Coherent Structure Effects on the Optical Performance of Plane Shear Layers

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Although there has been extensive research on the optical properties of shear layers, there have been no reported studies of the optical effects on large scale coherent structures existing in turbulent shear layers. The research reported here investigated the effects of such coherent structures and of external perturbation of the shear layer on the optical quality of a propagating laser beam. High-speed pictures suggest that the presence of large eddies influences the shape of the far-field intensity profiles. In addition, time-averaged pictures show that perturbing a shear layer can affect the Strehl ratio. These results demonstrate that the optical properties of shear layers may be controlled and improved.

Nomenclature

a = beam radius
n = refractive index
SR = Strehl ratio
U = fluid velocity
w_x = view angle to the far field
X = downstream distance from the splitter plate
β = Gladstone-Dale constant
δ = visual shear-layer thickness
λ = wavelength of laser beam
ρ_{ref} = reference fluid density
( ) = time averaged

Introduction

THE effects of randomly varying refractive index on propagating beams have been studied since the early 1950s,[1] and in recent years, the study of laser-beam refractive scattering by shear layers has become important. This is due, in part, to current interest in imaging systems and in the application of high-power lasers. In high-power lasers, aerodynamic windows are used instead of solid glass windows to prevent overheating. Most aerodynamic windows use a gas jet normal to the laser beam, so the optics of shear layers is of primary concern.[2] In addition, applications such as energy transfer from a ground station to a point in space and optical imaging using telescopes may involve light beam/shear layer interactions.[3]

In a mixing layer, fluid turbulence produces random spatial and temporal fluctuation in gas density which causes refractive-index fluctuations in the flow. The relationship between gas density and refractive index is given by the Lorentz-Lorenz formula[4]:

$$n = 1 + K\rho$$

where $K = \beta/\rho_{\text{ref}}$.

Until recently, fluctuation in the refractive index due to turbulence in a shear layer has been assumed homogeneous and isotropic. This assumption was the basis for analytical work such as that of Vu et al.[5] and Legner et al.[6] In 1969, Vu et al. modeled the optical performance of a homogeneous shear layer in terms of its Strehl ratio defined as the ratio of the peak intensity of a beam with phase aberrations to the peak intensity of an ideal diffraction-limited beam. For a lack of a better model, this work has been accepted by many researchers as a means of predicting the Strehl ratio, although the model has not been adequately tested experimentally. In addition, the many assumptions on which this model is based restrict its application to very limited situations. For instance, the model assumes that the turbulence in a shear layer is homogeneous. However, Brown and Roshko[7] saw large vortices, which they called coherent structures, during their experimental flow visualization of a shear layer in 1971. These vortices convected downstream at the mean speed of the two mixing-layer streams. A question arises as to whether the presence of coherent structures produces special optical effects that should be incorporated into methods of predicting the Strehl ratio. If they do, then it becomes necessary to understand how these structures affect the optical quality of a laser beam. Furthermore, in 1982, Oster and Wygnanski[8] showed that external perturbation affects the fluid mechanics of shear layers, and in particular, the growth rate of these coherent structures. These observations raise an even more interesting question. Does perturbing a shear layer affect the coherent structures in a manner that might allow control over the optical performance of a shear-layer? If so, the techniques for controlling shear-layer optics might be available.

Experimental Design

This research project investigated the effects of shear-layer coherent structures on the optical quality of a beam propagating through a mixing layer. A second phase of this research examined the possibility of perturbing a shear layer to control its optical behavior.

A small low-speed wind tunnel generated a plane shear layer through which a laser beam was propagated normal through the shear layer. The wind tunnel (see Fig. 1) consisted of two separate tunnels discharging two streams of fluid through nozzles into a common test section with zero pressure gradient. Honeycomb and three screens (3-, 2-, and 1-mm mesh sizes) were used in both tunnels to straighten the flow and to reduce turbulence. Calibration of the wind tunnel by a hot wire anemometer revealed turbulence intensities of less than 0.5%. A splitter plate extended throughout the entire length of

Received June 12, 1989; revision received Feb. 5, 1990.

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the wind tunnel ending just at the exit of the nozzles, each of which has a 4:1 contraction ratio. The test section measured 12 in. long by 4 in. wide by 2 in. high (1 in. for each tunnel) an was constructed largely out of plexiglass. Four windows with an optical quality of $\lambda/8$ were used in the test section for transmission of the laser beam. The top and bottom streams of the shear layer were a helium/argon mixture (1.8 m/s) and air (3.0 m/s) respectively. The velocity ratios of the streams were therefore 0.6 Helium (30.6%) and argon (69.4%) were premixed to provide a gas with density equal to that of air and also to provide a refractive-index difference ($\Delta n = 6.4 \times 10^{-5}$) between the two streams. At these low speeds, index fluctuation is caused by mixing of optically dissimilar gases and not due to any pressure or temperature variations in the flow. A 10-mm-wide flap which could be oscillated by two voice coils was placed at the end of the splitter plate separating the two streams. The voice coils were driven between 0–350 Hz and the peak-to-peak amplitude was set to 0.7 mm thus externally perturbing the flow.

The optical components, shown in Fig. 2, consisted of a helium-neon laser at a wavelength of 6328 Å and an expanding 6.5-cm-diam telescope that provided collimated light through the test section. Two beam paths were formed by a beam splitter; the first beam was directed through the shear layer via three-axis mirrors and then intercepted by a receiving telescope. The second telescope focused the far-field profile onto the image plane of an electronic charge coupled device (CCD) camera. The second beam of the same size as the first beam was passed through the shear layer at right angles to the first beam. The image received on the photographic plate gave side-view pictures of the shear layer at the same instant as the beam-intensity profiles. The camera recorded the intensity profile image which was digitized and stored in computer memory. Simultaneous shadowgraph pictures of the side view revealed the position of large vortices relative to the laser beam.

To investigate the effects of coherent structures on the optics of shear layers, instantaneous Strehl ratios were measured while the beam passed through different areas of the vortices. Obtaining time-averaged Strehl ratios for the unperturbed and perturbed shear layer allowed examination of the changes in optical effects brought about by controlling the shear layer.

Results

The experimental results are presented in two parts: the first are short-duration (100-μs exposures) images of a laser beam propagating through the shear layer, and the second are time-averaged images (2-s exposures) of the same laser beam.

Short Exposure Measurement

Figure 3a is an example of a short-duration picture obtained by the imaging system under the condition of no flow. The X and Y coordinate of the figure correspond to the spatial coordinate of the image plane while the Z axis indicates the digitized intensity as shown by Fig. 3b. The image plane was

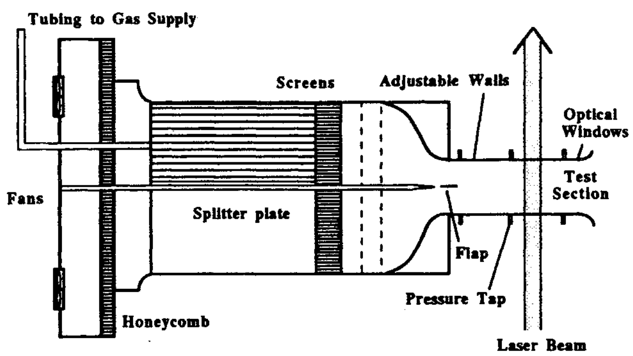


Fig. 1 Schematic diagram of the wind tunnel.

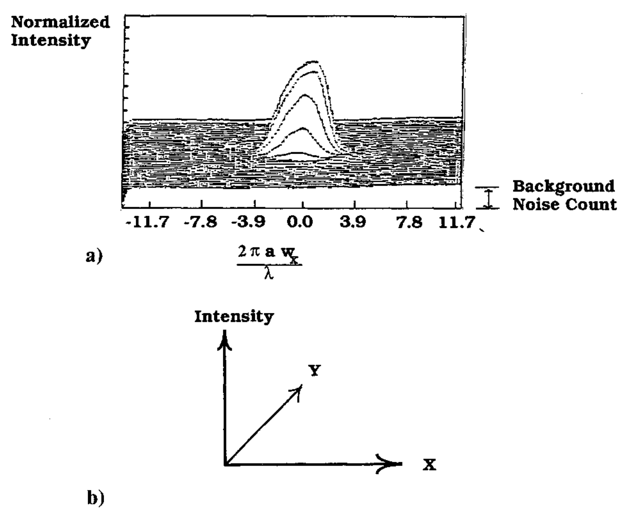


Fig. 3 a) Intensity profile of the transmitted beam under condisions of no flow (horizontal scale is nondimensionallized for the far-field optics) and b) coordinate system.

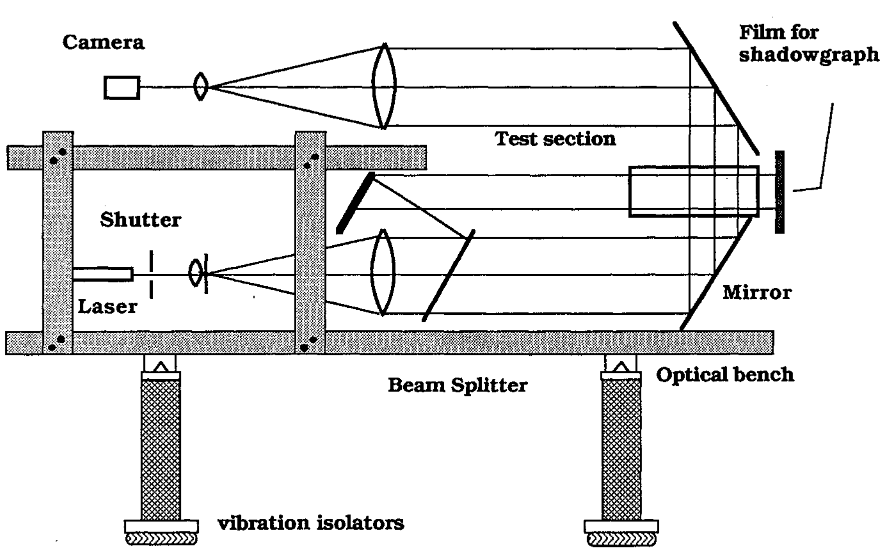
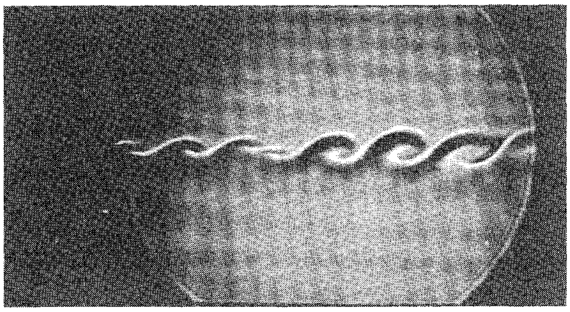
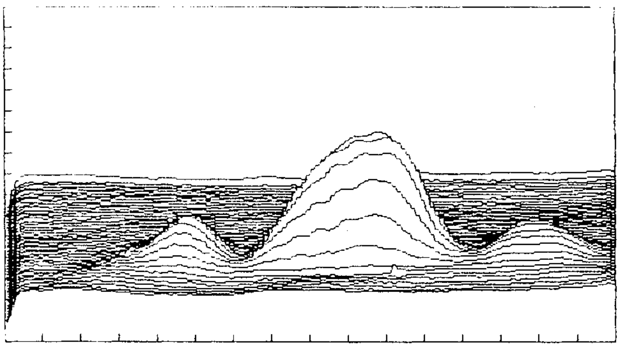


Fig. 2 Optical setup.

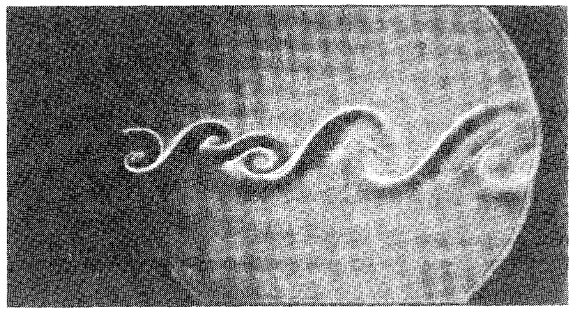


a) Instantaneous shadowgraph of the unperturbed shear layer.

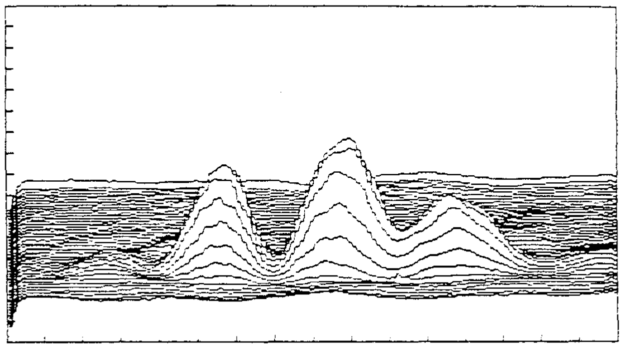


b) Far-field intensity profile showing a main peak with smaller satellite peaks (the scales are similar to fig. 3).

Fig. 4 Effects of coherent structures. (The 6.5-cm-diam laser beam is centered at 5 cm from the splitter plate. The exposure time is 100 μs.)



a) Instantaneous shadowgraph of the flow perturbed at the subharmonic frequency (140Hz).



b) Far-field intensity profile showing multiple peaks (the scales are similar to fig. 3).

Fig. 5 Optical effects of perturbed coherent structures. (6.5-cm-diam laser beam is centered at 5 cm from the splitter plate.)

positioned in the far-field region of the Fraunhofer diffraction pattern.[4] The X coordinate of the image plane is a non-dimensional scale $2\pi a w_x/\lambda$, where a is the beam radius, w_x is the view angle to the far field, and λ is the wavelength of the laser.[4] Figure 3a is a pseudo-three-dimensional intensity profile of the reference pattern for a 6.5-cm-diam test beam case. The idea far-field diffraction pattern of a circular, uniform phase laser beam is called an Airy pattern.[4] This reference pattern (Fig. 3a) is as close as the experimental setup would permit to the ideal diffraction pattern. The first ring of the test pattern can barely be seen in the figure because its peak intensity is about 1% of the central peak intensity, which is at the limit of the dynamic range of the detector. The base width of this disk measures 3.90 on the nondimensional scale while the ideal theoretical value should be 3.83. Some of the discrepancy is undoubtedly due to the small aberrations in the optical train and in the laser-beam alignment that affects the symmetry of the recorded image. The Strehl ratio can be calculated by dividing the peak pixel amplitude (after subtracting the background noise count) of a distorted beam by that of the experimentally determined reference beam. The background noise count is the camera signal without light exposure and is represented by the arrow in Fig. 3a. The reference signal was obtained at the beginning and end of each session measurement and was repeatable to within 1%. The instantaneous reference images agree well with the reference images for the long-exposure measurements too.

Figure 4 shows the effect of the coherent structures on a 6.5-cm-diam laser beam centered at 5.0 cm downstream from the splitter plate. The upper picture is a 100 μs time exposure side-view shadowgraph of a mixing layer with a visual growth rate (δ/x) of 0.1. The shadowgraph is 6.5 cm in diameter and shows the vortices that affect the laser beam. The lower picture is a far-field laser intensity profile that shows a main peak with smaller satellite peaks on both sides, indicating the effects of the coherent structures on the beam propagation. The shape differs from the expected for a homogeneous shear layer with a wide spectrum of turbulent scales. The far-field intensity profile for a homogeneous turbulent layer would be a single-peak, bell-like shape with small amplitude fluctuations in the profile.

To further test the observation that coherent structures affect the optics, the 6.5-cm-diam beam was passed through a series of pairing vortices caused by perturbing the flow at its subharmonic frequency. Like the previous pictures, Fig. 5 is also a 100 μs exposure and the beam is centered 5 cm downstream from the splitter plate. In the figure, the initial vortices amalgamated to form large vortices[8]; their effects are apparent in the intensity profile shown. These large vortices cause phase distortions in the laser beam. The beam's complicated far-field diffraction results in multiple peaks in its intensity profile. A sequence of pictures also reveals that the intensity profiles recorded by the CCD camera moved in synchronization with the vortical structures captured in the shadowgraphs. Typically, the maximum movement of a peak corresponded to a tilting less than the spot-image size. This observation further demonstrates that the large vortices cause the multiple peaks in the intensity profiles. From these last two figures, there is little doubt that coherent structures actually do affect shear-layer optics.

Long-Exposure Measurements

Time-averaged pictures (2-s exposures) include the optical effects of approximately 80–200 vortices passing through the beam. These long exposures are used to obtain the time-averaged Strehl ratio that gives the time-integrated effects of coherent structures on a continuous laser beam.

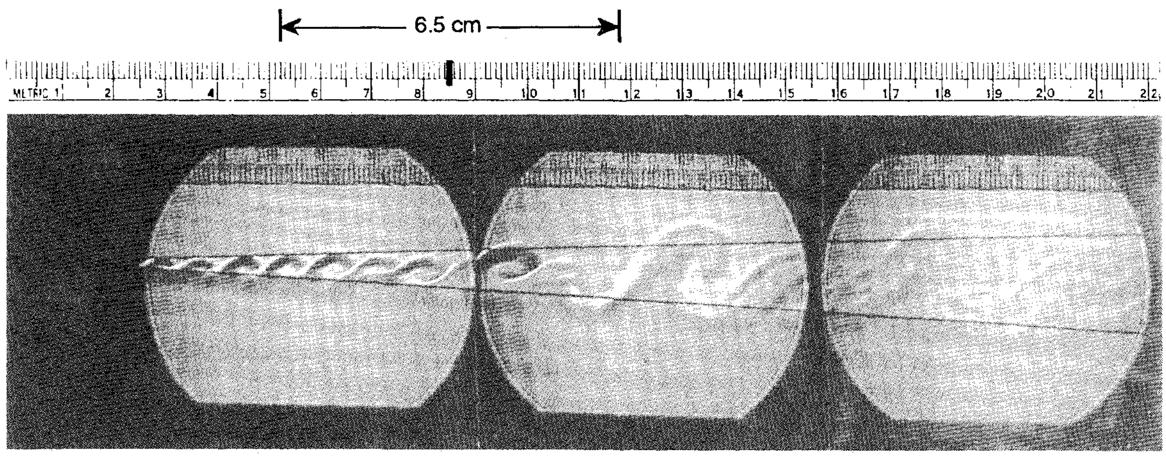
Figure 6 shows instantaneous shadowgraphs of an unperturbed and a perturbed shear layer. The shear layer grows linearly with a growth rate (δ/x) of 0.1 that agrees with the results of Brown and Roshko. For this shear layer, a hot wire anemometer and a spectrum analyzer measured the splitter-plate shedding frequency to be 280 Hz. This is the natural Kelvin-Helmholtz frequency and also the most amplified frequency according to instability analysis. When the vibrating flap was oscillated at 280 Hz, the layer stops growing (see Fig. 5b). The vortices of the perturbed layer have constant spacing and move downstream uniformly. About 11.5 cm from the splitter plate, the layer resumes its original growth rate. A region of no growth and a region of regrowth have also been observed.[8]

To show the effects of perturbing a shear layer on the optical quality of the laser beam, a series of long-exposure images were obtained using the information of the vortices sizes and positions from Fig. 6. A 6.5-cm-diam laser beam was therefore centered 8.5 cm from the splitter plate. The beam's size and position is marked on Fig. 6 to show the beam's position relative to the shear layer. A 2-s time-averaged picture of the ideal diffraction-limited beam is given in Fig. 7a. The smaller peak on the left-front corner is a reference peak used to normalize the peak intensity to remove the effects of laser power fluctuation. When the beam propagated through the linearly growing, unperturbed shear layer, the intensity profile in Fig. 7b spreads and the peak intensity decreases. The beam is now Gaussian-like in shape (because of time averaging). The time-averaged Strehl ratio $\overline{SR}$ is 0.66. Phase distortions, produced by the turbulent shear layer cause the peak-intensity reduction. However, when the same flow is perturbed at 280 Hz, the beam's intensity profile narrows again and the Strehl ratio increases to 0.91 (see Fig. 7c). This improvement is merely a reflection of improvements in the short-exposure pictures that also show improved instantaneous Strehl ratio. It is also interesting to note that, in 1985, Roberts and Roshko observed reduced mixing in the frequency-locked region (region of constant shear-layer thickness) of a forced shear layer.[9] In view of this result, the optical measurements suggest that reduced mixing causes improvements of the Strehl ratio. The remarkable improvement in Strehl ratio demonstrates that the optical quality of a shear layer may be changed by changing its fluid mechanics; this opens new and interesting avenues of research for controlling optical behavior of shear flows.

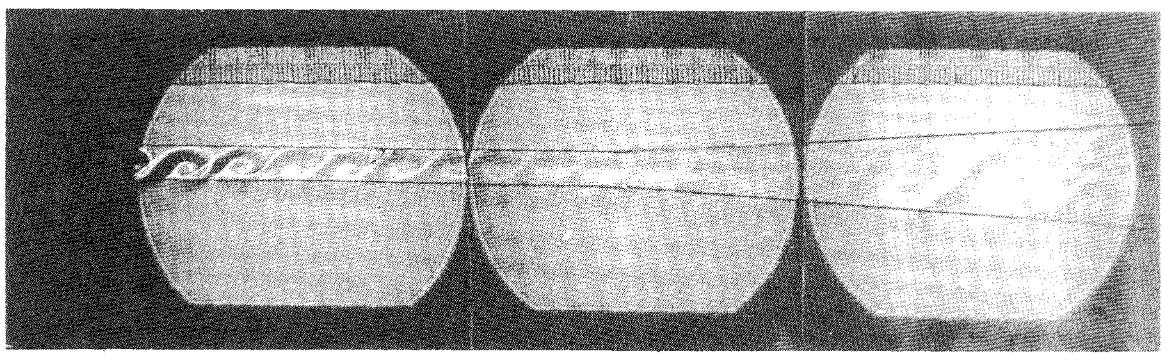
The most obvious difference between a unperturbed and perturbed shear layer is in their respective growth rates. However, the question as to whether this difference in the growth is the apparent reason for the modified optics of the shear layer cannot yet be answered. Whether the improvement in Strehl ratio is due wholly, or in part, by the cessation in layer growth is still not clear at this moment. Further experiments are currently being conducted to determine this point.

Discussion

A wind tunnel generated a low-speed shear layer with two optically dissimilar gases in which a 6.5-cm-diam laser beam was propagated through the shear layer. Intensity profiles of the resultant beam showed the effects of coherent structures on the optics of shear layers. Multiple peaks in the instantaneous intensity profiles, instead of single Gaussian-like peaks, clearly showed the coherent structures in a shear layer affect beam propagation. Externally perturbing the shear layer indi-

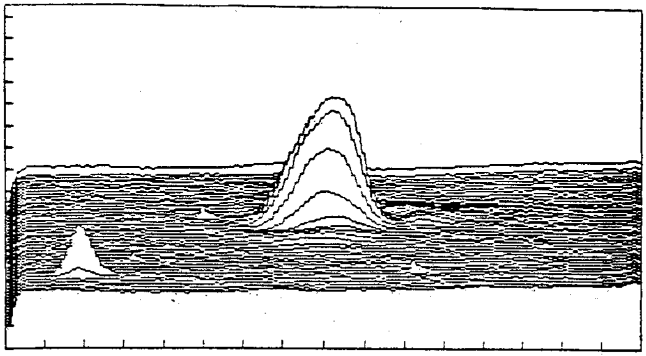


a) Unperturbed shear layer showing a linear growth rate: $\delta/x = 0.1$

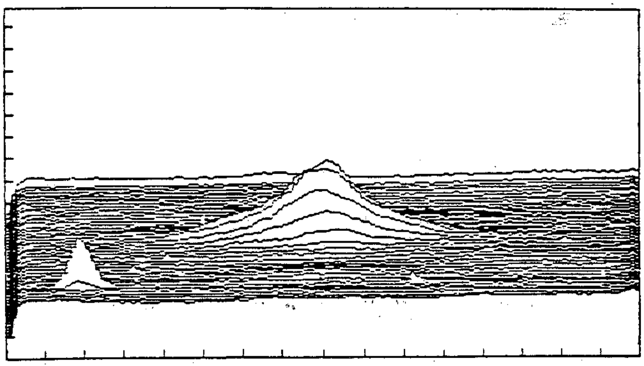


b) Shear layer perturbed at its fundamental frequency (280 Hz) showing no growth from the splitter plate to $X = 11.5$ cm

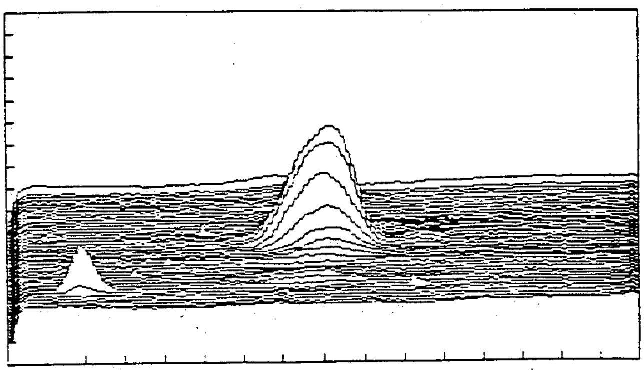
Fig. 6 Example shadowgraphs of unperturbed shear layers (6.5-cm-diam laser beam is centered at 8.5 cm from the splitter plate).



a) Far-field reference laser beam with no shear layer present: $\overline{SR} = 1.0$



b) Far-field laser beam after passing through a shear layer: $\overline{SR} = 0.66$



c) Far-field laser beam after passing through a shear layer forced at 280 Hz: $\overline{SR} = 0.91$

Fig. 7 Effects of shear-layer forcing on Strehl ratio. (The 6.5-cm-diam laser beam is centered at 8.5 cm from the splitter plate. The exposure time is 2 s. The scales are similar to Fig. 3.)

cated the possibility of controlling the optics via changes in the fluid mechanics of the flow. Perturbing the shear layer at its resonant frequency changed the fluid mechanics of the flow which in turn improved its time-averaged Strehl ratio. Changing the fluid mechanics of a perturbed shear flow therefore provides a way for controlling the optics of a shear layer. These results promise new and interesting methods of controlling the optics of some turbulent media, and perhaps, methods of improving the transmission of lasers and the reception quality of imaging systems.

Acknowledgments

This work was supported by the Air Force Office of Scientific Research Contract AFOSR-87-0258, whose support is gratefully acknowledged. The authors would like to thank B. Wu of the Beijing Institute of Mechanics, Chinese Academy of Sciences, Beijing, for his help with the shutter and shadowgraphs and also his expertise in optics. We would also like to thank J. McMichael for his interest in the project.

References

[1]Booker, H. G., and Gordon, W. E., "A Theory of Radio Scattering in the Troposphere," *Proceedings of the IRE,* Vol. 38, Institute of Radar Engineers, New York, 1950, pp. 401–412.

[2]Avidor, J. M., "Improved Free-Vortex Subsonic Aerodynamic Window," *AIAA Journal,* Vol. 17, No. 11, 1979, pp. 1267–1268.

[3]Sutton, G. W., "Aerooptical Foundations and Applications," *AIAA Journal,* Vol. 23, No. 10, 1985, pp. 1525–1537.

[4]Born, M., and Wolf, E., *Principles of Optics,* Pergamon, London, 1975, pp. 461–465.

[5]Vu, B. T., Sutton, G. W., Theophanis, G., and Limpaecher, R., "Laser-Beam Degradation Through Optically Turbulent Mixing Layers," AIAA Paper 80-1414, July 1980.

[6]Legner, H. H., Otis, J. H., and Theophanis, G. A., and Feinbeg, R. M., "Laser-Beam Degradation Through Turbulent Interfaces," AIAA Paper 78-71, Jan. 1978.

[7]Brown, G. L., and Roshko, A., "On Density Effects and Large Structure in Turbulent Mixing Layers," *Journal of Fluid Mechanics,* Vol. 64, July 1974, pp. 775–816.

[8]Oster, D., and Wygnanski, I., "The Forced Mixing Layer between Parallel Streams," *Journal of Fluid Mechanics,* Vol. 123, Oct. 1982, pp. 91–130.

[9]Roberts, F. A., and Roshko, A., "Effects of Periodic Forcing on Mixing in Turbulent Shear Layers and Wakes," AIAA Paper 85-0570, March 1985.