High Speed Scanner for Transverse Radiation Measurements of Luminous Hypersonic Wakes

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The current interest in ballistic range studies of hypersonic wakes[1, 2] has led to the development of an instrument capable of providing both spatially and time-resolved photometric measurements of the luminous wake. This instrument, the wake scanner, uses a six-faced rotating mirror, a set of fixed apertures, and a photomultiplier to measure the radiation intensity from a small volume element that is repetitively scanned transversely across the wake. From successive scans, profiles of the radiation history of the luminous wake may be obtained.

A schematic of the wake scanner instrument is shown in Fig. 1. The volume element from which the radiation intensity is to be measured is defined by rays from an aperture (*A*) on a fixed plane mirror. This aperture is imaged in the test section by the lens (*B*) and is scanned across the range in a vertical plane by the revolution of the pneumatically-driven six-faced mirror (*C*). In order to increase the number of scans per revolution, i.e., per time interval, additional apertures are mounted on a circular arc about the rotating mirror. As each face of the rotating mirror sweeps across this arc, the image of each aperture in turn is scanned across the wake. The present instrument uses up to 17 apertures, permitting 102 scans of the wake per revolution of the mirror.[‖] At the maximum mirror speed of 3000 rps, a scan may be made every 3.2 μsec. The radiant energy passed by the aperture is collected by the photomultiplier (*D*), whose output is recorded on an oscilloscope.

The size of the collecting volume element depends on both the aperture size and the optical magnification. The apertures are machined into a sheet metal mask positioned in front of the fixed mirrors by means of slots in each side of the mirror assembly, with the aperture sizes chosen as a compromise between the requirements of spatial resolution and useful signal in the far wake. Small magnifications normally are used to avoid degradation of the optical resolution. The width of the limiting aperture in the wake scanner is determined by the face of the rotating mirror (0.35 in.) rather than by the lens. A useful signal requires that only one aperture be imaged in the radiating area at a given instant. The aperture image spacing is controlled by the distance between apertures on the fixed mirrors (0.63 in. on the present design) and the optical magnification. The image separation may be increased by masking off intermediate apertures, at a sacrifice in the number of scans per mirror revolution. A photograph of the instrument with the cover removed is given in Fig. 2. Not shown in Figs. 1 and 2 are internal light baffles used to reduce stray radiation incident upon the photomultiplier.

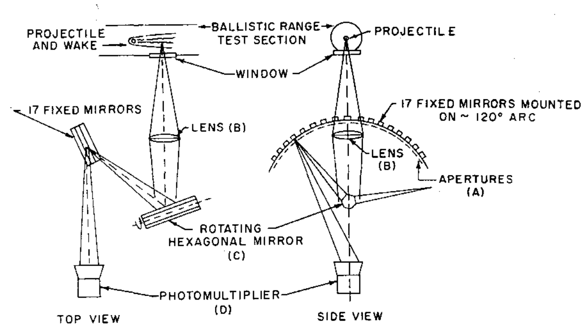

Fig. 1 Schematic of the wake scanner instrument.

Sample oscillograms are shown in Fig. 3a and b for two firings of 0.55-in.-diam zelux spheres into air. The optical radiation observed under such conditions is due predominantly to ablated impurities in the viscous core of the wake.[2, 3] In Fig. 3a the upper beam of this oscillogram is the signal from a photoelectric recorder (PER),[4, 5] an instrument consisting of a photomultiplier tube monitoring the radiation through a vertical slit imaged in the range. The sharp downward deflection of this beam just after triggering corresponds to the passage of the stagnation point of the projectile by the PER slit image. The PER and the wake scanner are aligned to view the same position in the test section. Thus, the top trace of Fig. 3a acts as a time mark indicating passage of the stagnation point by the wake scanner station. The lower trace on this oscillogram is the signal from the scanner. All but five of the 17 apertures have been masked off, and scans across the wake are obtained about every 17 μsec or about every 6 body diam in the wake. In this data the aperture size was $\frac{1}{16}$-in. high by $\frac{1}{8}$-in. wide, and the optical magnification was about 2. These parameters afforded radial resolution of about one-quarter of a body diameter and axial resolution of about one-half of a body diameter. The time-dependent base level upon which the scans are superimposed represents background radiation. It is difficult to eliminate this background from the intensely

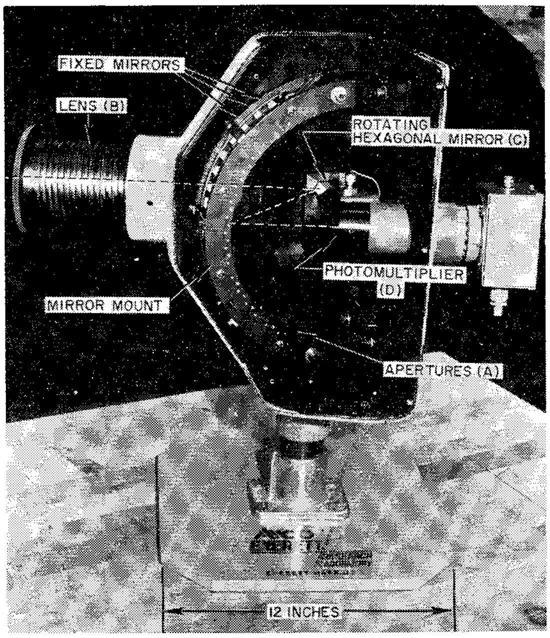

Fig. 2 Photograph of the wake scanner with cover removed illustrating components described in Fig. 1.

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[‖] The rotating mirror used was developed at Avco-Everett Research Laboratory and is manufactured by Avco Research and Advanced Development Division, Wilmington, Mass.

luminous region about the body, although it has been minimized by carefully designed internal baffling. Figure 3b, from another round, shows a section of data taken more than a millisecond after the projectile passage, demonstrating the capability of the instrument to make radiation measurements in the far wake. The signals in Fig. 3b correspond to a wake radiance of the order of 10^{-8} w/cm²/sr, which is approximately the threshold of the existing instruments.

Figure 4 illustrates the reduction of the data of Fig. 3a by the procedures described in Ref. 6. In Fig. 4a the radiation profiles are plotted at their proper projectile coordinate location in the wake in order to provide a reconstruction of the radiation history of the luminous wake. These intensity measurements have been normalized to the first peak value. If the spectral emittance of the source is known, it is possible to calibrate the response of the instrument on an absolute basis. For the conditions of this round, the viscous core of the wake is in unsteady turbulent motion.[4, 7] The radiation profiles are consistent with this interpretation, each scan showing considerable structure that varies from profile to profile. Further back in the wake, the large scale unsteadiness decays into small scale turbulence,[7] producing the more symmetric scans observed in Fig. 3b. Note in Fig. 4a that the profiles are not perpendicular to the axis of the projectile-fixed coordinate system, since the projectile moves as the image scans the wake. In these data the projectile and image velocities are nearly equal, and the profiles are inclined at about 45° to the axis. The widths of the luminous profiles (defined as the full width determined at the base line) are shown in Fig. 4b, together with a linear least-squares curve fit to this data. In Fig. 4c the peak intensity of each profile (normalized to the first peak value) is plotted, along with the PER signal for illustration of the comparison observed between these two measurements.

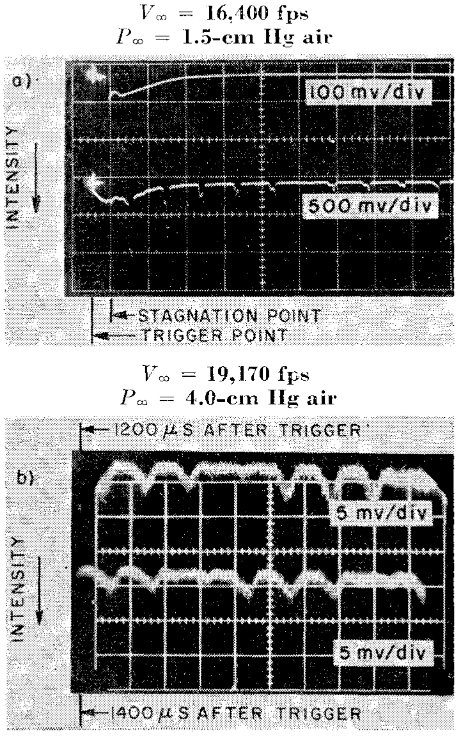

Fig. 3 Typical wake scanner data for the firing of a 0.55-in.-diam zelux sphere into air. The writing rate for all traces is 20 μsec/div. a) The top trace is the photoelectric recorder signal; the lower trace is from the wake scanner. b) Both traces are from the wake scanner. These data were recorded in the far wake, starting 1200 μsec after the projectile passed the measuring station, and illustrate the sensitivity available with this instrument. The instrument conditions were aperture image speed = 0.202 in./μsec; aperture image separation = 1.28 in.; aperture image dimensions = 0.14 × 0.29 in. A 7.0-in. focal length Aeroektar lens was used at an object distance of 22.0 in. and a magnification of 2.1. The detector was a DuMont 6292 photomultiplier with S-11 response.

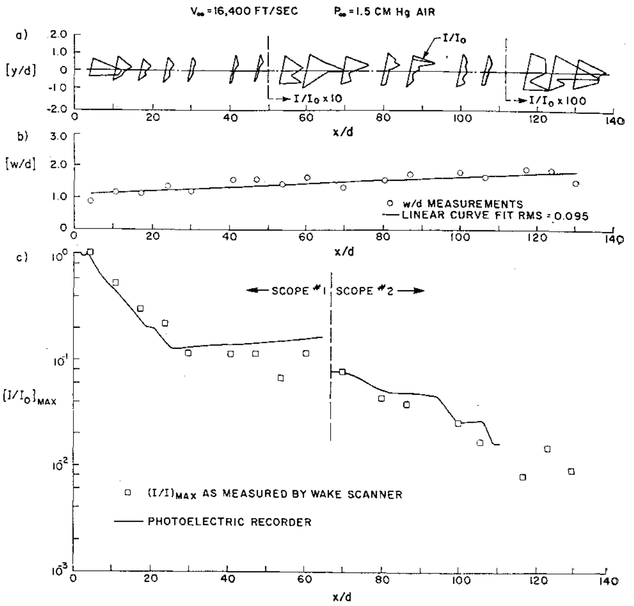

Fig. 4 Reduced data from Fig. 4a. a) Wake radiation profiles. Each profile is located at its proper position *x/d* in a projectile-fixed coordinate system. b) Width of luminous wake *w/d* plotted against *x/d*, and linear curve fit to data. c) Peak intensity of each profile *I* normalized to the peak intensity of the first profile I_0 plotted against *x/d* and compared with the wake intensity measured by the photoelectric recorder. The PER signal is in arbitrary units and has been normalized to agree with I_0 of the first scan of each scope.

A number of tests were performed to evaluate the model of the optical system and to determine the optical constants required in the data reduction. The photomultiplier was replaced with a light source and the image of the illuminated aperture projected back through the optical system and photographed. With this procedure, it was possible to produce accurate maps in the optical field of the image width, image separation, and the field of view. For the values of projectile dispersions encountered to date, it was found that the image separation did not vary from its nominal value at the optical axis by more than 3%, and the width of the image was found to vary only 13% from the axial value. The image width (resolution) correction to the data is a small quantity and, in actual practice, the error due to its variation over the optical field was reduced by applying the correction as a function of the actual wake location in the optical field. The field of view of the wake scanner was approximately ±3.1 in. from the optical axis. From experimental data with 0.55-in.-diam projectiles, such as Fig. 4, it is estimated that this field of view permits luminous wake width measurements out to 1000–1500 body diam in the wake.

A simple calibration source of known variable width was constructed and used to simulate a luminous wake. The output signals from the wake scanner were reduced in a manner similar to a ballistic range experiment, including the correction for the resolution of the instrument. The differences between the measured and actual widths were less than 3%. The measurements with this calibration source established the validity of applying the measured values of the image width as a resolution correction and verified the use of the values of the optical constants measured from the image pictures.

In summary, the wake scanner has been shown to be a versatile instrument for studying the luminous hypersonic wake in ballistic ranges. Profiles of the radiation intensity across the wake may be made every few body diameters with an optical resolution of a small fraction of a body diameter. The data from the instrument have been used to reconstruct radiation histories, measure intensity decay, and measure the growth of luminous wakes.[8] Because of the greater sensitivity of photoelectric devices relative to photographic film, the wake scanner can provide luminous growth data farther downstream in the wake than the race track technique.[9] By using optical filters, the wake scanner can provide spectral as well as time and spatial resolution, yielding further information on the chemistry and temperature of the wake.

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Compressible Jet Spread Parameter for Mixing Zone Analyses

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By a representation of reference density and mixing zone density ratio, a new formulation of the compressible jet spread parameter is attained. This analytic approximation is shown to be in good correlation with the existing experimental data. The use of the present formulation in the mixing zone analysis is believed to yield a better fit of the analytical results with experimental data in the high Mach number range.

Nomenclature

c = Tollmien constant
C = Crocco number
D = divergence constant of an incompressible jet
l = mixing length
M = Mach number
R = compressible divergence factor
T = temperature
ρ = density
τ = shear stress
$\bar{\alpha}$ = constant for a given Crocco number
β = stagnation temperature ratio, T_{0_1}/T_{0_2}
σ = jet spread parameter
γ = specific heat ratio

Subscripts

r = some reference condition
0 = stagnation condition
$*$ = transformed or incompressible value
1 = freestream or jet
2 = secondary stream or still air region

THE jet spread factor σ, often used in the analysis of jet mixing and base heating problems, has been formulated in the past on engineering intuition and experimental verification. However, so far no rigorous analysis or basis has been presented [except for the experimental values (*) in the thus arrived at value of σ]. Korst and Tripp[1] have taken the first step in formulating an empirical relation for the compressible jet spread parameter ($\sigma = 12 + 2.76M$).

In the absence of any relevant theory, this note presents a semiempirical relation that is believed to be an improvement on the existing values and formulations of the compressible jet spread parameter. From a comparison with the experimental data, it is observed that the present approach does show the correct trend.

Phenomenological Model for a Compressible Jet Spread Parameter

Various phenomenological models for turbulent fluxes have been presented in the past, and almost all of them hinge upon the unknown variable density of the dissipative region. The density ratio (ρ_r/ρ) has been represented in terms of the mean properties of the flow, with some knowledge of predicting these distributions in the mixing zone. Such formulations can be checked only against experimental data.

Because of lack of experimental data for flows at high Mach numbers, authors have resorted to extrapolation of values of jet spread parameter.[3] Some results of the empirical formulations and extrapolated values of σ are shown to have been in good correlation with experimental data.[1, 3]

In view of the foregoing, this note presents a formulation of the compressible jet spread parameter based on a representation of the density ratio with the mean flow properties. Here, free jet mixing into still air will be considered.

From Prandtl's mixing length hypothesis, the shear stress in a turbulent flow is given by

$$\tau = \rho l^2 (\partial u/\partial y)^2 \tag{1}$$

Using Howarth[2] transformation, one has for shear stress τ_*, in the transformed plane,

$$\tau_* = \rho_r l_*^2 (\partial u/\partial y_*)^2 \tag{2}$$

The transformation is essentially stretching of the y coordinate and is defined by

$$\begin{aligned} \frac{\partial}{\partial x} &= \frac{\partial}{\partial x_*} + \frac{\partial y_*}{\partial x} \cdot \frac{\partial}{\partial y_*} \\ \frac{\partial}{\partial y} &= \left(\frac{\rho}{\rho_r}\right) \frac{\partial}{\partial y_*} \end{aligned} \tag{3}$$

Following Mager's[4] assumption (the invariancy of shear

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