or shear-wall type structure, gives a frequency that is 50% higher than indicated by equation (2), which is for moment resistant space frames. The calculated range for the lowest natural frequency is $0.8 < f < 1.2$ Hz.

The computer analysis was used to determine the first three natural frequencies in a direction parallel to the narrow dimension of the structure. The computer program SAP (14) was used on the UNIVAC 1108 EXEC 2 system at NBS. Principal assumptions used in the frequency analysis were:

1. The structure was divided into 5 typical cross-sections representing various column arrangements. Structure heights, and elevator shafts.

2. Lateral floor displacements at a particular floor were the same for each section (twist of the structure was not considered).

3. Axial deformation of beams and columns was neglected.

4. Material properties used were: $E = 24\ KN/m^2$ (3,500 ksi) [modulus of elasticity estimation, ACI 318-71(15)] and $u = 0.15$ (Poisson's ratio).

5. Damping was neglected in the calculation of the natural frequencies.

6. The relative stiffnesses of columns and floors were based on gross concrete sections. Effective widths of the plate floors were assumed to be 9 times the slab thickness, which was extrapolated from information in Ref. (16). The stiffness due to block walls in the stairwells and the brick walls at the ends of the building was not considered.

7. In addition to flexural deformations, shear deformations in the elevator walls were considered using a shape factor of 1.2.

8. The values of mass used in the analysis were based on dead load calculations and live load values from Ref. (17). The resulting values correspond to a gross density of 260 kg/m^3 (16 pcf) for the building.

9. Mode shapes were necessarily assumed for analysis by SAP. The first four mode shapes were excited with a system of forces in order that reasonable numerical accuracy could be obtained for the first three modes.

Table I gives the natural frequencies that resulted from the analysis of the structure using SAP. The first through third frequencies are 0.7, 2.7 and 6.6 Hz respectively. The corresponding calculated mode shapes are shown in Fig. 9. The comparison of measured frequency from analysis of response data and calculated frequency is reasonable in all cases (Table I). The SAP analysis indicates that the first and second natural frequencies were detected by the deflection measurement system. Also frequencies predominant in the deflection measurements corresponded approximately to those predominant in the acceleration measurements.

13. Thermal Deflection

Along with the dynamic response to windloads, a structure responds to long term time-dependent loads which are superimposed on the shorter duration loads. These long term loads have to be accounted for in the design of a measurement system and analysis of the data. These deflections are induced by creep and shrinkage for reinforced concrete structures and temperature changes for structures in general. The latter is most critical in the case of the electro-optical deflection system and will be considered here.

The Administration Building is exposed to solar heating on one broad side only the year round. Part of this side incorporates one of the short walls of each of the elevator shafts;

the other short walls are on the interior of the structure (Fig. 4). A diurnal drift cycle in a direction parallel to the narrow width is induced in the elevator shaft due to the solar heating and atmospheric temperature changes. A typical record of this is shown in Fig. 10 for a period of 48 hours during which there was range of air temperature from -2.2 to 16.1 °C (28 to 61°F). During this period the total wind speed was less than 3.4 m/s (7.5 mph) and there were neither clouds nor overcast. Peak-to-peak displacement was 1.5 mm (0.06 in). The record was obtained directly from the north-south component of the electro-optical deflection system and recorded on a slow speed (1/2 in/hr) low frequency response (dc to 1Hz) stripchart recorder. The width of the trace represents the dynamic activity of the deflection measurement.

Methods have been recommended (references 18, 19 and 20) for calculating temperature-induced deflection of high-rise structures. These methods consider temperature gradients in structural members, geographical temporal changes, and the structural characteristics among the items for consideration. The complexity of temperature deflection calculations for the Administration Building extends the study beyond the scope of this report. However, the small magnitude of measured deflection as previously shown would be anticipated for this structure. The columns at the exterior faces of the structure are shielded from direct exposure. The only directly exposed portions of the structure are the exterior walls of the elevator shafts. Thus the majority of temperature induced deflections of the entire structure would be introduced only at the elevator walls.

The thermal deflection is mentioned here only to demonstrate the ability of the electro-optical device to record these deformations even though they are in the order of 0.25 mm (0.01 in).

An important consideration is the ratio of peak-to-peak lateral thermal deflection in typical diurnal cycles to the possible peak-to-peak dynamic response activity during the same period of time. For example, the ratio of thermal deflection to peak-to-peak dynamic deflection was determined from the windstorm and thermal deflection perviously presented, figures 5 and 10 repsectively. This ratio is 1.5 which shows that each deflection is of the same order of magnitude. Linear ranges and deflection capacity of the instrumentation must be within acceptable boundaries when these deflections are superimposed. In this case, measurements obtained by the electro-optical deflection system are well within acceptable boundaries.

14. Optical Path Interference

As previously described, refraction of the light beam from the light source to the tracking telescope causes an apparent deflection to be recorded. Temperature gradients perpendicular to the light path will cause such refraction. This was studied in the performance evaluation of the electro-optical deflection system by the comparison of the N-S deflection components of two deflection systems placed in the same elevator shaft. One system from which the data has been previously described was placed at the interior wall and the other system at the exterior wall (Fig. 4). It was assumed that torsional displacements were insignificant. The exterior wall is exposed directly to the atmosphere. Outputs of the two deflection systems were analyzed by comparing the ratio of calibration signal [approximately 3.8 mm (0.15 in)] to background signal activity (noise due to thermal activity, electronics and dynamic structural response). The ratio of signal activity was obtained when the wind was negligible; thus most of the signal activity was attributed to the optical path interference, electronics and mechanically induced structural vibration of which the latter two were estimated to be small by separate studies. The ratio of calibration output to background signal activity magnitude varied from 10 to 20 for the interior wall and was consistently 3 at the exterior wall. This provides conclusive information that the location of deflection measurement near the exterior wall has approximately 5 times as much noise attributable to optical path inference. It also demonstrates the importance of consideration of position for instrumentation when installing an optical deflection measurement system. The ratio of calibration to signal activity level of 10-20 was found to be acceptable for adequate structural response measurements; however, the ratio of 3 was found to be marginal for resolution of short-term dynamic response measurements.

In order to establish consistency of readings between the two units, mean deflections measured by the two tracking telescopes are compared in Fig. 11. The readings were obtained under a variety of conditions, ranging from clear to overcast and from calm to windy. They are based upon visual averages of 30-second records and are estimated to be within $\pm$ 0.13 and $\pm$ 0.3 mm ($\pm$ 0.005 and $\pm$ 0.01 in) of the true mean for Units No. 1 and No. 2, respectively.

The sensitivities of the two units are obviously different. Problems were encountered with the calibrating mechanism of Unit No. 2 shortly after installation in the shaft. This, coupled with optical path interference, made it difficult to establish identical sensitivities for the two units. Even though the sensitivities were not the same, the measured amplitudes are consistent.

15. Summary

Measurements made with the electro-optical deflection system have been shown to be in agreement with trends of observed structural response and with theoretical models.

The Administration Building provided a critical performance environment for the measurement system due to low magnitude and high frequency dynamic response. It is believed that this instrument performed adequately in this structure and that the system could be expected to perform as well or better in a more flexible and taller structure.

16. Future Studies

An operational deflection measurement system has been developed and tested. However, certain details of the system's behavior remain to be studied. Deflections associated with thermal environment will be more closely correlated by the simultaneous measurement of solar radiation and atmospheric temperature. Optical path interference will be studied in more detail by the comparison of the dynamic response of the two deflection systems and by controlled variation of the optical path environment. This will qualify the use of the optical system in various environments which might be encountered. Long term stability of the electronics (on the order of months to a year), associated mechanical components and light source will be studied in a controlled environment calibration tunnel to quantify possible measurement errors.

Various types of incandescent and monochromatic laser light sources are being investigated. The present system is compatible with these types of light sources. The light source selection has to be made compatible with each configuration in which the system is required to operate.

A compact electronics package is being considered which would ruggedize the system for transportation to the site, reduce setup time and extend unattended operational periods. Such items as a variable range of signal amplification and variable filter bandwidths are also being considered.

Uses of the system other than in high-rise structures should be investigated. The system is not restricted to direction and is operational in lateral as well as vertical orientations. Remote measurement of deformations on an inaccessible structure is a possible application. The placement of a simple target on the structure will facilitate this type of measurement.

17. Acknowledgements

The cooperation and assistance of Mr. H. D. Cook (Electronic Optical Development Section, National Bureau of Standards) in the design and assembly of the first operational model and initial calibration are gratefully acknowledged. The assistance of Mr. Randy Williams and members of the electronics group of the Structures Section is also acknowledged.

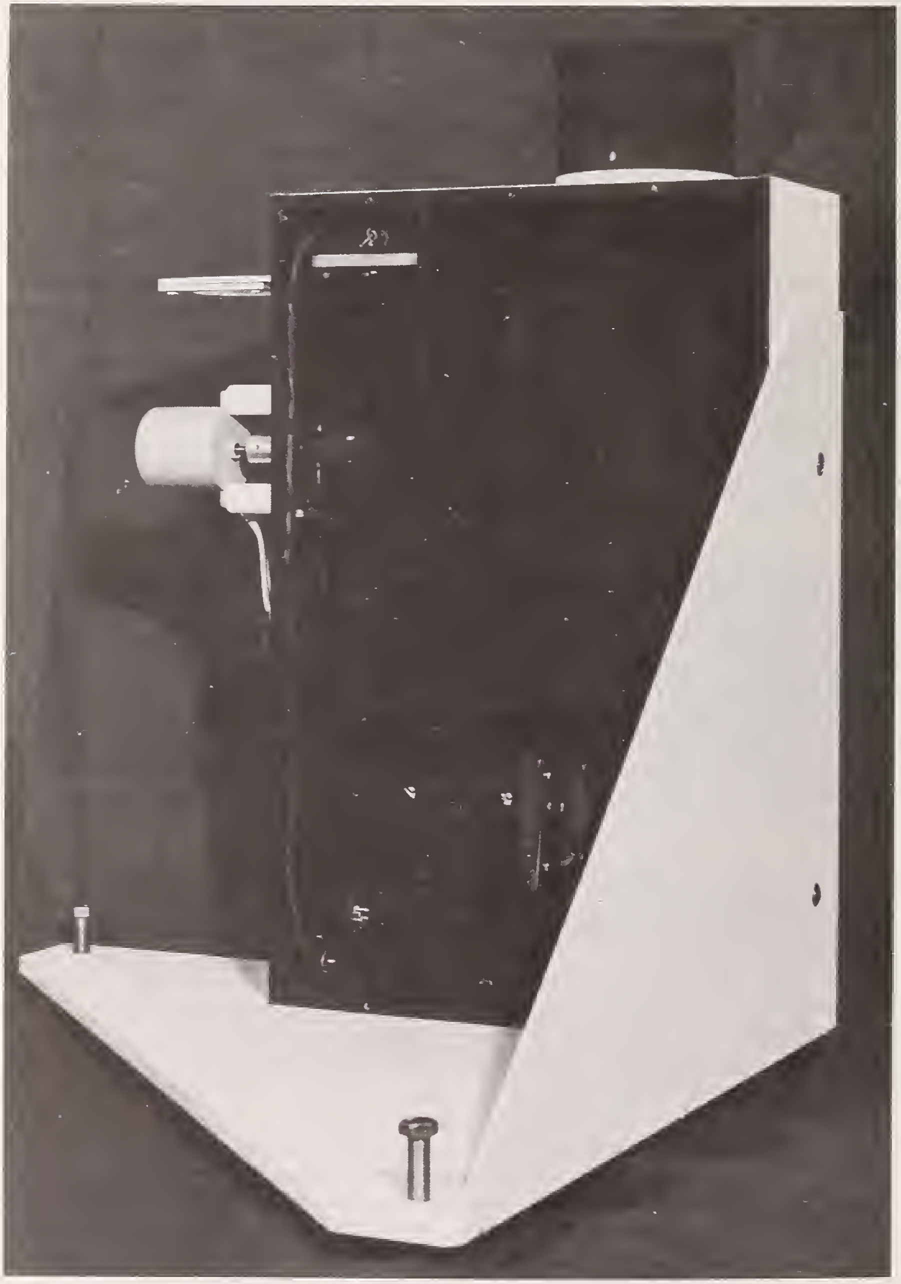


FIG. 1 TRACKING TELESCOPE IN OPERATING POSITION (COVER REMOVED).

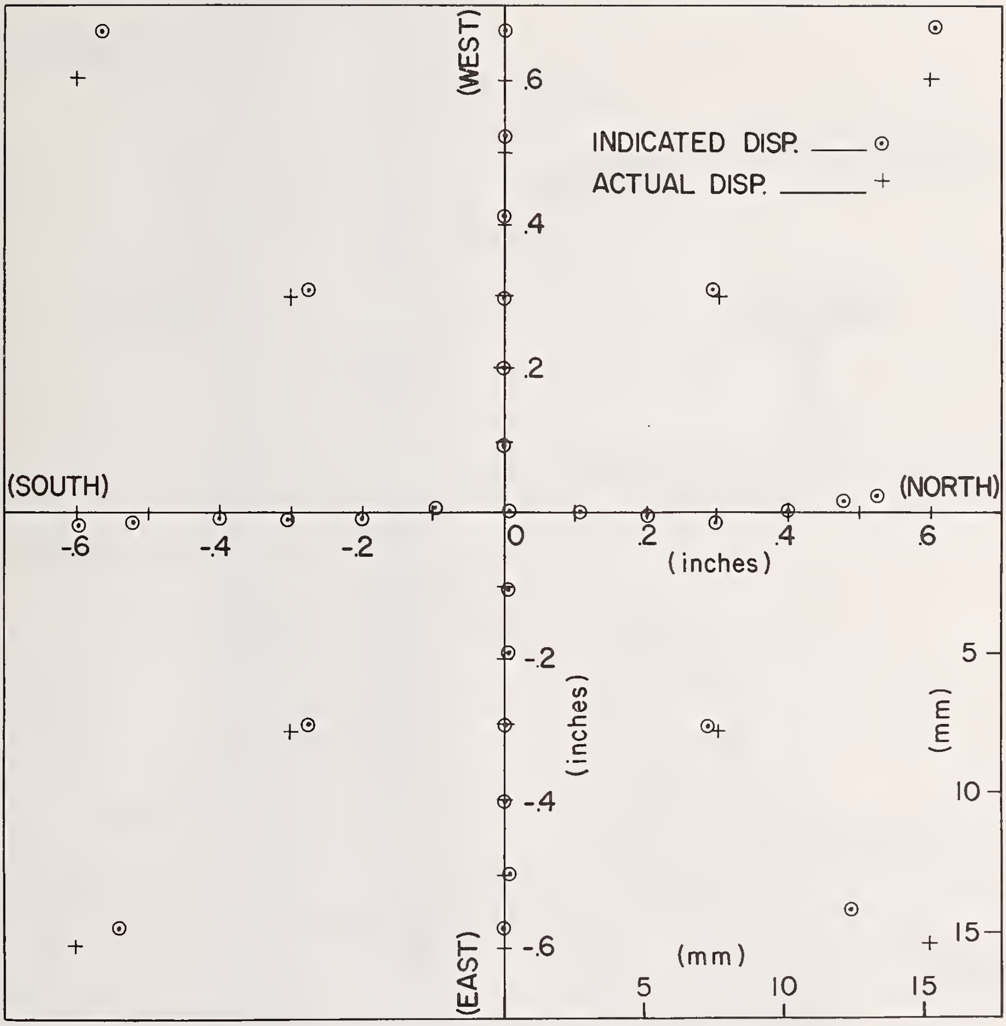


FIG. 2 INDICATED AND ACTUAL SOURCE DISPLACEMENTS - UNIT NO. 2.

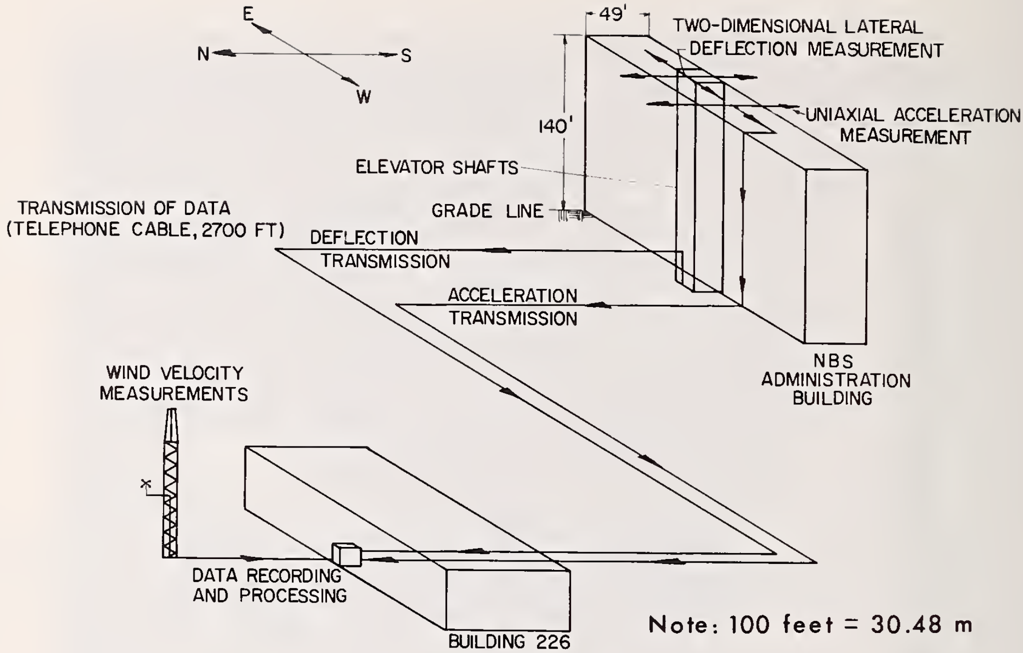


FIG. 3 SCHEMATIC OF NBS CAMPUS

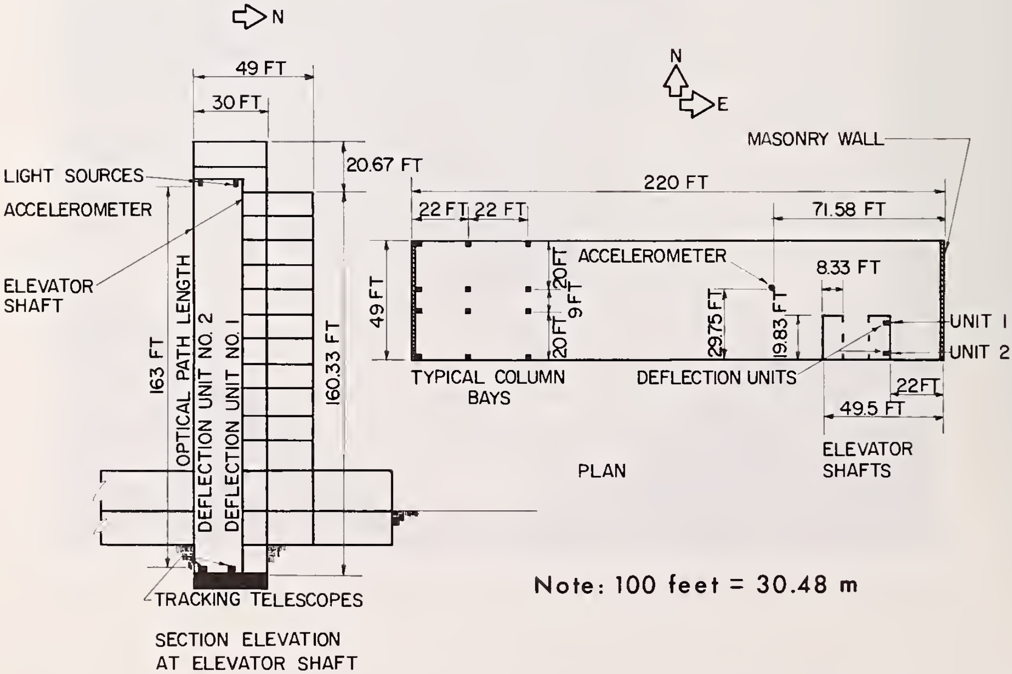


FIG. 4 PLAN VIEW AND SECTION ELEVATION OF ADMINISTRATION BUILDING

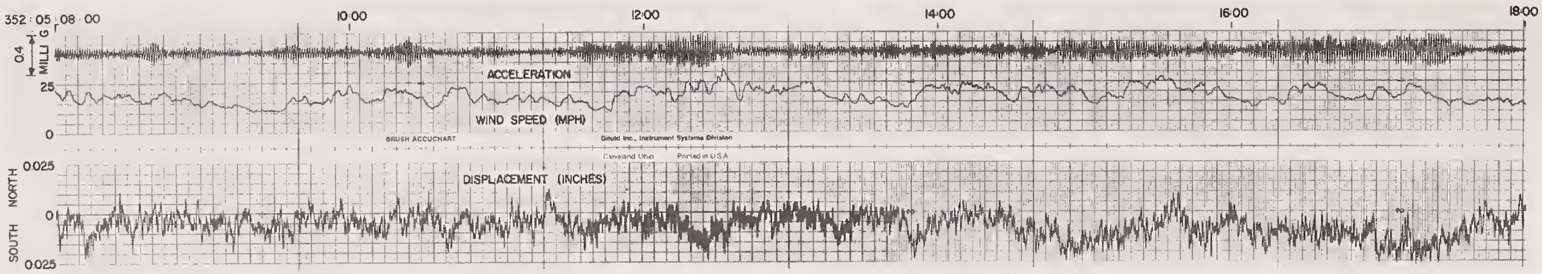


FIG. 5 RECORDS OF N-S BUILDING MOTION AND WIND SPEED

Note: 5 mph = 2.24 m/s
0.005 in = 0.127 mm

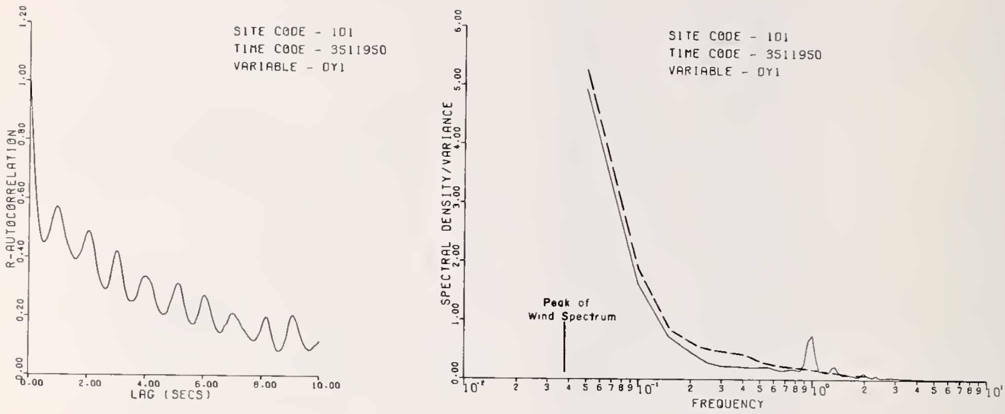


FIG. 6 AUTOCORRELATION AND SPECTRAL DENSITY FUNCTIONS FOR N-S DEFLECTION

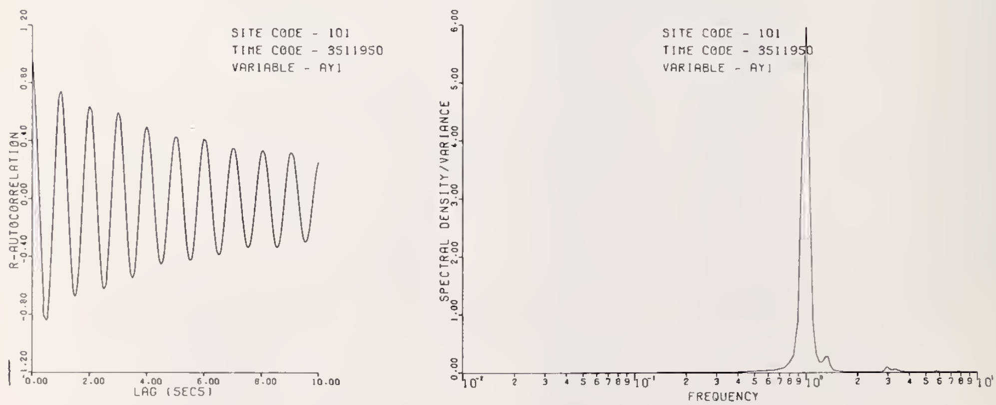


FIG. 7 AUTOCORRELATION AND SPECTRAL DENSITY FUNCTIONS FOR N-S ACCELERATION

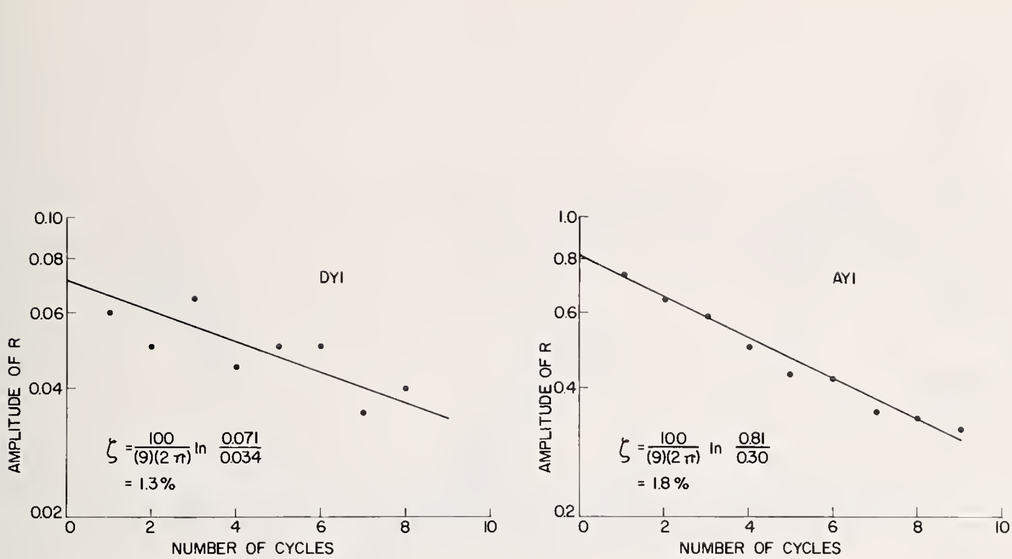


FIG. 8 DAMPING ESTIMATES OBTAINED FROM DEFLECTION AND ACCELERATION AUTOCORRELATION FUNCTIONS

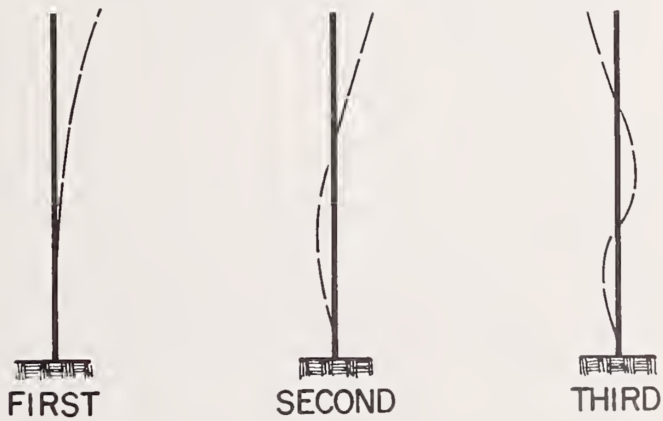


FIG. 9 CALCULATED MODE SHAPES FOR ADMINISTRATION BUILDING

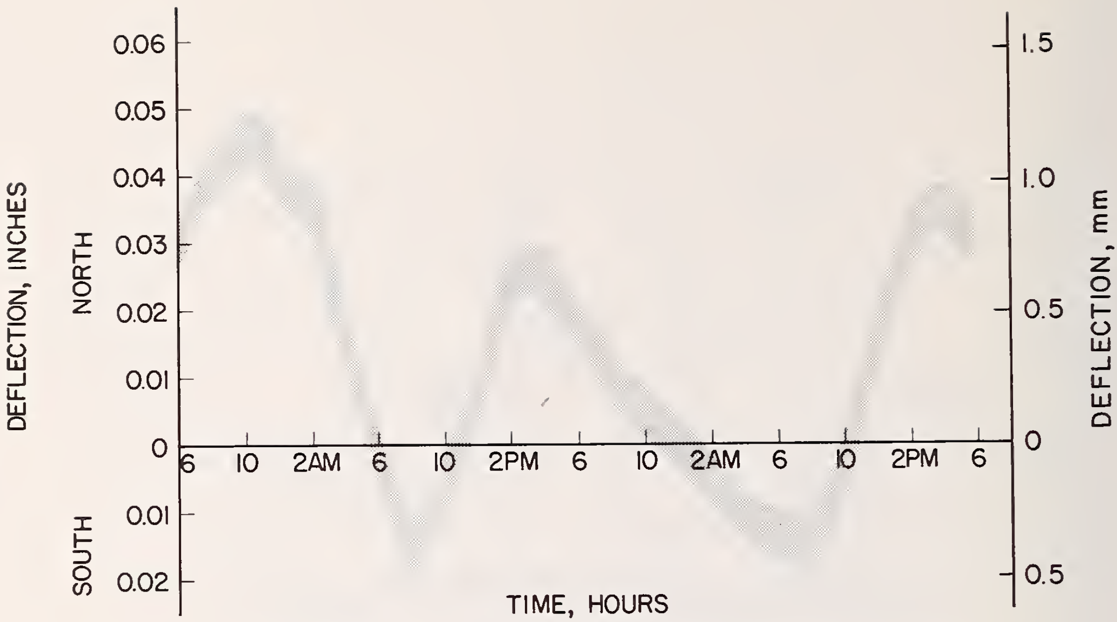


FIG. 10 DIURNAL THERMAL DRIFT CYCLES FOR ADMINISTRATION BUILDING, N-S DIRECTION

Source	Natural Frequencies, Hz			$\frac{f_1 \text{ accel.}}{f_1}$
	Fundamental (f_1)	Second (f_2)	Third (f_3)	
UBC/ANSI A58 Eq. 1	1.2	-	-	0.83
UBC/ANSI A58 Eq. 2	0.8	-	-	1.25
SAP Computer Analysis	0.7	2.7	6.6	1.43
Measured from Defl. Spectrum	1.0	2.9*	-	1.0
Measured from Accel. Spectrum	1.0	3.0	5.8	1.0

* Estimated

TABLE I. COMPARISON OF CALCULATED AND MEASURED FREQUENCIES OF TEST STRUCTURE

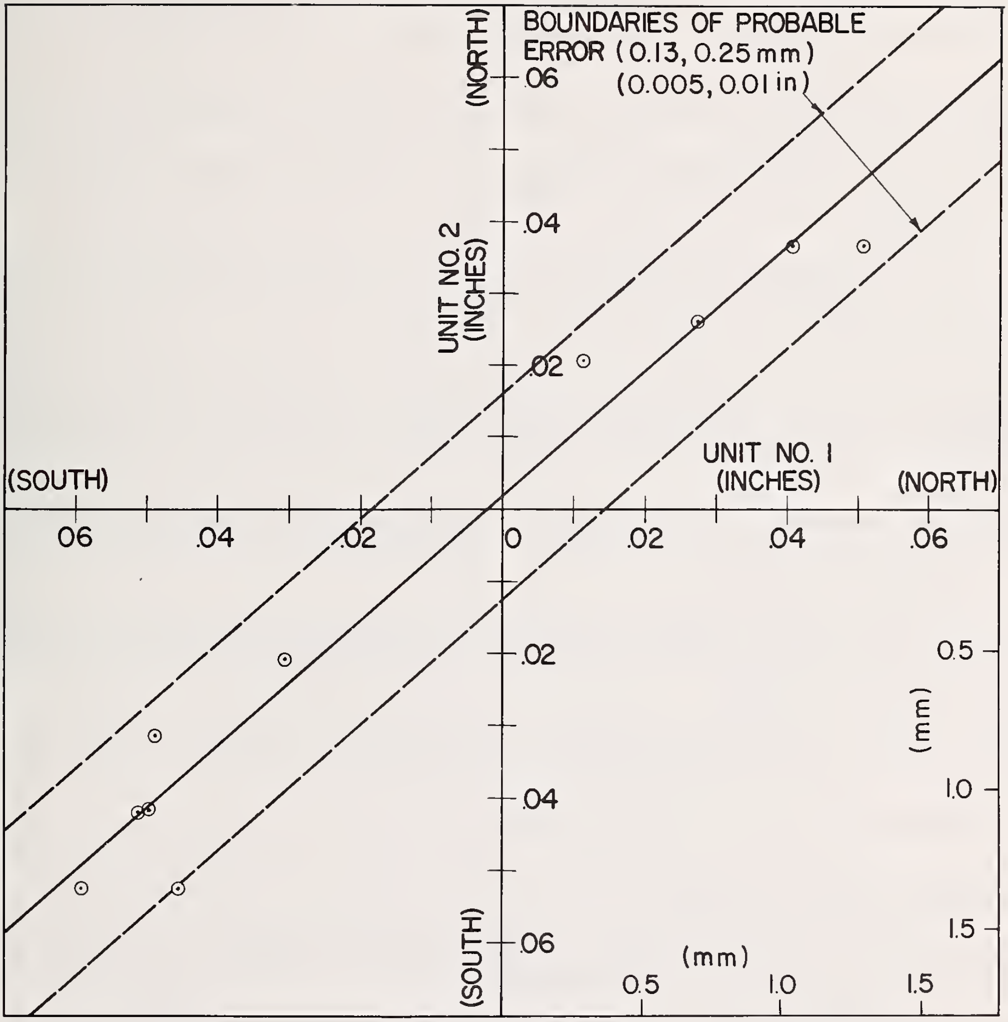


FIG. 11 COMPARISON OF N-S DEFLECTIONS MEASURED BY THE TWO TRACKING TELESCOPES

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

The development and testing of an electro-optical device for the direct measurement of lateral deflections of tall structures are described. The device utilizes a tracking telescope mounted on a fixed reference and a light source attached to the structure of the level for which lateral deflections are to be measured. Operating characteristics of the system are based on the results of tests carried out over a period of several months in one of the elevator shafts of a 12-story building.

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