Variation in displacement values along projection moire fringes in contour difference and vibration analysis of structures

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Abstract. This paper presents a qualitative and quantitative analysis of time-averaged projection moire vibration measurements for a plate and a cylindrical shell. It is pointed out that although moire fringes are generally considered to represent a *constant* contour difference or *constant* vibration level, in practice, variations in local grid pitch values on the test-item surface result in wide variations in measured displacement levels for given fringe numbers, which must be taken into consideration for quantitative evaluation.

Subject terms: projection moire; noncontact measurement; vibration analysis; contour difference; fringes.

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CONTENTS

1. INTRODUCTION

Moire fringes, generated from a grid and projected from a conventional slide projector, are widely used to determine contour differences between reference- and test-item surfaces (TISs) or, by time averaging, to determine vibration amplitudes of the TIS.[1–4] To produce the moire fringes, the grid must be projected at an angle to the optical axis of the recording system (eye, camera, etc.), which is itself in the plane of bending/loading of the TIS.[5] Quantitative analysis of the resultant fringes is performed by use of equations involving the pitch of the projected grid on the TIS; moire fringes are considered to represent either constant contour difference or constant vibration amplitude.

Because of the constant angle of projection, the value of the grid pitch for curved surfaces varies considerably over the surface and the fringes are produced at each point according to the *local* value of pitch. Hence, moire fringes *do not* represent constant values of contour difference or vibration amplitude. The true values may be calculated from the measured local values of pitch.

In practice, even for a flat surface (plate), we have observed considerable variation of pitch (up to 15% for a 20×20 cm plate, projected 500 lines/in. grid, for a perpendicular distance of 150 cm, at an angle of 36° to the normal to the plate, recording along the normal). These results appeared when projection moire methods were applied relatively close to large objects. The source of the distribution lies in the fact that the projecting system is not a point source and that the angle between the projected grid and the normal to the TIS produces varying grid pitch with progression in wavefront.

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2. EXPERIMENTAL METHOD

To investigate the projection moire fringe method, we performed experiments for a flat aluminum plate (20 × 20 × 0.15 cm) and for a cylindrical aluminum shell segment (straight edges—17 cm; across flats—17.5 cm; length of straightened shell—19.1 cm; depth—3.35 cm; thickness—0.03 cm).

The method involved projecting a slide constructed of the grid onto the TIS and recording the time-averaged image with a 35 mm single lens reflex camera. The projection/recording plane was perpendicular to the representative plane of the TIS (plane of the flat plate or plane tangential to the cylindrical shell) and included the optical center of the slide projector (considered to be the center of the slide) and of the camera (considered to be the center of the film plane). The camera was placed with its optical axis coincident with the center of the TIS and normal to the representative plane. The optical axis of the slide projector was inclined by 36° with respect to the camera axis and was also coincident with the center of the TIS.

The slide projector was a Gaf 501 with a Maginon 85/2.8 lens. To improve the quality of the moire fringes, the field of the projector was restricted with an iris of typical opening diameter 6 mm, placed at the outer surface of the lens at the center of the field. The pitch of the grid slide was 500 lines/in. The camera was a Nikon FM2 with a Telesar 135/2.8 mm lens. The separation distance between the camera/projector plane and the representative plane of the TIS was 150 cm, and projection angle was 36° to the normal to the TIS. A single 15 mm extension ring was placed between the camera lens and the body to increase magnification of the recording system. The lens f-stop was 2.8, and typical recording time was ½ to 2 s.

The test items were attached to the electrodynamic shaker by an impedance head and a 10-32 UNF screw, approximately 2 cm long (see Figs. 1 and 2). The impedance head (Bruel and Kjaer 8001) provided a useful means of transferring the excitation to the test item, while its accelerometer output provided an indication of the input excitation level. The 2 cm screw was used to increase the isolation between shaker and test item. The shaker was a Goodmans Industries Vibration Equipment with a Phillips T1961722/Goodmans Industries Vibration Equipment PA250 power amplifier. The test item was excited at resonant frequencies with the aid of a Krohn-Hite 4200 oscillator, and the shaker excitation level was measured with a Fluke 8010A digital voltmeter. In prac-

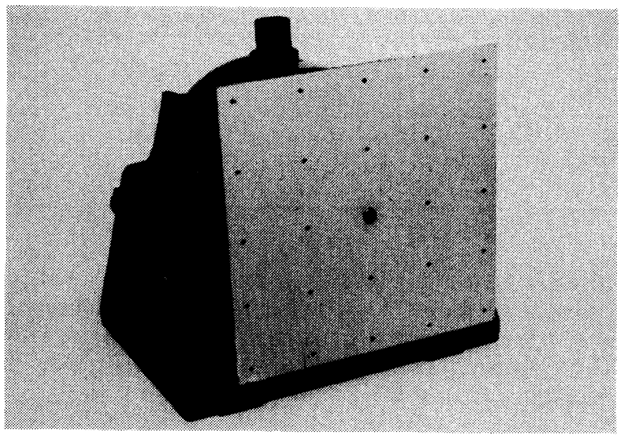

Fig. 1. View of the flat plate (20×20×0.15 cm) mounted on an electrodynamic shaker.

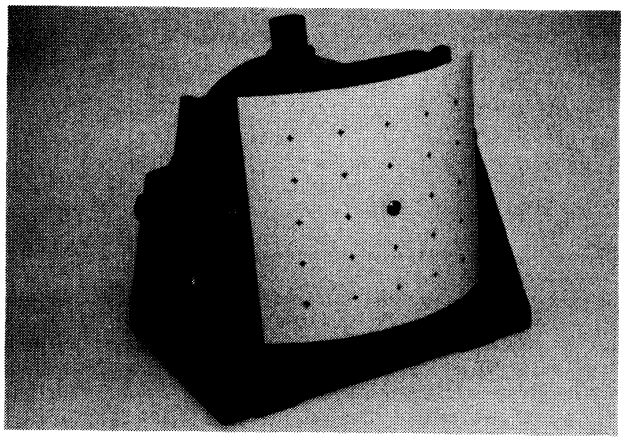

Fig. 2. View of the cylindrical shell (straight edges—17 cm; across flats—17.5 cm; length of straightened shell—19.1 cm; depth—3.35 cm; thickness—0.3 cm) mounted on an electrodynamic shaker.

tice, the system response included higher harmonics, and these were filtered out with a Krohn-Hite 3343 low pass filter. The exciting frequency was measured with a Hewlett-Packard 5315A counter. The impedance head output was amplified with an Unholtz-Dickie Model 22 charge amplifier.

3. ANALYSIS

Quantitative analysis of the time-averaged moire fringes is performed with the aid of equations developed according to the method described in Ref. 1. The intensity distribution of the projected grid on the TIS is integrated over a vibration period, resulting in more fringes that represent the argument values for which the zeroth-order Bessel function is nulled. This results in solutions of the form

$$Z_{0,N} = \frac{p'\xi_N}{2\pi\alpha'\tan\alpha} , \qquad (1)$$

where N is the moire fringe number; $Z_{0,N}$ is the peak vibration value for moire fringe N; ξ_N is the argument value for which the zeroth-order Bessel function is nulled, fringe N; p′ is the local grid pitch, measured on recorded photograph; α' is the magnification ratio of recording system, measured as the ratio of distance between two identifying points on the photograph and divided by the corresponding distance on the TIS; and α is the projection angle to the normal to the TIS.

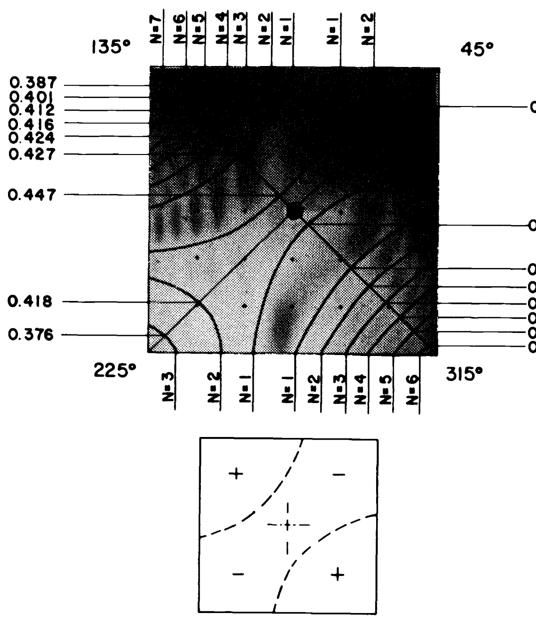

Fig. 3. Moire fringe pattern for 20×20×0.15 cm aluminum plate with sinusoidal excitation at center at 142 Hz. Grid pitch values are in millimeters.

4. RESULTS AND DISCUSSION

Figure 3 shows the moire fringe pattern for the aluminum plate excited at 142 Hz. At this frequency, the first mode was observed for the plate in a free-free-free-free configuration.[6] The lack of symmetry in the four quadrants of the plate indicates greater excitation response in the upper left and lower right corners. This behavior was noticed when the plate was excited slightly off the resonant frequency (of the order of 0.1 Hz).

The schematic representation of the vibration mode appears on the right-hand side of Fig. 3, indicating common phase between upper left and lower right corners with opposite phase in the central region and upper right and lower left corners. The nodes, indicated by the dashed lines, appear between the two sets of N = 1 moire fringes. The moire fringes represent the excitation mode shape, relative to the center of the plate, with maximum response at the perimeter. Hence, the fringes are numbered from the center outward. One would thus expect the moire fringes to represent constant vibration amplitude levels. However, Fig. 3 indicates a 15% distribution in measured pitch values (relative to the center of the plate). Considering, for example, fringe number 1 (closest to the plate center), the value of pitch at the right-hand side is 0.46 mm, while that at the left is 0.38 mm. These figures result in a difference of 21% in calculated vibration level for a given moire fringe.

The problem is more apparent in the fringe pattern for a curved surface (Fig. 4). Here, the grid lines are considerably more spread out on the side of the shell, farthest from the slide projector (right-hand side of the figure). The vibration levels

TABLE I. Local pitch and peak vibration amplitudes for the cylindrical shell of Fig. 4, moire fringe number 5. All values are given in millimeters.

Left-hand side						Right-hand side					
Upper		Center		Lower		Upper		Center		Lower	
Pitch	$z_{0,5}$	Pitch	$z_{0,5}$	Pitch	$z_{0,5}$	Pitch	$z_{0,5}$	Pitch	$z_{0,5}$	Pitch	$z_{0,5}$
0.38	2.2	0.38	2.2	0.36	2.1	0.93	5.4	0.79	4.5	0.69	4.0

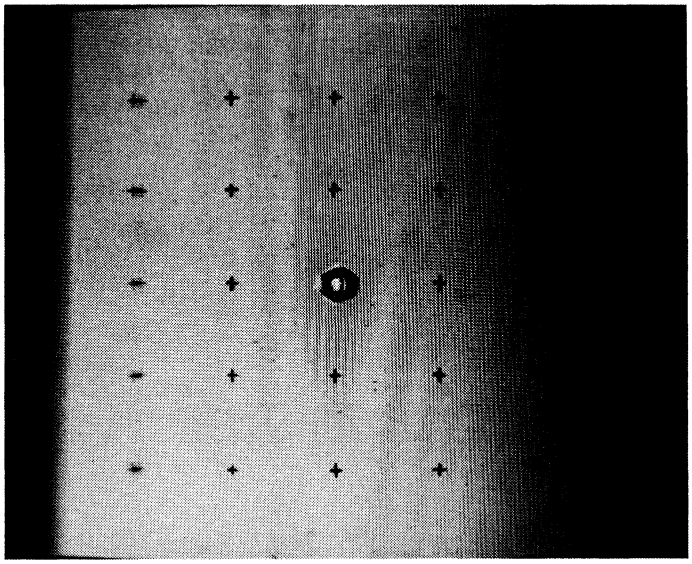

Fig. 4. Moire fringe patterns for cylindrical aluminum shell, sinusoidally excited at 24.5 Hz.

are thus greater on the right-hand side than on the left for a given moire fringe number. This result is demonstrated in Table I, where the vibration levels are calculated for the fifth moire fringe as a function of position, for the cylindrical shell of Fig. 4, excited at 24.5 Hz. The vibration levels on the right-hand side are more than double those on the left.

The solution to the above-mentioned problems is twofold. For an item that is symmetrical about a given axis and has a simple geometry (such as the cylindrical shell), progressively graded grids may be used, where the grid pitch changes with position in such a way as to counter the changes produced by the TIS. This may improve the spread in pitch values, but it is not expected to counter the distribution completely. With the improved distribution of moire fringes, one may then apply the method that is used at present. Vibration levels are calculated over the TIS, using the locally measured pitch value. One may then construct a new set of curves that are the loci of constant vibration amplitude levels. At present the process is performed manually, but automatic measurement of local pitch values, digitization, and application of graphics software may be used to significantly shorten the analysis time (see, for example, Ref. 7).

5. CONCLUSIONS

Although projection moire provides a useful means for the noncontact measurement of whole surfaces with the use of simple equipment, the resulting fringe pattern requires the application of analytical methods that to our knowledge have yet to be reported in the literature. Moire fringes are generally considered to represent constant contour difference/constant vibration amplitude. However, it has been shown that variation of grid pitch on the test-item surface in projection moire results in wide variation in amplitude along moire fringes. Quantitative analysis may be performed, using locally measured pitch values.

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