Remote Vibration Measurement by Time-Averaged Holographic Interferometry

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This report describes the first successful demonstration of the use of fiber optics in the study of vibrating objects by time-averaged holographic interferometry (HI), as well as the first recording of remote holograms without the use of an output lens to image the transmitted object onto the hologram. These experiments further extend the practical range of fiber-optic HI and demonstrate the convenience, flexibility and applicability of such systems, even in the presence of significant mechanical disturbance.

Experiments

In each experiment the vibrating test object was an aluminum alloy cantilever beam (90-mm long by 25-mm wide by 1-mm thick) excited at its free end by a shaker driven by a variable-frequency* audio oscillator set at 600 Hz. Figure 1 shows the fiber-optic system used in the first and simplest of these tests. A HeNe laser (λ = 632.8 nm) operating at 20 mw was used as a coherent light source. After light from the laser was passed through the beam splitter one output beam was launched through a low-power microscope objective into a single-mode optical fiber (SMF). All SMFs used in these experiments were designed for single-mode operation at around 0.6 μm with NA = 0.1159 and a 7.3 μm core diameter. This object beam was used to illuminate the vibrating cantilever, which had been painted white to improve its reflectivity. A second SMF, similarly illuminated, was used to provide a reference beam. The steering mirror shown in the schematic, Fig. 1, was used to manipulate this beam. If desired in order to further simplify the setup, it could easily be eliminated and the SMF positioned to illuminate the hologram plate directly, just as the object illumination SMF was positioned to illuminate the object directly.

Throughout these tests, the laser, launch optics, shaker-cantilever and hologram recording system were all firmly mounted to a rigid optical bench, while the SMFs were left virtually unconstrained, except at their ends. Since both of the fiber-optic elements were single mode the system was very stable, even in the presence of significant mechanical

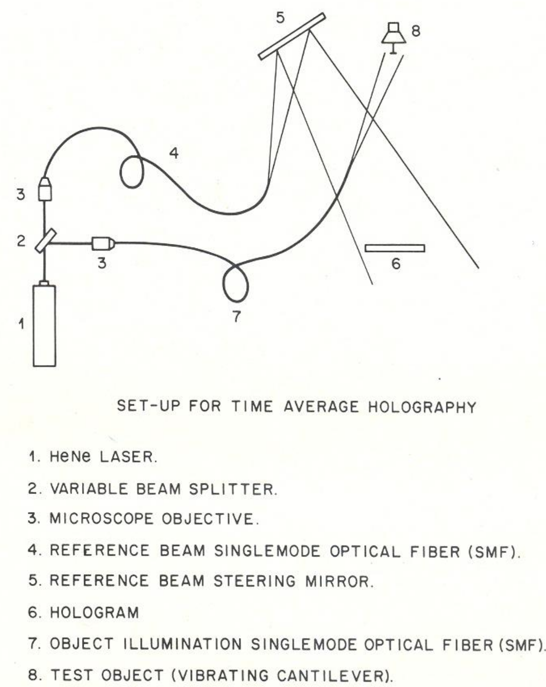


Fig. 1—*Diagram of a single-mode fiber-optic holographic interferometer for studies of a vibrating object*

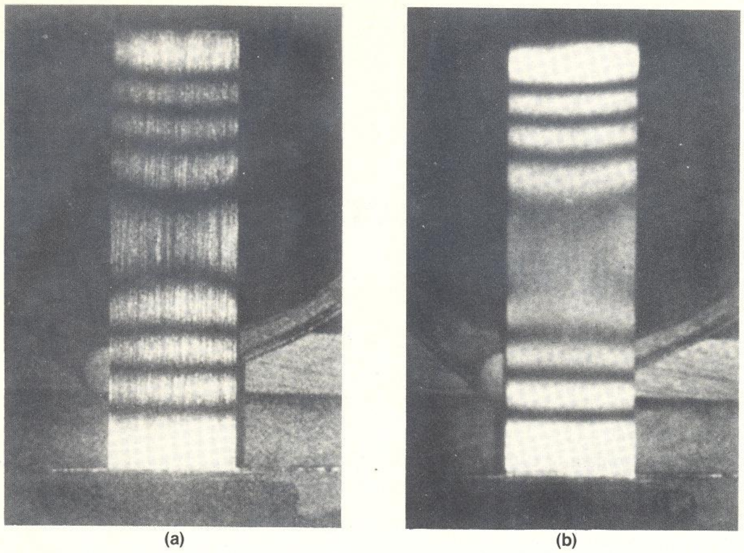


Fig. 2—*Holographic interferogram of a cantilever beam vibrating at 600 Hz as recorded (a) directly on a film plate, and (b) through an imaging lens onto a film plate*

activity during the exposure. Figure 2(a) shows the resulting high-resolution time-averaged Fraunhofer (far-field) holographic interferogram which was obtained with an exposure on the order of 30 seconds on a high-resolution photographic plate. Here the displacement occurs along the Z direction, measured normal to the cantilever whose surface initially lies in the XY plane. The fringes vary in intensity and are not cosinusoidal as in double-exposure or real-time HI. Areas on the ends of the beam represent nodal points and are zero-order Bessel function $[J_0(Z)]$ fringes at $Z = 0$. They are easily identified by their brightness. Higher order fringes, apparent in the central portion of the specimen, represent subsequent maxima of $J_0(Z)$ and decrease in brightness with increasing fringe order.

A second experiment was run using the same configuration but with a rigidly mounted lens positioned to focus an image of the vibrating cantilever beam onto the hologram recording plane. Figure 2(b) shows a white-light reconstruction of the resulting time-averaged holographic interferogram. This reconstruction exhibits good contrast and only a small loss of resolution in comparison with the Fraunhofer hologram reconstruction shown in Fig. 2(a). A second run using essentially the same setup was made later (at a slightly greater vibration amplitude) with the high-resolution film plate used originally replaced by an HC-300 'instant' holocamera system which can produce a highly efficient, bright hologram in 30 seconds. A coherent-light reconstruction of the resulting time-averaged holographic interferogram compared very favorably with the image-plane reconstruction shown in Fig. 2(b), although there was some noise associated with dust on the thermoplastic visible in the image plane. In all three of these examples it was quite evident that the presence of significant vibration on the bench had little effect on the data quality, regardless of whether or not the holograms were recorded directly or on the image plane.

A primary objective of this study was to evaluate the performance of a combined system using both the SMF illumination fibers and a coherent multimode fiber-optic bundle (MMB) for the return imaging. Figure 3 shows the present laboratory system as adapted for this purpose. Here an MMB of 4-mm diameter and 90-cm length, having a resolution of 27

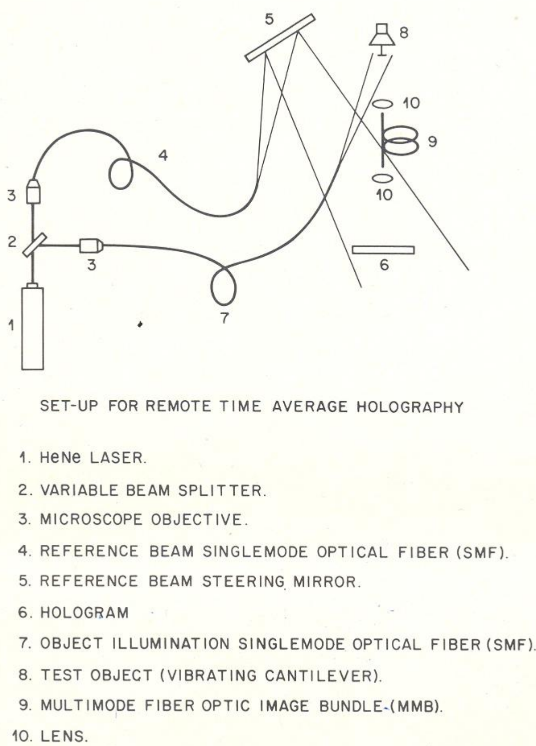
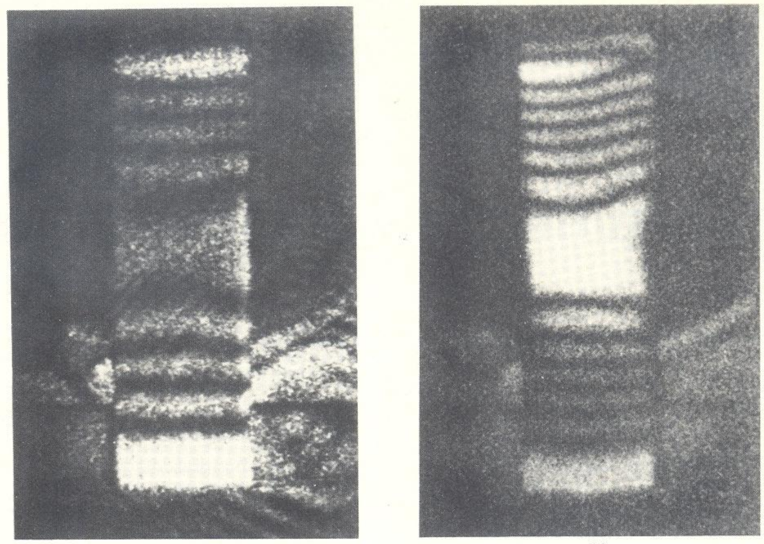


Fig. 3—*Schematic diagram of a combined-mode fiber-optic holographic interferometer for remote studies of a vibrating object*



(a) (b)

Fig. 4—*Holographic interferogram of a remote cantilever beam vibrating at 600 Hz (a) through a 4-mm diam MMB with an imaging-lens output as recorded on a high-resolution photographic plate, and (b) through a 10-mm diam MMB without an output imaging lens as recorded on the HC 300 instant holocamera*

ℓ/mm (and composed of many thousands of individual 12-micron diameter multimode fibers) was used to transmit the image of the test subject from the test site to the hologram. Both ends of the MMB were rigidly mounted to the optical bench while the length between was taped to the flat surface of the bench. The real image transmitted through the MMB was focused on a high-resolution photographic plate and combined with a reference beam to form a 'remote' image-plane hologram. The object beam SMF was trimmed to the appropriately shorter length required to maintain the proper match between object and reference beam path lengths. The white-light reconstruction in Fig. 4(a) shows the corresponding time-average HI fringe pattern taken at 600 Hz over a period of 25 seconds. As might be expected, there is some graininess associated with the limited resolution of the MMB itself, as well as the usual artifacts (associated with dust in the system) which can appear in white-light reconstructions of any image-plane hologram (even when it is bleached, as this one was). Nevertheless, this combined-mode fiber-optic holographic system provided enough long term stability for the generation of interferometric data, even in the presence of unisolated vibration on the optical bench.

A final test was run on the same system with the MMB output lens removed so that the resulting Fraunhofer hologram provided a direct recording of its output. In addition, the photographic plate was replaced by the instant holocamera. A reconstruction of the resulting J_0^2 fringe field was photographed by a camera focused on the output end of the MMB through a hologram recorded during an exposure of around six seconds. This interferogram showed good contrast with none of the spots or artifacts associated with the image-plane reconstructions, but still exhibited a significant loss of resolution associated with the MMB itself. This experiment was repeated with the tape used to stabilize the MMB removed. Since no significant change was seen, it was concluded that as long as the MMB was held firmly at its ends and supported along its length, the present combined-mode fiber-optic system would function satisfactorily. Finally, Fig. 4(b) shows the result obtained for almost one and a half times the original J_0^2 fringe density obtained using the same system and holocamera, but with the 4-mm diameter MMB replaced by a 10-mm MMB of about the same length and resolution. Here the larger diameter MMB permitted the transmission of a much larger object image, so that while there is some loss of contrast and intensity, there is also a significant improvement in resolution. The contrast and intensity can readily be improved through the use of a more powerful laser and/or a larger image input lens to the MMB.

Conclusions

(1) As expected, SMF elements are very stable under many different circumstances and provide excellent illuminators for time-averaged holographic interferometry of vibrating objects.

(2) Imaging through MMBs for remote applications can be used for time-average studies of vibrating objects provided they are stabilized to prevent gross motions which would change their propagation characteristics and destroy correlation during exposure.

(3) Both image and Fraunhofer (far-field) plane time-averaged holograms may be recorded using the combined-mode fiber-optic holographic interferometer.

(4) Image-plane holograms appear to be noisier and consequently less satisfactory than Fraunhofer holograms, especially as generated through an MMB.

(5) The use of a fiber-optic imaging bundle for remote access necessarily reduces the resolution of the system, although a larger diameter (e.g., 10 mm) MMB can readily be made to generate time-averaged holograms of better resolution than can a standard 4-mm diameter MMB.

(6) It would be highly desirable to have a single-mode coherent optical-fiber image bundle for remote application, since real-world applications rarely include isolated optical benches for stable mounting.

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