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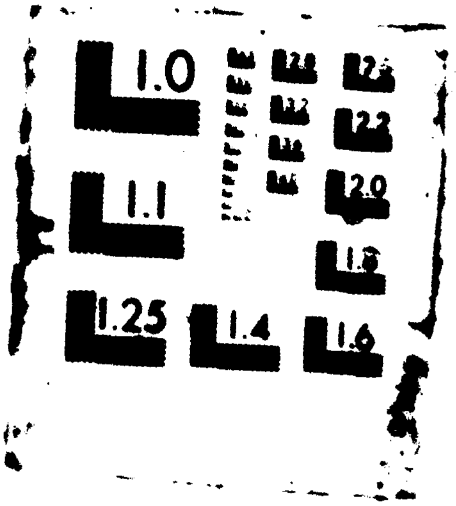
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This paper describes the application of two different computer-based optical methods for locating the positions and amplitudes of nodes and antinodes in vibrating members. In a technique called "shadow speckle metrology," artificial speckles are projected at an angle onto a vibrating surface using a 35mm projector and a speckled slide. In the second technique called "line broadening," a single line is used for projection. The vibrating surface and the projected images are captured either directly using a vidicon camera/digitizer system, or indirectly using an ordinary camera to record a time-average

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VIBRATION ANALYSIS USING SHADOW SPECKLE METROLOGY AND LINE BROADENING TECHNIQUES

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ABSTRACT

This paper describes the application of two different computer-based optical methods for locating the positions and amplitudes of nodes and antinodes in vibrating members. In a technique called "shadow speckle metrology," artificial speckles are projected at an angle onto a vibrating surface using a 35mm projector and a speckled slide. In the second technique called "line broadening," a single line is used for projection. The vibrating surface and the projected images are captured either directly using a vidicon camera/digitizer system, or indirectly using an ordinary camera to record a time-average photograph which is digitized subsequently. Computer programs compare these images to images recorded prior to excitation in order to determine the mode shape and the amplitude of vibration.

INTRODUCTION

In a previous paper, an analogy was drawn between artificially generated speckles, and the "subjective" and "objective" laser speckles observed in the neighborhood of an appropriately illuminated diffusely reflecting surface [1]. Artificial "subjective" speckles can be generated on an object by splattering paint on its surface. These speckles move with the surface and have been used in experimental mechanics to measure in-plane displacement and strain. One approach is to use double exposure speckle photography and optical correlation. An alternative procedure is to correlate systematic pairings of intensity samples extracted from digitized speckle patterns separately recorded at different times during a load cycle [2,3]. Recent studies have shown that this approach is not limited to making in-plane measurements. For example, "subjective" speckles have been used in conjunction with photogrammetry and digital correlation techniques to measure out-of-plane displacements [4]. The novel idea of relating decorrelation of "subjective" speckle patterns to nodal and antinodal locations in a vibrating member has also been suggested [5]. Unfortunately, qualitative evaluation of this approach, in which the decorrelation is associated with misfocus and image distortion, met with limited success.

Artificial "objective" speckles, on the other hand, can be produced by projecting a real image of a random pattern into a localized region of space. These speckles can be digitized and analyzed to measure out-of-plane motion and form the basis for a technique called "shadow speckle metrology" [6]. Prior developmental research in this area includes a study of rigid body rotation [6], contouring of a curved surface [6], deflection of a flat plate as measured through a fiber optic system [1], and profiling of relatively large structural members [7].

The first portion of the present work demonstrates that shadow speckle metrology can be applied to characterize the dynamic response of a vibrating component. Artificial speckles are projected onto the surface at an oblique angle using a 35mm projector and a speckled slide. The resulting speckle patterns, which move laterally as the surface moves out-of-plane, are captured either directly using a vidicon camera/digitizer system, or indirectly using a camera to record a time-average photograph which is digitized subsequently. Correlation coefficients are computed by numerically correlating small subsets from the stationary speckle pattern originally projected onto the sample with small subsets extracted from the digitized images recorded during vibration. The analysis of data taken in experimental tests shows that decorrelation takes place in areas where motion occurs. More importantly, the results of these tests indicate that the correlation coefficient can be used as an indicator to predict dynamic behavior.

Recently, a simple method of measuring local buckling of thin walled members by projecting a pattern of parallel equispaced lines on a test surface was demonstrated [8]. These lines were tracked by a computer and changes in their locations were related to movements in the out-of-plane direction. A similar scheme was applied in a device and associated process designed to contour or measure deflections on the inner surfaces of cavities [9]. The second portion of the present work demonstrates that these approaches can be modified and applied to characterize dynamic behavior using a technique called "line broadening."

Finally, the advantages and disadvantages of shadow speckle metrology and line broadening are discussed; some guidelines are formulated for future research.

DISPLACEMENT ANALYSIS USING SHADOW SPECKLE METROLOGY

Figure 1 shows a typical set-up for making shadow speckle measurements using a light source and camera located at equal distances from a structure. An artificial "objective" speckle pattern is projected from point S onto the undeformed surface (AB) using a 35mm slide projector equipped with a clear glass slide splattered with black paint. When the surface deforms or changes its location (to A'B'), speckles appear to shift in the x-direction. The corresponding displacement, u, is related to the out-of-plane displacement, w, by[5]

$$w = \frac{-u}{\tan\alpha + \tan\beta} \qquad (1)$$

Although both α and β vary from point to point, the sum of their tangents is constant, and w is linearly proportional to u over the full field. When the speckle pattern is projected onto the surface at a 45 degree angle (α), and the test object is viewed along the normal to the surface ($\beta = 0$), the apparent in-plane movement of the speckle pattern corresponds directly to the out-of-plane displacement of the surface.

In shadow speckle metrology, images of the test surface and the projected speckles are digitally recorded before and after deformation. Computer programs are used to extract subsets surrounding selected points in the initial recording. These 9 x 9 pixel subsets are numerically correlated with subsets extracted from the deformed image. Displacement measurement is accomplished by searching for the "best" match between the subsets. The evaluation is based on a parameter called the correlation coefficient which lies between +1.0 and -1.0, with higher values indicating a better agreement. Each point in the initial image is assumed to have displaced to the point in the deformed image which has the highest calculated value of the correlation coefficient.

To date, all of the structures studied using shadow speckle metrology have been subjected to quasi-static and sequential step loadings. The following section explores the ability of the technique to characterize the dynamic response of a vibrating component by numerically correlating speckle patterns recorded during vibration with the pattern recorded prior to vibration.

VIBRATION ANALYSIS USING SHADOW SPECKLE METROLOGY

The set-up shown in Figure 2 was designed and built to illustrate that shadow speckle metrology can be used to measure mode shapes and vibration amplitudes of a structural component. Speckles are projected from the right at 45 degrees with respect to the normal to the test surface ($\alpha = -45^{\circ}$). A beam splitter, positioned in the direction along the normal to the surface, allows normally viewed images of the projected speckles and the test surface to be digitally recorded both: (1) directly using a vidicon camera/digitizer system, and (2) indirectly by initially photographing the image using polaroid film, and then digitizing the photographic recording. The set-up also allows measurements to be made using an alternative method called line broadening by projecting a line onto the surface from the left ($\alpha = 45$). This approach is discussed later in the paper.

The test specimen consisted of a stiff plastic strip 76.2 mm (3 inches) wide, 609.6 mm (24 inches) long, and 1.01 mm (0.040 inches) thick, whose surface was painted flat white to increase contrast of the projected pattern. The upper end of the strip was attached to an audio speaker which was driven through a variable amplifier by a signal generator capable of producing a sinusoidal wave. The lower end of the strip was allowed to hang free. This arrangement was used to excite different transverse modes of vibration. The behavior of points along lines parallel to the longitudinal axis of the strip exhibit behavior analogous to that of a vibrating string described in the classic Melde vibration problem [10].

A speckle pattern was projected onto the surface and recorded with the strip in the stationary position. The digital and photographic records were used as a reference in all subsequent tests. The specimen was then excited at a frequency of 36 Hertz and images were recorded: (1) digitally in four separate fields using a sampling rate of 13.1k pixels/second (5 seconds are required to digitize a complete 256 x 256 pixel array with 256 grey levels), and (2) photographically using an exposure time of 0.5 seconds. Even though the polaroid photographs (which gave "time average" images) were considered more likely to produce useful results, the "live" images captured directly by the vidicon camera/digitizer were recorded simply to see if the extra step of recording the time-average photographs could be eliminated without significantly diminishing the quality of the test results.

All tests were performed with the specimen excited at an antinodal location; three and one half periods were observed over the length of the specimen. Live and time-average images were recorded over a portion of the specimen, containing two nodes and one antinode, for peak to peak amplitudes of 2, 4, 6, and 8 mm. The time-average images (from the polaroid photographs) were digitized and stored in a PDP 11/23 computer in the same format as the live images, as 256 x 256 pixel arrays with 256 grey levels.

Figure 3 shows a typical time-average photograph of the vibrating beam. The illuminated area to the right of the specimen contains test patterns and a scale for calibartion of the optical system. This portion of the image can be used to study the size of speckles relative to the pixel size; the vertical span of the image covered 256 rows. The speckle pattern shown on the specimen in Figure 3 was recorded as the specimen vibrated through 18 cycles at a peak to peak amplitude of 8 mm. Speckles retain their shapes at the nodal locations while "smearing" occurs, to different degrees, in other areas of the image. The hypothesis is that a meaningful decorrelation will occur when speckles in the modulated image are compared to those in the stationary image recorded prior to vibration.

Computer programs were written to analyze points along the vertical center line of the specimen (parallel to the longitudinal axis of the strip). Correlations were made between the initial speckle pattern recorded in the static condition and the modulated patterns recorded while the object was vibrating. Software was written to search for the maximum correlation coefficient in a limited area surrounding each point along the scan. The purpose of this search was to take into account rigid body motion of the specimen as it went into vibration, and any misalignment that might arise from inaccurate registration of the time-average photographs during digitizitation.

Figures 4 and 5 show plots of the correlation coefficient values versus position along the longitudinal axis of the strip for the direct digitizitation and digitized time-average photographs, respectively. Slightly different magnification factors were used to store direct (digitized) and indirect (photographed and then digitized) images; consequently, the mode shape spans a different number of columns. However, both figures show results for a peak to peak amplitude of 8 mm; curves drawn for smaller peak to peak amplitudes display similar characteristics. In Figures 4 and 5, the upper curve represents the distribution of numerically calculated correlation coefficients (shown as dots), while the lower curve shows the sinusoidal shape to be expected from a theoretical solution for a peak to peak amplitude of 8 mm. Clearly, in both cases, there is a strong relationship between the distribution of correlation coefficient values and the mode shape. Tests were conducted at different amplitudes of vibration to explore the possibility of relating the value of the correlation coefficient to the amplitude of vibration. Figure 6, for example, shows plots of the correlation values versus peak to peak vibration amplitudes. Even though the data are non-linear, they also show that the correlation cofficient decreases with increasing amplitude.

These findings demonstrate that the correlation coefficient can be used as an indicator to monitor the behavior of a vibrating specimen. More importantly, Figure 4 suggests that it is not necessary to record a time-average pattern. Meaningful data can be recorded digitally while the structure vibrates through many cycles using a vidicon/digitizer system scanning at an appropriate data acquisition rate! In both plots, values for the correlation coefficient approach the theoretical maximum of 1.0 at nodal locations; smaller values are found at other locations. Some periodic fluctuations are observable in the data. These may be due to the presence of higher order harmonics and/or the effects of variations in the size of the "objective" speckle within different sampling subsets. The latter becomes important when the size of the speckle becomes significant as compared to the area of the subset used to establish correlations. In addition, the size and shape of the projected speckles may change as the test surface moves away from the reference position. For example, any oblique motion of the test surface with respect to the reference position causes the speckles to elongate in the direction parallel to the plane formed by the propagation vectors from the illuminating source to the object and from the surface to the observation position. If the projected beam is not collimated, even motion normal to the reference surface causes speckles to change in size.

In the case of the vibrating strip, speckles at the antinodal locations grow in size due to the divergent illumination, but retain their shapes, since the tangent plane to the surface remains parallel to its original position. Speckles behave differently in adjacent areas where both the size and shape of the speckles change. This combination of factors will be considered in the development of new algorithms which incorporate suitable transformations and mappings to correct for distortions.

VIBRATION ANALYSIS USING LINE BROADENING

The main drawback of the shadow speckle method in measuring mode shapes and vibration amplitudes is that the numerical correlation routines are time consuming from a computational standpoint. An alternative approach for making such measurements is to project a line, as opposed to speckles, onto the test specimen. The main advantage of this approach, called line broadening, is that the shape and the amplitude of a vibrating component can be detected using a simple algorithm. The main disadvantage of line broadening is that information can be obtained only along a single line, as opposed to the full field information that can be measured using shadow speckle metrology.

As mentioned previously, the set-up shown in Figure 2 also allows tests to be conducted using line broadening. As shown in the figure, a line is projected from the left at an angle of 45 degrees with respect to the surface normal, along the center line of the strip parallel to the longitudinal axis of the specimen. The movement of the line is governed by Equation (1). The only difference in projection is that, in this experiment, the line is projected from the left while the speckles were projected from the right. Consequently, the projections shift in opposite directions when the test specimen moves away from its reference position. Images were recorded for a line projected onto the stationary surface and for the mode shape at all the amplitudes previously described. Each state was recorded directly with the camera/digitizer, and photographically using the still camera. The time-average photographs were digitized and stored in the same format as the direct recordings.

Figure 7 shows a time-average photograph of a bright line projected onto the test surface while it was vibrating with a peak to peak amplitude of 8 mm. The test patterns and the scale used for calibration of the optical system are shown to the right of the test strip. This figure clearly demonstrates that the line is "broadened" at points which move away from the reference position. This is reflected in the transverse intensity traces shown in Figures 8 and 9. Figure 8 shows the transverse trace recorded prior to vibration, while Figure 9 is a trace taken from the vibrating strip at an antinodal location.

These results were analyzed by identifying the effective width of the line generated by the vibrating specimen (Figure 9) and scaling that against the effective width of the line recorded on the stationary specimen (Figure 8). An increase in width of 7.88 mm was found as a result of this analysis which compares very favorably with the expected amplitude of 8 mm. This technique can be extended over the length of the line. For example, Figure 10 shows a plot of the change in effective line width measured at every 10 pixels along the length of the line, plus the value calculated at the antinode. All data were obtained using digitized time-avarage photographs. The figure also shows a sinusoidal curve representing the mode shape for a strip vibrating at a peak to peak amplitude of 8 mm. It should be noted that the vertical quantization of the experimental data is associated with the pixel resolution of the system. That is, measured line widths must be integer multiples of a pixel; 13, 14, 15, 16 pixels etc. Similar results are obtained from analysis of data taken at 2, 4 and 6 mm peak to peak amplitudes by both direct digitization and digitization of the photographs.

CONCLUSIONS

This paper has demonstrated two different computer-based optical methods for monitoring mode shapes and amplitudes of simple vibrating structures. Both methods, shadow speckle metrology and line broadening, rely on the projection of a high contrast pattern onto the test surface.

In shadow speckle metrology, numerical correlations between a projected speckle pattern recorded prior to excitation and the modulated speckle pattern recorded during excitation are computed. Both patterns can be captured directly using a camera/digitizer system, or indirectly in photographs which can be digitized subsequently. Results show that numerical correlation routines can be used to monitor the mode shape of the vibrating specimen. Further work has been suggested to improve the technique by taking distortions in the projected speckle patterns into account.

In the line broadening method, changes in effective line width are calculated from comparisons between the initial line width recorded prior to excitation and the modulated line width recorded as the specimen vibrates. Results obtained using this technique show that this approach can be used to measure mode shapes and vibration amplitudes.

The main advantages of shadow speckle metrology and line broadening are that they can be applied to any surface, they are non-contacting and non-destructive, and the analysis can be completely automated. In both methods the sensitivity may be altered by varying the directions of observation and projection. In addition, both may be conducted under normal room lighting.

The main advantage of line broadening over shadow speckle metrology is that line broadening can readily determine both the shape and amplitude of a vibrating component by a simple analysis, as opposed to the need to perform numerical correlations between various speckle patterns. The main disadvantage of line broadening is that measurements can be made only along a single line, as opposed to the full-field information that may obtained with shadow speckle metrology.

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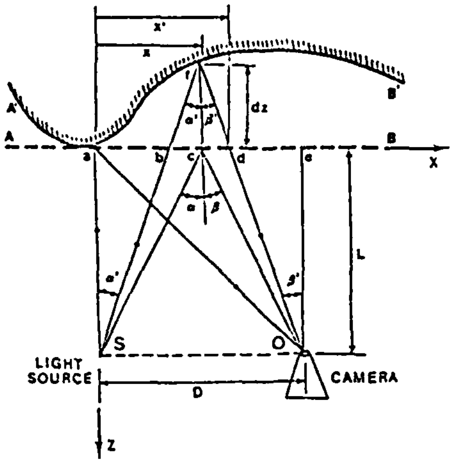

Fig. 1. Set-up for Shadow Speckle Metrology.

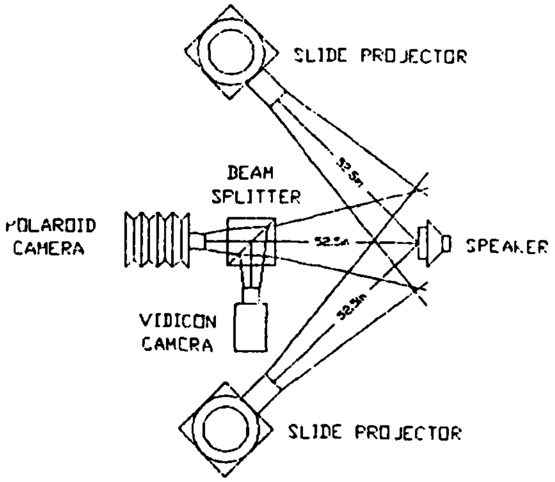

Fig. 2. Set-up for Vibration Analysis.

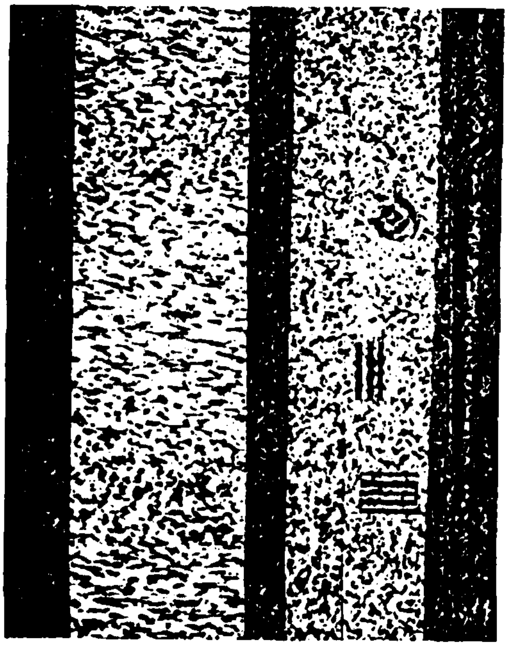

Fig. 3. Time Average Photograph of Vibrating Beam with Projected Speckles.

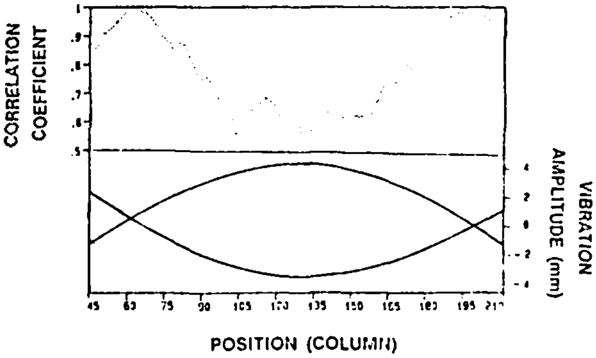

Fig. 4. Correlation Coefficient Versus Position by Direct Digitization

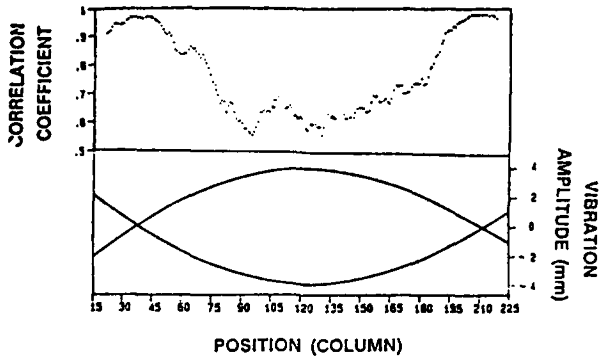

Fig. 5. Correlation Coefficient Versus Position by Time-Average Photography.

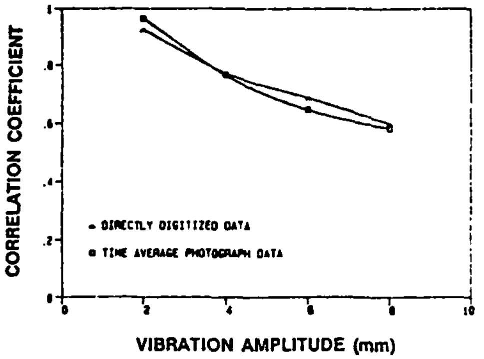

Fig. 6. Correlation Coefficient Versus Amplitude at the Antinode.

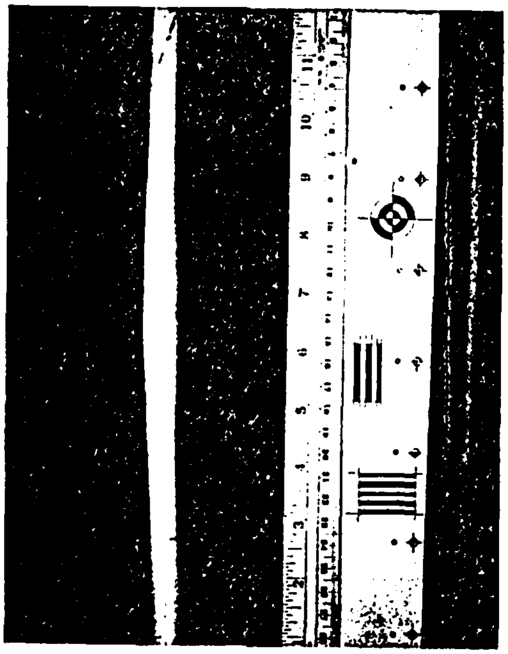

Fig. 7. Time-Average Photograph of Vibrating Beam with Projected Line.

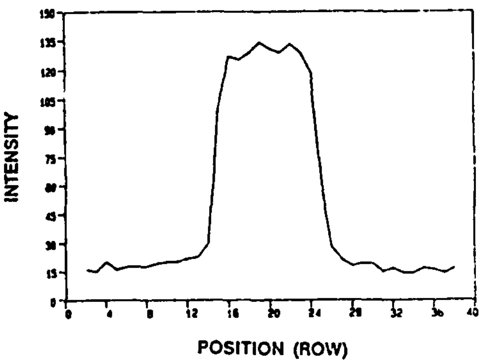

Fig. 8 Transverse Intensity Trace for the Stationary Line.

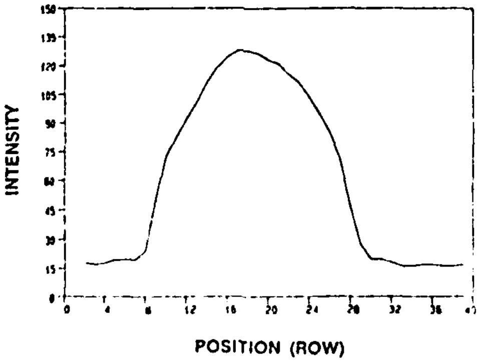

Fig. 9. Transverse Intensity Trace across Projected Line at an Antinode.

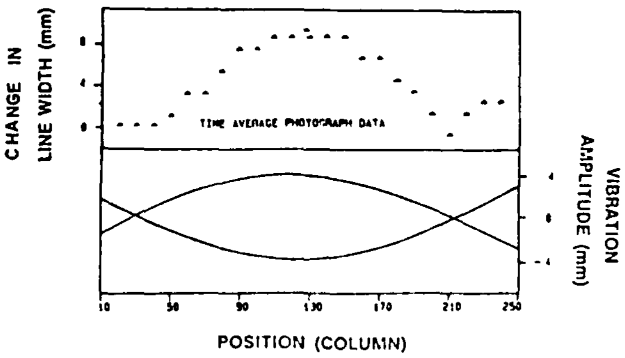

Fig. 10. Displacement Versus Position along the Vibrating Strip.

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