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Final Technical Report
6/87 - 10/90
AFOSR Contract #87-0258

Walter H. Christiansen

OPTICAL PROPERTIES OF PLANE SHEAR LAYERS UNDER PERIODIC DISTURBANCES

Aerospace and Energetics Research Program

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The optical properties of low-speed shear layers was investigated. This included a preliminary study of the basic fluid mechanics of shear layers in which the role of coherent eddies was deemed important. A low-speed wind tunnel was used in which parallel flows of different gases could be studied in a shear layer configuration. Additional provisions for movement of a splitter plate were incorporated into the design to affect the mixing process. Measurements have shown that coherent structure does have a profound effect on the optics of the syhstem and that these effects can be markedly changed with forced perturbation of the splitter plate. Numerical analyses of the problem also confirms the potential of optical control of the shear flow.

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ABSTRACT

Shear layers and wakes are a major source of optical degradation. The structure of these flows has been studied experimentally with special attention given to their optical properties. An apparatus for development of a low speed shear layer, including periodic forcing of the shear layer, was built for this study. Gases with different refractive indices were investigated and the optical effects were measured. The instantaneous and time averaged optical properties of inhomogeneous shear layers were measured wherein the principal far field measurement was the Strehl ratio. In addition we have numerically analyzed the fluid mechanical mixing process in a 2D shear layer and predicted its optical performance. Qualitative comparison between calculation and observation was very satisfactory.

1. Introduction

In recent years, the study of refractive scattering by shear layers has become an important topic due to current interest in imaging systems and in the application of high powered lasers. In such applications, an optical beam is usually propagated through a shear layer. If a shear layer consists of fluids with different refractive indices (either from velocity induced fluctuations or from optically dissimilar gases), then random phase variations can be produced in the beam. Phase variations may cause substantial reduction in far field beam intensity. These intensity reductions may be high enough to be of concern and consequently it is important to understand what happens to the beam when propagated through such a medium. Some examples of these occurrences are aerodynamics windows, beam transmission through aircraft boundary layers and atmospheric turbulence.

Shear layers commonly occur when two streams of fluid at different velocities come together to meet at a common interface, resulting in a turbulent flow field. This mixing produces random spatial and temporal fluctuations in gas concentration, which causes refractive index fluctuations in the flow. Until recently, fluctuations in refractive index due to shear layer turbulence had been assumed to be homogeneous and isotropic. In 1971, however, Brown and Roshko observed large-scale coherent structures (vortices) during a flow visualization of a shear layer. These vortices were convected downstream at about the mean speed of the two mixing layer streams. A question arises as to whether the presence of coherent structures really produces special optical effects which should be incorporated into methods of predicting the optimal performance of the shear layer. We have shown that it becomes necessary to understand how these structures affect the optical quality of a laser beam. Furthermore, systematic external perturbation of the shear layer 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? We have shown this to be the case and so, techniques for controlling shear layer optics might be available.

2. Summary of Progress

A. Flow Apparatus and Preliminary Observations

A new low speed wind tunnel was constructed early in the grant period which permitted mixing between two plane parallel and different composition gas streams. The tunnels' test section was rectangular and constructed largely from optical glass so that testing of laser beams up to 6.0 cm in diameter could be done. The splitter plate separating the two streams was also fitted with a thin oscillating flap with a width of 10 cm and connected to a variable audio oscillator. The flap provided a source of external perturbation both in aplitude (0-2 mm) and in frequency (0-350 cps) for stimulating the shear layer. The details of this construction were described in an earlier annual report.

Using dissimilar gases such as He and Ar and N_2 provides differences in the index of refraction that can be be used to obtain optical details on the mixing process. However, experiments were started using an air-to-air mixing layer and only then to a dissimilar gas mixture mixing layer which is optically visible. The results of the air-to-air experiments using smoke visualization and shadowgraph techniques showed that the evolution of mixing layer downstream can roll up into an array of vortices with extreme sidewall influence. This observation was described in an AIAA J technical note with Kurosaka.

Using hot-wire anemometry, the mean-flow field and the streamwise and cross-stream components of the turbulent intensity and Reynolds stress were measured using two airstreams. The measurements were made at a velocity ratio of 0.6 and a mean velocity of 3.3 m/sec. The frequency, f_n, of the most amplified (unstable) oscillation of the velocity field, due to the initial Kelvin-Helmholtz instability, was determined experimentally.

The spreading rate of the mixing layer was deduced from the mean velocity profile measurement and in the unforced layer, momentum thickness increased linearly with x. We have perturbed the layer at forcing frequencies equal to the fundamental and to its first subharmonic. In both the forced conditions there is a very rapid initial linear growth due to the strong interaction of the amplified fundamental disturbance with the mean flow. This situation is typical of mixing layers perturbed at a frequency equal to a subharmonic of the fundamental frequency. Spectral analysis of the hot wire response revealed highly periodic signals with distinct sidebands in certain locations in the shear layer under resonance conditions. This observation was published in the AIAA J by Tordella.

B. Numerical Studies

Numerical simulations of plane 2-D mixing layers were carried out with the help of significant amounts of NSF Cray computing time. The spatially developing plane shear layer and its optical properties were modeled for the free shear with velocity ratio 0.5 and density ratio 1.1. Two-dimensional Euler equations are solved directly using the second-order, explicit, MacCormack predictor-corrector and Godunov methods alternately for the investigation of free shear layer optical properties. Introducing random phases to the forcing modes makes the simulation of a natural mixing more realistic and produces a linear growth of the shear layer. In the forced mixing layer, a region of non-growth was identified, which is crucial to optical quality improvement in the far-field. It is found that, at the edge of coherent structures, the optical quality is the worst. For relatively large size beam, degradation is correlated to the turbulence structures of the mixing layer. For a small size beam, however, the main degradation mechanism is wavefront tilt. Beam degradation is found to increase with increasing beam diameter and turbulence integral scale. The Strehl ratio can be significantly enhanced by retarding the growth of the mixing layer via fundamental frequency forcing. Numerical simulation provides a method by which it is easy to change the flow and optical parameters for a systematic investigation of the interaction between shear layers and lasers.

These numerical calculations are the first optical calculations of this type to our knowledge. An archival paper by Tsai shows these initial results. Further calculations and details are available in a Ph.D. dissertation by Y. Tsai as shown in the publication list.

C. Optical Experiments and Results

The optical part of the investigation concerns the inhomogeneous mixing layer in which two optically different gases were used. The experiment conditions were basically the same as the air-to-air mixing layer in order to be comparable. Experimental results confirmed the two-dimensional nature of large streamwise coherent structures in both the homogeneous and inhomogeneous mixing layers. They are a Kelvin-Helmholtz instability and are highly susceptible to external perturbation.

A new optical setup to measure and record far field information was built during this grant. (The apparatus has been tested or calibrated on various size beams ranging from 0.5 cm to 5.0 cm in diameter.) Pictures were taken with flow in air and a density matched He-Ar stream. When the exposure time was limited to 4.3 μsec in an effort to get near instantaneous results, the far field patterns show interesting multilobed patterns. The multilobed nature clearly gives evidence of large scale structure in the flow. These are the first observations of this type to note this effect. Preliminary measurements were described by Chew in the AIAA student conference in San Luis Obispo and also reported at the national meeting of the AIAA.

Fluid mechanical effects of a shear layer on the optics is clearly reflected in measurements of Strehl ratio versus downstream position. Minimal phase distortion to the beam is observed in the pre-transition region and the Strehl ratio remains constant at 0.9. When transition occurs, there is a sudden increase in the number of small scale vortices per unit volume which causes additional scattering and there is a sudden decrease in Strehl ratio. Loss of beam intensity is further enhanced by the growth of the layer thickness, which increases the optical path length through which the beam has to propagate through while being phase distorted. In the post-transition region, the Strehl ratio levels off to a constant asymptote value and this value is a function of the velocity ratio. This was unexpected as it was originally thought that as the layer becomes thicker, Strehl ratio should decrease due to linear growth of the layer. The constant Strehl ratio is attributed to fast mixing that occurs within the core of the vortices in the fully developed region. The onset of small Kolmogorov microscale results in a uniformly mixed core (to first order) and therefore has no effect on the beam except at the interfaces.

Perturbing the shear layer at its resonant frequency altered the fluid mechanics of the flow in a manner which improved the Strehl ratio. Two improvements were observed: first, the region of no layer thickness growth exhibited a marked improvement in Strehl ratio; second, there was a general improvement throughout the entire length of the shear layer. This improvement may be attributed to the forcing function causing the vortices to be more two dimensional. This shows that laser transmission through turbulent media may be improved and controlled via external control of shear layer fluid mechanics. This important result was reported in the AIAA J by Chew. Additional details and more complete observations are also available in the Ph.D. dissertation by L. Chew as shown in the publication list.

List of Publications

Several publications have been wholly or partly supported by this grant. These publications are:

1. "Optics of Inhomogeneous Shear Layers" (W.H. Christiansen, G. Yu et al.) in Proceedings of the Intl. Conf. of Fluid Mechanics, Beijing, China, pp. 96-103 (1987).
* 2. "Crossflow Transport Induced by Vortices" (M. Kurosaka et al.), *AIAA Journal* **26**:1403 (1988).
* 3. "Spectral Observations in a Forced Mixing Layer" (D. Tordella and W.H. Christiansen), *AIAA Journal* **27**:1741 (1989).
** 4. "Two-Dimensional Numerical Simulation of Free-Shear-Layer Optics" (Y-P. Tsai), Ph.D. Dissertation (1989).
5. "Coherent Structure Effects on Shear-Layer Optics" (L. Chew), AIAA preprint 89-0185 (1989).
6. "Two-Dimensional Numerical Simulation of Shear Layer Optics" (Y-P. Tsai and W.H. Christiansen), *AIAA Journal* **28**:2092 (1990).
** 7. "Experimental Investigation of Free Shear-Layer Optics" (L. Chew), Ph.D. Dissertation (1990).
* 8. "Coherent Structure Effects on the Optical-Performance of Plane Shear Layers" (L. Chew and W.H. Christiansen), to be published shortly in the *AIAA Journal*.

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*attached to this report

**abstract attached to this report

Presentations

1. W.H. Christiansen et al., "Optics of Inhomogeneous Shear Layers," Intl. Conf. on Fluid Mechanics, Beijing, China, 1987.
2. Y. Tsai et al., "Numerical Simulation of 2-D Shear Layers with Periodic Disturbance," APS Bulletin 40th Div. of Fluid Mech., Eugene, OR, 1987.
3. D. Tordella et al., "Experiments in an Incompressible Forced Shear Layer," APS Bulletin 40th Div. of Fluid Mech., Eugene, OR, 1987.
4. W.H. Christiansen, AFOSR Contractors Meeting, USC, 1988.
5. L. Chew, "Experimental Study of Shear Layer Optics," APS Bulletin, 42nd Div. of Fluid Dynamics, Palo Alto, CA, 1989.
6. L. Chew et al., "Experimental Study of the Optical Properties of Shear Layer Optics," Lasers '89, New Orleans, LA, 1989.
7. L. Chew, "Coherent Structure Effects on Shear Layer Optics," AIAA Regional Student Conference, San Luis Obispo, CA, 1989 (1st place award); also given at the National AIAA meeting, Reno, NV, 1990 (1st place award).

Crossflow Transport Induced by Vortices

M. Kurosaka, W. H. Christiansen, J. R. Goodman,
L. Tirres, R. A. Wohlman

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Technical Notes

TECHNICAL NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Crossflow Transport Induced by Vortices

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and
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THE three experimental results to be described here are all independently obtained, but they display a common feature: vortical structures induce vigorous crossflow current to such a degree that in a flowing apparatus, which may be presumed to produce reasonably two-dimensional flow, strong three-dimensonality appears. The reason is as follows. The cores of vortices, with their lower pressure, lift and draw the fluid out of the side-wall boundary layer of the apparatus, in a manner quite similar to that of the updraft induced by a tornado near the ground.

The phenomenon first came to our attention through a study of large-scale structures in a shear flow, followed by the similar observations obtained for the von Kármán vortex street. Figure 1 shows a shear layer (a plan view) formed between two streams of air at 160 and 300 cm/s separated by a movable splitter plate. The layer is perturbed under conditions of a two-dimensional sinusoidal oscillation at 115 Hz, corresponding to the Kelvin-Helmholtz inviscid instability. The flow is from left to right, and the end of the splitter plate is slightly to the left, off the picture. The width of the flow is 10 cm. Smoke is introduced on both sides of the splitter plate and is used to view the flow at five spanwise locations. The large-scale coherent structures show up through accumulation of smoke and show their transverse nature in the photograph. Of particular notice are the tornado-like structures at the end of each of the main coherent structures. This appears to be the result of a suction inflow from the wall boundary layer. For spanwise locations closer to the centerline, the apparent transverse flow is smaller and disappears altogether at the centerline. Thus, two-dimensional flow only seems to exist in a triangular region at the beginning of the flowfield, even though the unit Reynolds number of the flow is relatively small. This transverse flow was also seen and studied by Koochesfahani,[1] although in wake flows of airfoils rather than in a shear layer (see also Ref. 2).

We now turn to the von Kármán vortex street. In Figs. 2a and 2b, a cylinder of 1.27 cm diam is placed in a water tunnel, spanning two sidewalls; the flow is from left to right, the freestream velocity being uniform and equal to 4.57 cm/s. (The Reynolds number based on the diameter is 467.) The centerline of the tunnel is marked by a dark solid line drawn on the bottom, quarter-span lines by broken lines, eighth-span lines by chain lines. In Fig. 2a, where a dye is injected at the leeside and near a sidewall, the presence of a strong spanwise crosscurrent is clearly visible. Its direction always remains away from the wall. Observe in particular the hooked shape of a darker filament near the wall, which indicates a change from the initial streamwise convection to the lateral transport, carried presumably through a vortex core.

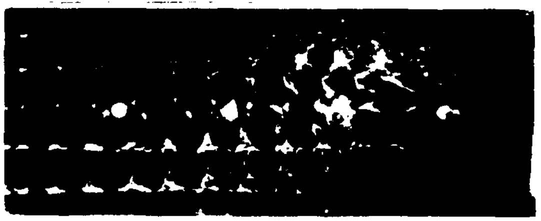

Fig. 1 Crossflow transport in a shear flow.

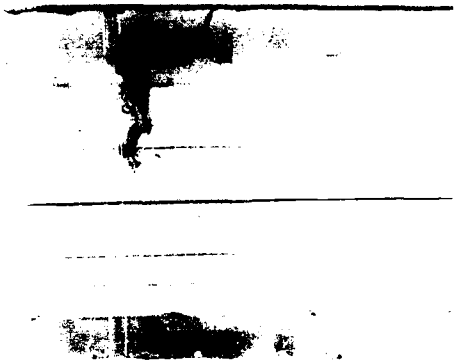

Fig. 2a Crossflow transport in a von Kármán vortex street; dye injected near a sidewall.

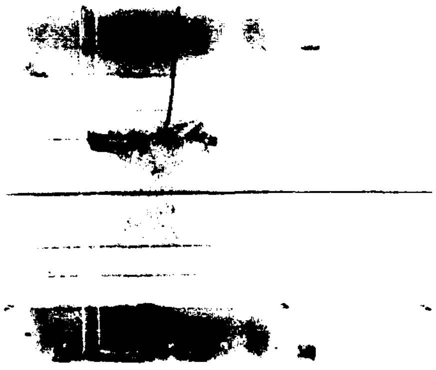

Fig. 2b Dye injected near a quarter-span point.

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Because of the symmetry, two spanwise currents are induced from each wall. They flow counter to each other, toward the midspan, where they collide. Hence, the strength of the cross-currents becomes weakened toward the midspan, as observed from Fig. 2b, where a dye is injected near a quarter-span point. A dye, when injected at a midspan, is observed to be washed downstream without showing movement in the spanwise direction.

The overall pattern shown in Fig. 3, taken at the same condition, now exhibits the long-familiar vortex street; here dye is released from a number of ports on the cylinder, rather than the aforementioned off-cylinder positions. This conventional means of dye release tends, however, to conceal the strong spanwise transport, although even in Fig. 3 its vestige is not unidentifiable.

In order to quantify this crossflow transport, a gas tracer experiment was conducted in a wind tunnel. Six ports, arranged in a line parallel to the cylinder axis, are provided on the leeside of a cylinder of 1/2 in. diam; each port is connected to outside via a hyperdermic tubing embedded on the cylinder (Fig. 4). CO_2 was chosen as a tracer gas. It was supplied from a bottle, fed to an injection port on the cylinder. A mixture of CO_2 and air was drawn by a vacuum pump from a suction port and sampled by a gas analyzer (Infrared Industries, Model No. 702). Digital outputs were processed by a data aquisition system.

Care was taken to limit the flow of CO_2 gas so that the injection and suction of the tracer itself would not set up any spurious crossflow. Also, in order to avoid the inadvertent intensification of the vortex strength (hence, the unnatural spanwise transport) at tunnel acoustic resonance,[3] the interior walls of the tunnel were covered with acoustic foam of 2.54-cm thickness. In a preceding experiment, it was confirmed that acoustic resonance at the so-called lock-in Mach numbers[3] could be averted by this means of sound absorption. In the test, the freestream Mach number M_∞, uniform upstream of the cylinder, was varied from 0 to 0.5. (The Reynolds number at $M_\infty = 0.5$ is equal to 1.5×10^5.)

Figures 4a-4c present the measured CO_2 concentration plotted against the freestream Mach number. In each figure two results are shown, both corresponding to two adjacent ports. For instance, at the top of Fig. 4a, suction s was applied at a port nearest to a sidewall, the injection i at an adjacent port. At the bottom, the role of suction and injection was reversed. The presence of spanwise transport, in a direction away from the wall, is obvious. In the subsequent Figs. 4b and 4c, the positions of the injection/suction ports were progressively moved toward the centerline of the wind tunnel; the opposing influence of two competing currents, both generated by two sidewalls, is self-evident.

The Mach number dependence observable in Fig. 4 appears to evidence a competition between the secondary spanwise transport and the primary steamwise flow. In contrast to lower Mach numbers, where the former is doubtless predominant, at a higher Mach number the latter appears to prevail, where the measured CO_2 concentration may simply be due to turbulent diffusion. Although we have not carried out any extensive investigations, the conflict between the two competing factors and their influence are evident in the following observation. In the water tunnel used for the flow visualization, we

Fig. 3 Overall pattern of the von Kármán vortex street.

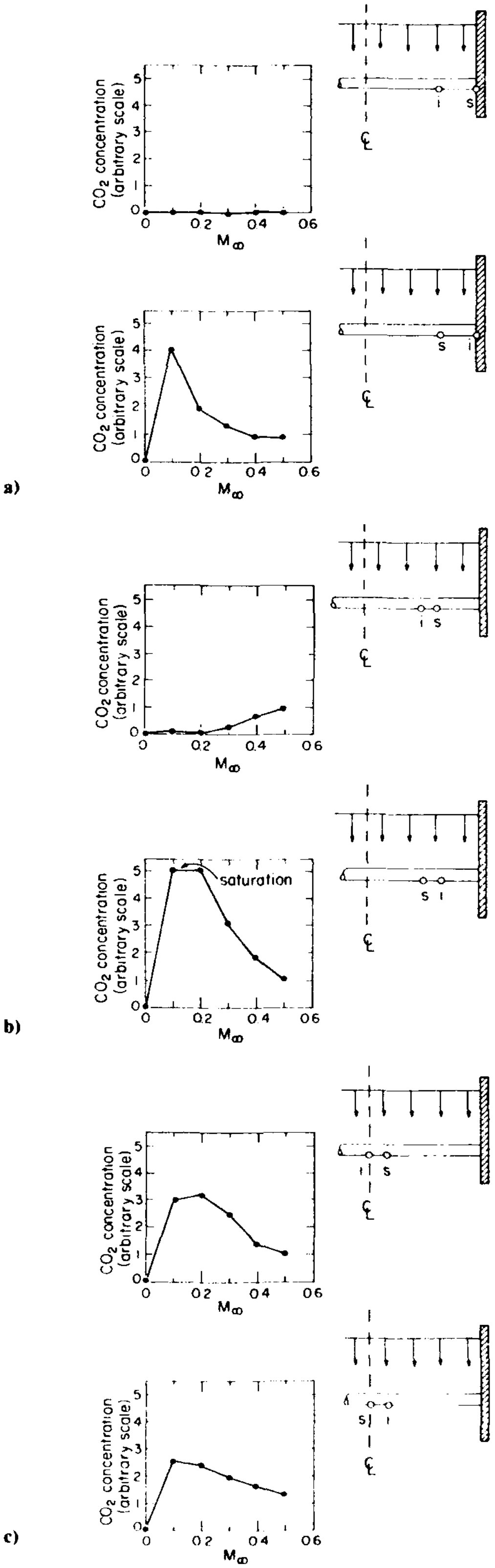

Fig. 4 Results of gas tracer experiment.

replaced the circular cylinder by an equilateral triangular one, with one of its flat surfaces facing upstream and an edge pointing downstream. Then the spanwise crossflow is found to disappear; the streamwise acceleration around the two sharp edges of the triangle apparently washes the vortices downstream too rapidly to allow the formation of the secondary spanwise transport.

With regard to the fluid-dynamical details, cross-transport through the vortex core appears to stem from two sources: 1) the solenoidal property of vorticity, and 2) the no-slip condition on a solid surface. (For a demonstration of this, see Ref. 1.) It is indeed from the latter condition, by which the normal component of vorticity is reduced to zero, in combination with the former property that excludes the possibility of the vortex tubes ending on any stationary solid surface.[4] This results in the enlargement, toward the surface, of the cross-sectional area of the vortex tube; the area change, together with the no-slip condition again, causes the variation of the swirl velocity in the direction of the vortex axis. This change in the circumferential velocity sets up, in turn, the pressure gradient along the vortex core, which then induces the cross transport. In addition to the preceding mechanism, which is applicable even to a stationary fluid, the sheared velocity profile within the boundary layer over the sidewalls may further enhance the foregoing effect, in much the same manner as discussed in Ref. 5.

Acknowledgment

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Spectral Observation in a Forced Mixing Layer

D. Tordella and W. H. Christiansen

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Spectral Observation in a Forced Mixing Layer

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The dynamics of an incompressible forced mixing layer formed downstream of a splitter plate were investigated. In the regions of zero growth of the mixing layer, spectral analysis of the velocity time fluctuations revealed the existence of locations in which the time variations of the velocity are quasimonochromatic. In these locations the power spectral density distribution presents sideband frequencies associated with the most amplified frequency component, i.e., the forcing frequency, and its harmonics. The sideband frequencies are symmetrically placed with respect to the carrier. The phenomenon also persists with forcing the layer at a frequency equal to either the lower or higher sideband frequency.

Introduction

HOMOGENEOUS mixing layers have been studied in detail, and their dynamics have been found to be controlled by coherent structures[1-6] that originate from the initial two-dimensional Kelvin-Helmholtz instability and also from three-dimensional instability.[7,8] It has been demonstrated that the spatial development of a mixing layer is largely determined by two sets of organized structures: the primary spanwise vortices and the secondary longitudinal counterrotating vortex pairs superimposed upon the spanwise vortices.[9]

In the nonforced condition the typical dimension of these vortices increases linearly with the distance from the splitter plate, resulting in a linear growth of the shear layer. It is believed that both the processes of a "vortex pairing"[3,5] and individual vortex growth play an important role in the shear layer spreading rate. It is also known that the forcing of the most unstable linear mode produces the suppression of the mixing growth and a negative production of turbulent energy.[2,6] In this paper we shall present new measurements of response of the mixing layer to forcing.

Apparatus and Experimental Procedures

The experimental apparatus consisted of a set of small blowers supplying the air, two consecutive settling chambers separated by a first convergence of 12.5:1 contraction ratio, a second convergence of 4:1 contraction ratio, and then a closed test section 25 cm long, 10 cm wide, and 5 cm high. In order to damp the internally generated acoustic noise, the apparatus was built largely of absorbing materials such as plywood and was insulated vibrationally from its supporting structure. The top and bottom walls of the test section were adjusted in order to eliminate the streamwise pressure gradient. The splitter plate, separating the two uniform parallel airstreams, extended upstream through the second convergent into the second settling chamber.

Periodic oscillations were imposed on the layer by the motion of a thin flap at the trailing edge of the splitter plate as shown in Fig. 1. The flap was pivoted at its leading edge and spanned the entire test section. Electromagnets led by a frequency generator drove the flap. The amplitude of the oscillation was maintained constant at 1 mm. To avoid propagation of external noise into the test section and the consequent spurious mixing layer excitation, the test section was enclosed by isolating plexiglass walls.

For the experiments, the velocity ratio U_1/U_2 between the two streams was 0.6 while the average speed $U_a = (U_1 + U_2)/2$ was 3.3 m/s. Using standard hot-wire anemometry techniques, the average velocity field and the average turbulence intensity distributions in the downstream and cross-stream flow direction were measured in order to check the apparatus in absence of forcing. The hot-wire probes were mounted on a y-direction traversing mechanism that could be positioned at six different x locations. The distance between adjacent x stations was kept constant and equal to 2.5 λ_n, where λ_n is the wavelength of the fundamental shear-layer oscillation due to the natural Kelvin-Helmholtz instability.

In Fig. 1 the mean velocity profiles, in the absence of forcing, are shown for different streamwise locations, indicat-

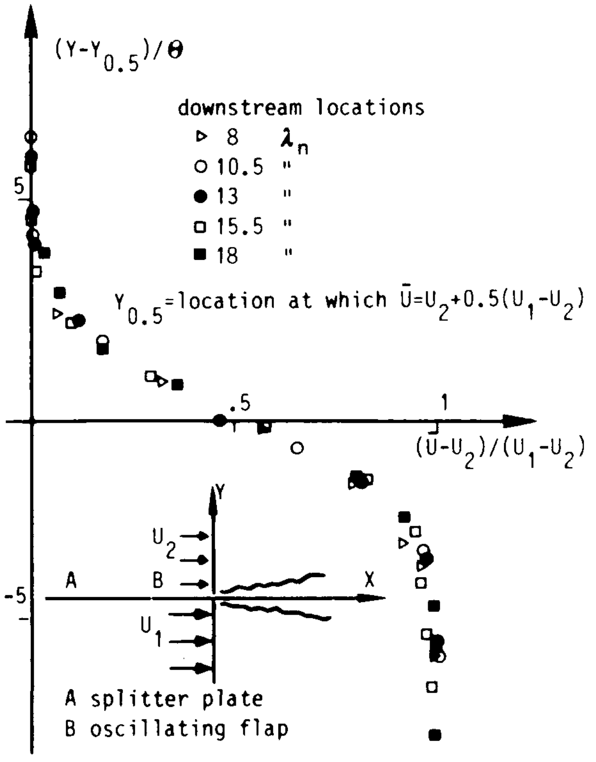

Fig. 1 Velocity profiles for the unperturbed mixing layer and flow schematic.

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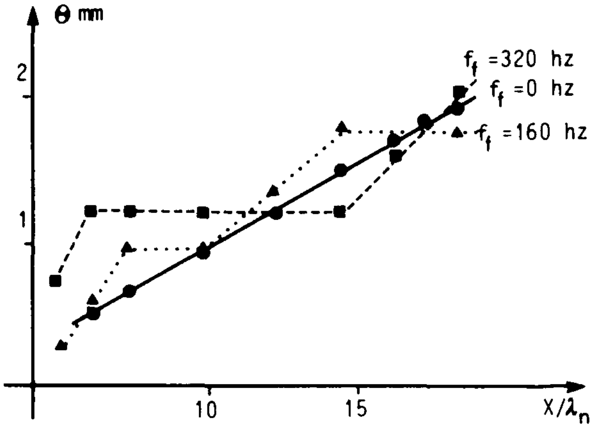


Fig. 2 Variation of the momentum thickness for the unforced and forced mixing layers at $U_2/U_1 = 0.6$.

ing a self-similar flow. The turbulence level at the nozzle exit was measured at 0.5%, and the turbulent intensity distributions agree well with those of other researchers.

Results and Discussion

The frequency f_n of the most amplified unstable oscillation of the velocity field due to the initial Kelvin-Helmholtz instability has been determined experimentally in three different and independent ways. First, the spectrum of the velocity field was measured by a straight hot wire placed immediately downstream of the splitter plate. Second, the initial momentum thickness θ_0 was calculated from the measured initial velocity profile, and the fundamental frequency was deduced from the value of the Strouhal number given by the linear inviscid stability theory ($St = f_n\theta_0/U_a = 0.032$).[3] Third, photographs of smoke flow visualization showed directly the fundamental wavelength $\lambda_n = U_a/f_n$. The fundamental frequency f_n was found to be about 320 Hz with a spread of 1%. To this f_n value corresponds a wavelength λ_n of 10 mm.

The spreading rate of the mixing layer was deduced from the mean velocity measurements, through computation of the variation of the momentum thickness θ along the streamwise direction[2]:

$$\theta = \int_{-\infty}^{\infty} \frac{\bar{U} - U_2}{U_1 - U_2}\left(1 - \frac{\bar{U} - U_2}{U_1 - U_2}\right) dy$$

In the natural layer θ increased linearly with x, as indicated by the circular points in Fig. 2. The layer was then perturbed at forcing frequencies f_f equal to the fundamental f_n and to its first subharmonic $f_n/2$. A comparison of the growths of the mixing layer for the three different conditions $f_n = 0$ Hz, $f_f = f_n = 320$ Hz, $f_f = f_n/2 = 160$ Hz is shown in Fig. 2. In both forced conditions there is a very rapid initial linear growth due to the strong interaction of the amplified fundamental disturbance with the mean flow as expected from the earlier discovery by Oster and Wygnanski.[2] In the initial part of the layer the subharmonic is always very weak, no matter whether or not the actual forcing frequency is exactly equal to $f_n/2$. There it is the fundamental that picks up most of the energy introduced into the flow. After this initial linear growth the spreading rate is suppressed in both the conditions $f_f = f_n$ and $f_f = f_n/2$. In these plateaus, the fundamental has reached its maximum amplitude. The plateaus are associated with a negative transfer of energy to turbulence; hence, the Reynolds stress distribution measured in these regions is largely negative, as seen in Fig. 3. After these regions the subharmonic amplifies rapidly, extracting energy in turn from the mean flow, which resumes growth of the shear layer. In the case of subharmonic forcing the layer reaches a second plateau, which indicates that the subharmonic too has reached its maximum amplitude. This situation is typical of mixing layers perturbed at a frequency equal to the subharmonic of the fundamental, as also was found experimentally by Ho and Huang[11] and analytically by Nikitopoulos and Liu.[10]

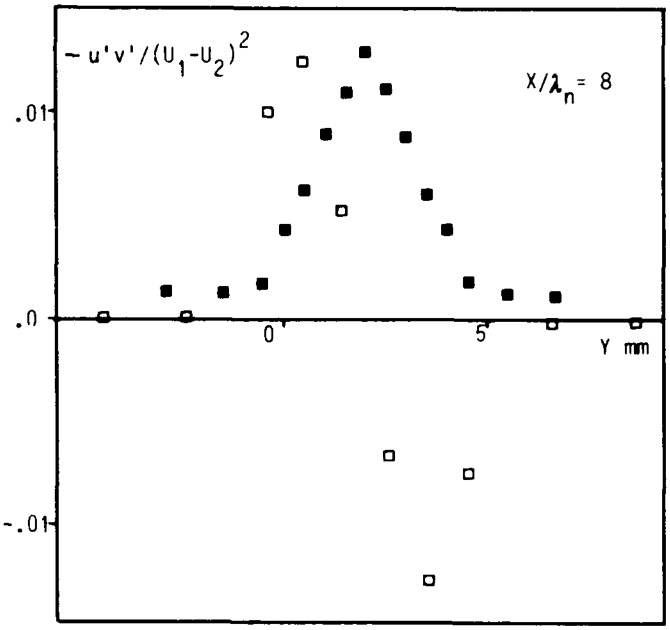
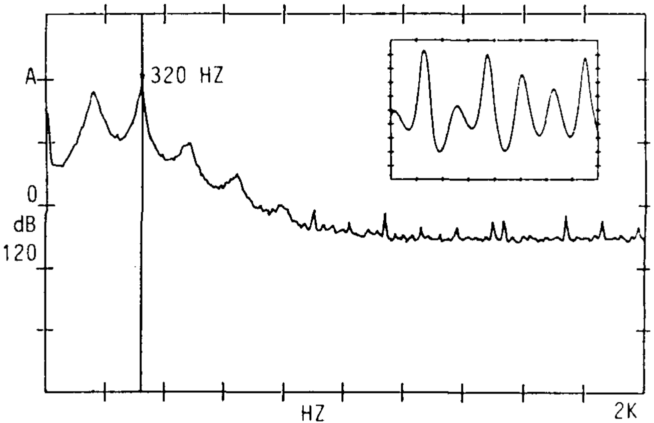
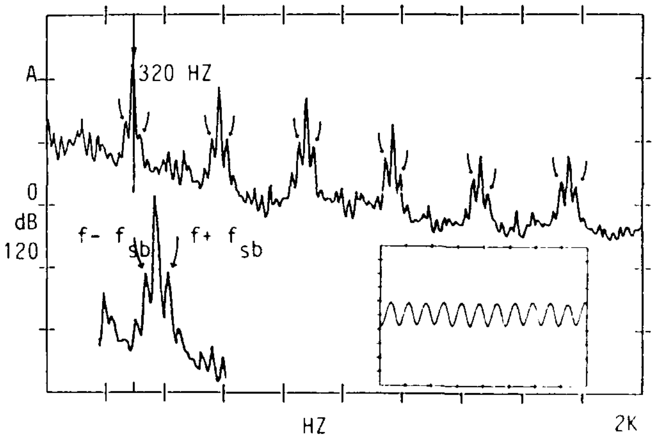


Fig. 3 Reynolds stress cross-stream distributions: ■ $f_f = 0$ Hz, □ $f_f = 160$ Hz.



Unperturbed mixing layer, X/λn=8, Y/λn=0.2.



Forced mixing layer: f_f =320 HZ, Δf_{sb}=25 HZ,

Fig. 4 Time spectra of the velocity signal. In the box inside the graphs, the time variation of the signal is shown: a) $f_f = 0$ Hz, $X/\lambda_n = 8$, $Y/\lambda_n = 0.2$; b) $f_f = 320$ Hz, $\Delta f_{sb} = 25$ Hz, $X/\lambda_n = 8$, $Y/\lambda_n = 0.2$.

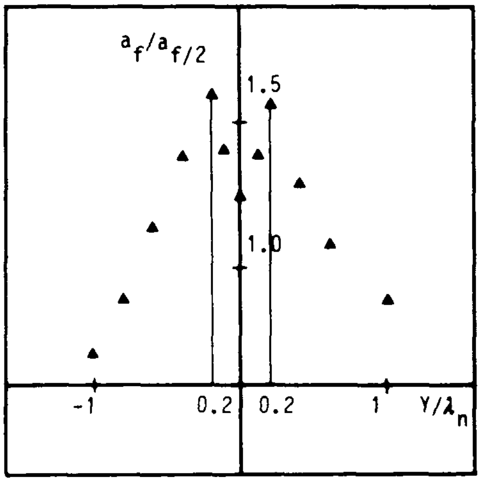


Fig. 5 Cross-stream distribution of the spectral amplitude ratio between the components at the forcing frequency and its first subharmonic $X/\lambda_n = 8$.

In the regions in which it is possible to suppress the growth of the layer, our measurements revealed that there are certain locations inside the layer in which the velocity signal has an impressive coherent time variation (see Fig. 4b). These regions are the parts of the layer where the fundamental saturates, resonating with the forcing frequency $f_f = f_n$, and also further downstream where the subharmonic saturates, resonating with the forcing frequency $f_f = f_n/2$. The velocity is quasisinusoidal in time, with a slight modulation of amplitude. The corresponding spectrum shows, symmetrically displaced with respect to the most amplified spectral component and its harmonics, two peaks of lower amplitude. This "sideband frequency interval" Δf_{sb} that separates these sideband peaks from their associated main spectral component ranged typically from 25 to 40 Hz, or about 10% of the fundamental component. The presence of the sidebands represents an energy transfer from the resonance frequency, the fundamental in this case, to a close resonance frequency. The interaction of $f_f + \Delta f_{sb}$ with f_n also produces the frequency $f_n - \Delta f_{sb}$, and vice versa. The same fact holds with strong regularity at the harmonic frequencies.

This phenomenon was evident in the region where the fundamental saturates. When forcing at the subharmonic frequency, in the region where the subharmonic saturates, the sidebands are still noticeable but not as pronounced as in the previous case. This is perhaps because of partial loss of the spatial coherence due to the occurrence of the small-scale three-dimensional transition taking place upstream of the region of subharmonic resonance, corresponding to the second vortex merging interaction. The phenomenon persists when forcing the layer at a frequency equal to one of the sideband frequencies, $f_f = f_n + \Delta f_{sb}$ or $f_f = f_n - \Delta f_{sb}$. The spectrum again displays sideband peaks on either side of the forcing frequency and its harmonics.

The phenomenon was observed close to the centerline of the layer. Moving the sensor in the y direction, we located these points as 1.5 λ_n apart from the centerline: actually corresponding to the two peaks of the cross-stream eigenfunction, giving the amplitude ratio between the forcing frequency and its subharmonic (see Fig. 5). This displacement remains constant because we are in the regions of suppressed flow growth, where there is no information transported laterally.

In Fig. 4a the corresponding situation in the unperturbed layer is shown at exactly the same streamwise and cross-stream position. The sidebands are not apparent in the spectrum, and the time velocity fluctuations, though not completely random, are not as regular as in the forced case.

The source of this phenomenon is evidently the inherent nonlinear coupling among the various oscillation modes present in such a flow. Very recently a similar phenomenon, in the case of subharmonic forcing, was discovered analytically by Monkewitz.[12] He studied the nonlinear interaction between the fundamental mode and its first subharmonic in an inviscid parallel shear layer using a quasilinear stability analysis. When the fundamental is taken exactly neutral, he shows that in exciting a close sideband of the subharmonic, the other symmetric sideband is also emerging from the solution of the equation describing the spatial-temporal subharmonic amplitude evolution.

Conclusions

Using spectral analysis, we observed the response of the forced mixing layer in both the regions of linear growth and no growth. The experiments revealed that in the resonance regions, where first the fundamental frequency saturates and then in turn the subharmonic saturates, the velocity signal was highly periodic in certain locations and showed a spectrum characterized by the presence of distinct sideband frequencies. This phenomenon can be described as a spectral energy transfer from the local resonance frequency to the two sidebands.

Theoretical support for these experimental observations has recently come from Monkewitz[12] in a paper dealing with the nonlinear mode interaction in inviscid parallel mixing layers. For the case of subharmonic resonance, he showed an analog one situation of sideband excitation.

Phenomenologically, these findings also could be associated with the presence of secondary three-dimensional streamwise vortical structures formed by counterrotating vortex pairs, which propagate under the combined effects of induction and interaction with the continuous shear and the main spanwise vortex system.

Acknowledgments

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Two-Dimensional Numerical Simulation of Free-Shear-Layer Optics

by

Yeong-Pei Tsai

A dissertation submitted in partial fulfillment
of the requirements for the degree of

Doctor of Philosophy

University of Washington

1989

Approved by____

(Chairperson of Supervisory Committee)

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Program Authorized
to Offer Degree____

Date____

University of Washington

Abstract

Two-Dimensional Numerical Simulation of Free-Shear-Layer Optics

by Yeong-Pei Tsai

Chairperson of Supervisory Committee: Professor Walter H. Christiansen
Department of Aeronautics
and Astronautics

The physical properties of spatially-developing mixing layers between two flows of different velocities and densities are calculated. The two-dimensional compressible Euler equations are solved directly using the second-order, explicit, MacCormack method and the Godunov method alternately. There is no subgrid scale turbulence in this direct numerical simulation scheme. Two air streams are modelled, each with different enthalpy, so that the density ratio is a parameter other than unity. A hyperbolic-tangent velocity profile is adopted for the initial streamwise velocity distribution at the splitter plate. Large vortical structures and their evolution are investigated for both natural and forced flows. In the forced cases, the forcing frequencies are the fundamental frequency and the first subharmonic. The forcing is applied at the end of the splitter plate. Temporal statistics of fluid dynamical variables of the mixing layer are calculated.

The optical effects of the shear layer and the coherent structures within the shear layer are calculated by passing a laser beam through it with circular aperture and uniform phase. The far-field intensity distribution, time averaged Strehl ratio and modulation transfer function are calculated for shear layers with different flow conditions. It is found that beam degradation increases with increasing beam di-

ameter, increasing index of refraction change across the shear layer and increasing growth rate of the mixing layer. For shear layers under periodic perturbations, it is seen that there is a region within which the growth rate of the shear layer is zero. The optical performance in the far-field is significantly improved when the laser beam passes through this "non-growth" region.

Experimental Investigation of Free Shear-Layer Optics

by

Larry Chew

A dissertation submitted in partial fulfillment
of the requirements for the degree of

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Abstract

Experimental Investigation of Free Shear-Layer Optics

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Chairperson of Supervisory Committee: Prof. Walter Christiansen
Dept. of Aeronautics and Astronautics

The effects of coherent structures and shear layer fluid mechanics on the optical quality of a propagating laser beam are detailed in this dissertation. A 2.4 m/s shear layer was generated using two parallel streams of gases (a helium/argon mixture and air) The effects of external perturbation on shear flows were also studied to obtain a method of controlling beam propagation. The optical quality of the beam was quantified by the Strehl ratio (ratio of the peak intensity of a beam with phase aberrations to that of an ideal diffraction limited beam). High speed pictures of the intensity profile revealed multiple peaks showing that coherent structures affect beam quality. Measurements of Strehl ratio versus downstream position show that fluid mechanical transition causes the Strehl ratio to be reduced substantially. In the post-transition region, the Strehl Ratio levels off to a constant value and its magnitude is a function of velocity ratio. Optical transmission through shear layers is shown to be governed by the combination of both small three dimensional vortices and large coherent structures that exist within the shear flow. The phase distortion caused by coherent structures is similar to that caused by a sinusoidal phase function. A model is proposed in which the large coherent structures may be modeled as a sinusoidal phase plate. In addition, the leveling off of the Strehl ratio is attributed to the uniformly mixed fluid in the post-transition region. Finally,

external perturbation is shown to change the evolution of these coherent structures in such a manner as to improve the Strehl ratio, thereby providing a means of controlling beam propagation through shear layers.

Submitted to AIAA J

COHERENT STRUCTURE EFFECTS ON THE OPTICAL-PERFORMANCE OF PLANE SHEAR LAYERS

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Abstract

While there has been extensive research on the optical properties of shear layers, there has been no study of the optical effects of 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.

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Nomenclature

n = Refractive index

SR = Strehl ratio

U = Fluid velocity

X = Downstream distance from the splitter plate

β = Gladstone-Dale constant

δ = Visual shear layer thickness

ρ_{ref} = Reference fluid density

$(\bar{\ })$ = Time averaged

Introduction

The effects of randomly varying refractive index on propagating beams have been studied since the early 1950's [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 $K = \beta / \rho_{ref}$ and β is the Gladstone-Dale constant.

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 and Sutton [5] modelled the optical performance of a homogeneous shear layer in terms of its Strehl ratio which is 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, in 1971, Brown and Roshko [7] saw large vortices, which they called coherent structures, during their experimental flow visualization of a shear layer. These vortices convected down stream at the mean speed of the two mixing layer streams. A question arises as to whether the existence of coherent structures changes the present methods of predicting the Strehl ratio. If they do, then it becomes necessary to understand how these structures determine 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, techniques for controlling shear layer optics might be available. Homogeneous shear layers preclude these possibilities.

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 wind tunnel generated a plane shear layer within which a laser beam was propagated normal through the shear layer. The wind tunnel (see figure 1) consisted of two separate tunnels discharging two streams of fluid into a common test section with zero pressure gradient. Calibration of the wind tunnel by a hot wire anemometer revealed turbulence intensities of less than 0.5 %. The top and bottom streams of the shear layer were a helium/argon mixture (1.8 m/sec) and air (3.0 m/sec) respectively. The velocity ratio of the streams was therefore 0.6. Helium (30.6%) and argon (60.9%) was mixed to provide a density ratio of 1.0 with air and also to provide the index difference ($\Delta n = 6.4 \times 10^{-5}$) between the two streams. At such low speeds any density fluctuation is negligible. At the end of the splitter plate separating the two streams was a flap which could be oscillated by a voice coil, thus externally perturbing the flow.

The optical components consisted of a helium-neon laser at a wavelength of 6328 Angstroms and an expanding 6.5 cm diameter telescope which provided collimated light through the test section (see figure 2). Another telescope focused the far-field profile onto the image plane of a electronic CCD camera. 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 effects of controlling shear layer fluid mechanics on the layer's Strehl ratio.

Results

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

Short Exposure Measurement

Figure 3 shows the effect of the coherent structures on a 6.5 cm diameter laser beam centered at 5.0 cm downstream from the splitter plate. The upper picture is a 100 microsecond 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 which affect the laser beam. The lower picture is a far field laser intensity profile which 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 that 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 diameter beam was passed through a series of pairing vortices caused by perturbing the flow at its subharmonic frequency. Like the previous pictures, figure 4 is also a 100 microsecond exposure and the beam is centered 5 cm downstream from the splitter plate. In the figure, the initial vortices amalgamated to form larger 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 with the vortical structures captured in the shadowgraphs - both temporally and spatially. 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 coherent structures actually do affect shear layer optics.

Long Exposure Measurements

Time averaged pictures (2 second exposures) include the optical effects of approximately 80-200 vortices passing through the beam. The time averaged Strehl ratio measures the quality of the beam after it passes through the vortical structures in a shear layer.

Figure 5 shows the effects of a perturbed shear layer on the time averaged Strehl ratio. It shows instantaneous shadowgraphs of an unperturbed and a perturbed shear layer. The shear layer grows linearly with a growth rate of 0.1 which agrees with the results of Brown and Roshko. For this shear layer, a hot wire anemometer and a spectrum analyzer measured the natural Kelvin-Helmholtz frequency (the most amplified frequency according to instability analysis) to be 280 Hz. When the vibrating flap was oscillated at 280 Hz, the layer stops growing (see fig. 5b). The vortices of the perturbed layer has constant spacing and moves downstream uniformly. *About 11.5 cm from the splitter plate, the layer resumes its original* growth rate.

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 figure 5. A 6.5 cm diameter laser beam was therefore centered 8.5 cm from the splitter plate. The beam's size and position is marked on figure 5 to show the beam's position relative to the shear layer. A two second time averaged picture of the ideal diffraction limited beam is given in figure 6a. 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 figure 6b spreads and the peak intensity decreases. The beam is now Gaussian-like in shape (because of time averaging). The time averaged Strehl ratio is now 0.66. Phase distortions produced by the turbulent shear layer cause the peak intensity reduction. However, when the same flow is perturbed at its 'natural' frequency of 280 Hz, the beam's intensity profile narrows again and the Strehl ratio increases to 0.91 (see figure 6c). This remarkable result 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 rate is the reason for the different optics cannot yet be answered. Whether the improvement in Strehl ratio is due wholly, or in part, by the halt in layer growth is still not clear at this moment. Further experiments are needed to fully the understand the fluid mechanical affects on the beam quality. 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.

Discussion

A wind tunnel generated a low speed shear layer with two optically dissimilar gases in which a 6.5 cm diameter 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. Externally perturbing the shear layer indicated the possibility of controlling the optics via changes in the fluid mechanics of the flow. Multiple peaks in the instantaneous intensity profiles, instead of single Gaussian-like peaks, clearly showed that coherent structures in a shear layer affect beam propagation. Perturbing the shear layer at its resonant frequency changed the fluid mechanics of the flow which in turn improved its Strehl ratio. Changing the fluid mechanics of a perturbed shear flow therefore provides a way for controlling the optics of a shear layer.

Acknowledgements

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Figure Captions

Fig. 1: Schematic Diagram of the Wind Tunnel

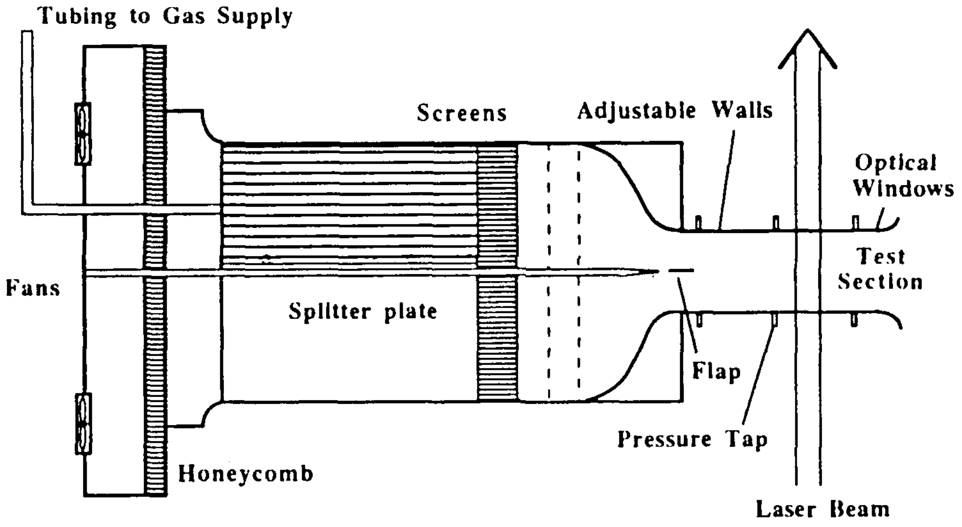
Fig. 2: Optical Setup

Fig. 3: Effects of Coherent Structures
(The 6.5 cm diameter laser beam is centered at 5 cm from the splitter plate. The exposure time is 100 microsecond.)

Fig. 4: Optical Effects of Perturbed Coherent Structures
(The 6.5 cm diameter laser beam is centered at 5 cm from the splitter plate. The exposure time is 100 microsecond.)

Fig. 5: Example Shadowgraphs of Unperturbed and Perturbed Shear Layers
(Note: The arrow represents the location of a 6.5 cm diameter beam used to obtain figure 6.)

Fig. 6: Effects of Shear Layer Forcing on Strehl Ratio
(The 6.5 cm diameter laser beam is centered at 8 cm from the splitter plate. The exposure time is 2 seconds.)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Optical Windows
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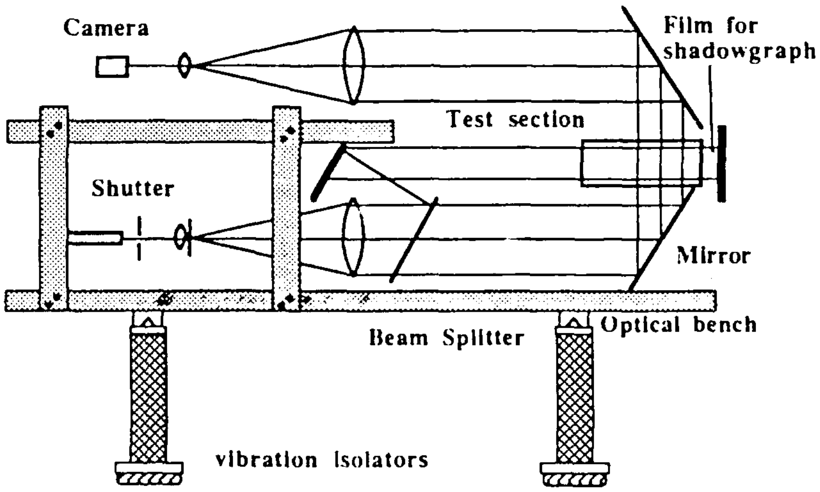
Fans
Splitter plate
Flap
Pressure Tap
Honeycomb
Laser Beam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Film for
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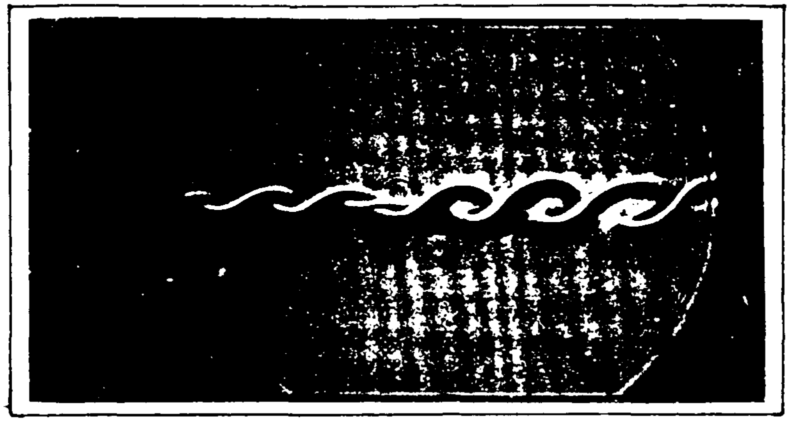
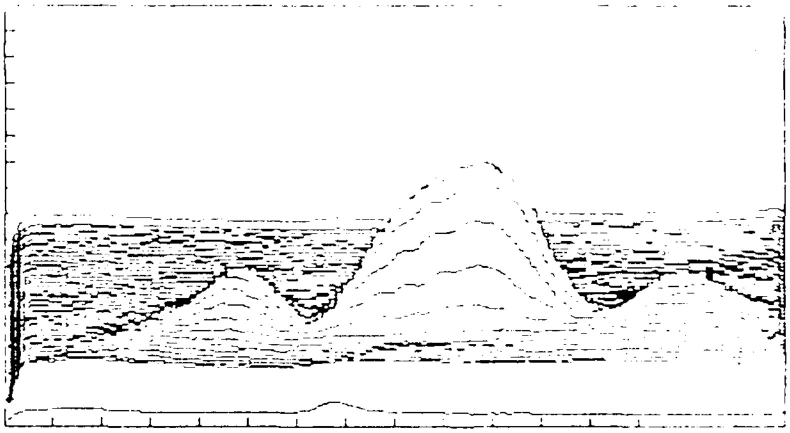
Test section
Shutter
Mirror
Beam Splitter
Optical bench
vibration isolators

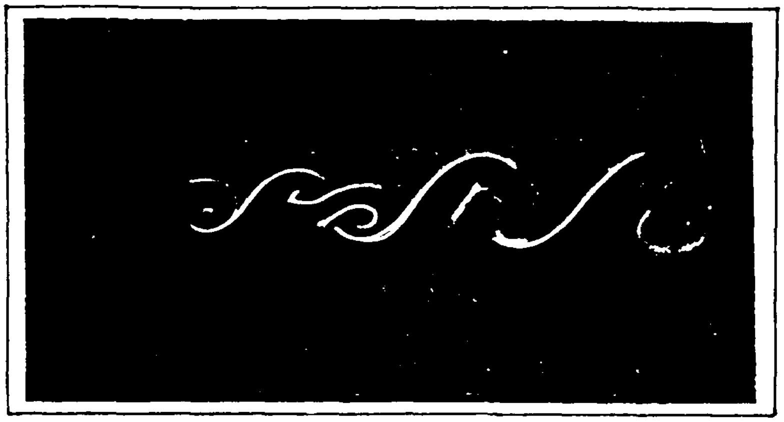
Fig. 2



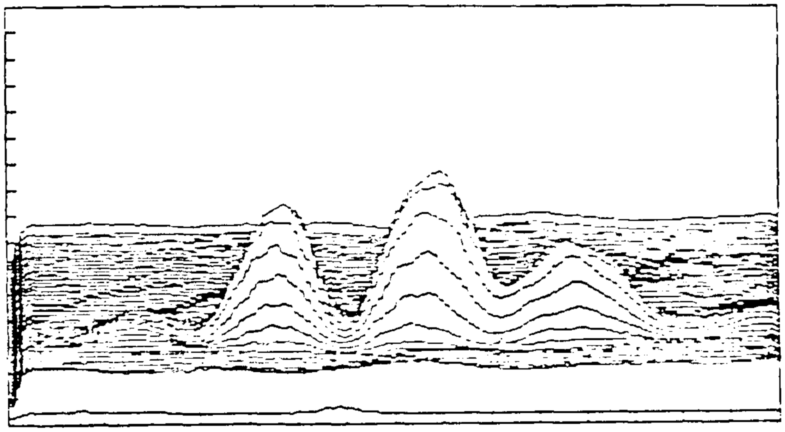
(a) Instantaneous shadowgraph of the unperturbed shear layer



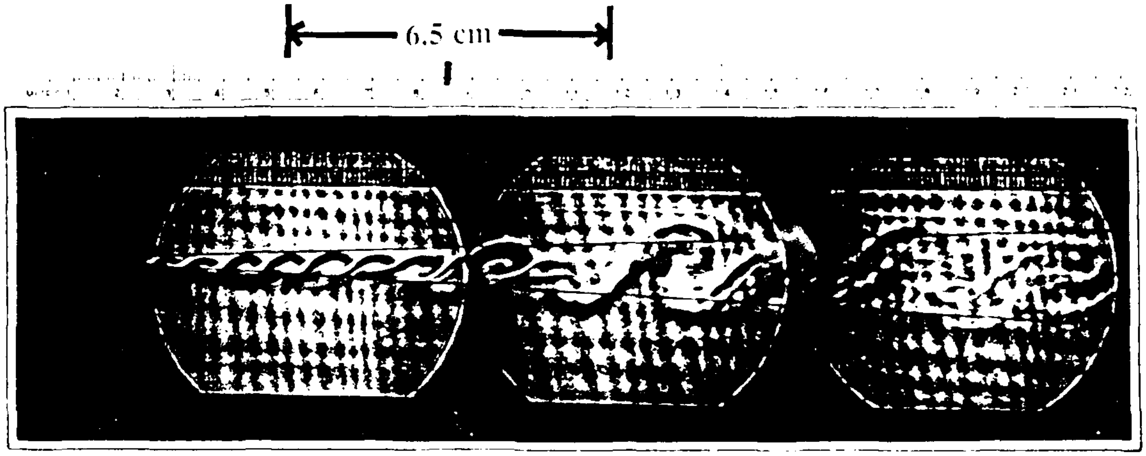
(b) Far-field intensity profile showing a main peak with smaller satellite peaks



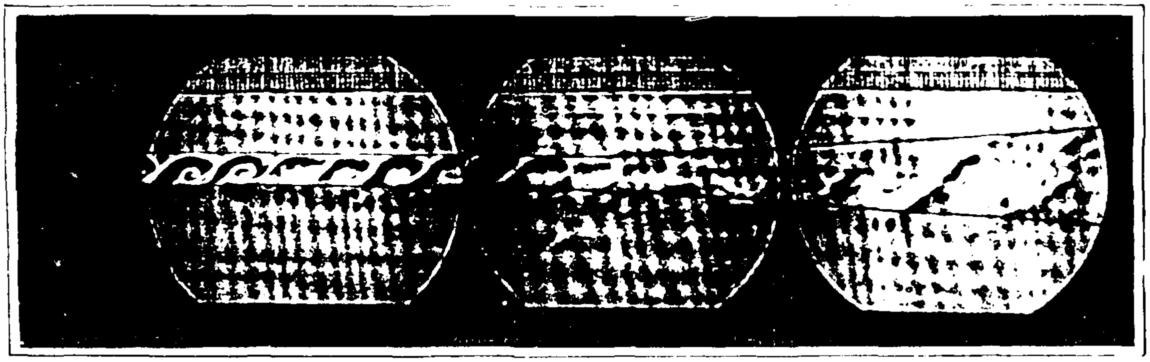
(a) Instantaneous shadowgraph of the flow perturbed at the subharmonic frequency (140Hz)



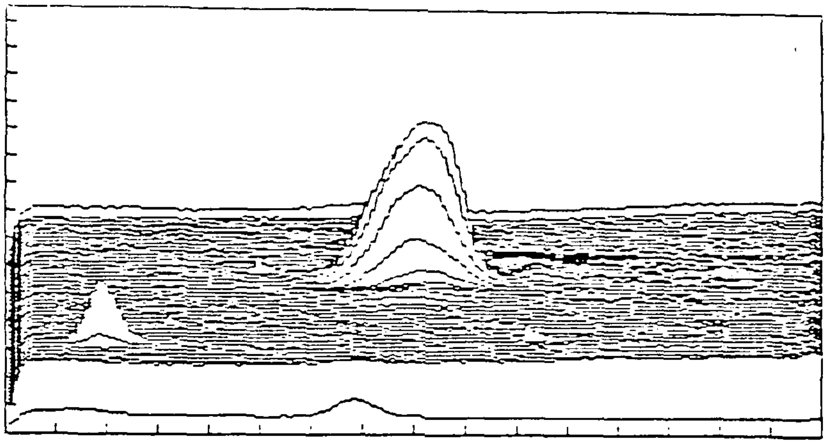
(b) Far-field intensity profile showing multiple peaks



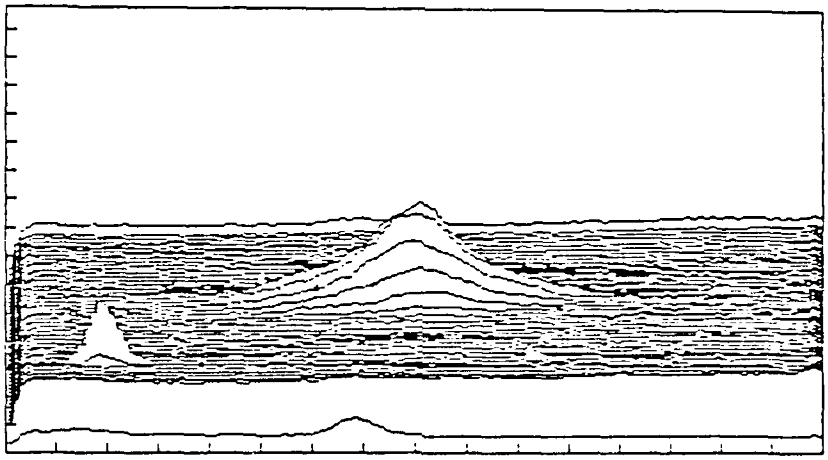
(a) Unperturbed shear layer showing a linear growth rate: $\delta x = 0.1$



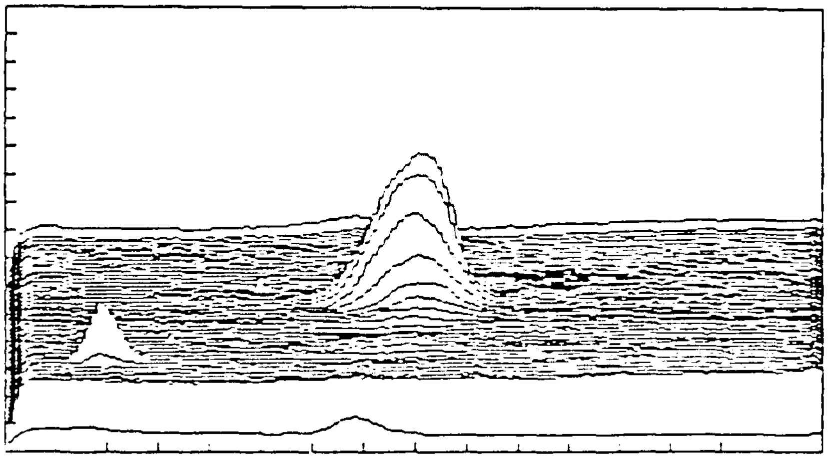
(b) Shear layer perturbed at its fundamental frequency (280 Hz) showing no growth from the splitter plate to X = 11.5 cm



(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: $\overline{SR} = 0.91$