Aero-Engine Applications of Laser Anemometry

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The measurement of flow inside an aero-engine or component rig is made difficult by the hot, high-pressure environment, problem of access, and the requirement not to disturb the flow. Laser anemometry offers an almost ideal solution to several of these problems and has been used under laboratory conditions for several years. However, because it is extremely difficult to add particles evenly to the very high mass flow involved, methods based on the naturally occurring particles in the flow have been developed and are described here. The information available from the light signal scattered from particles in a flow is examined and a real fringe system with fringe counting or photon correlation is chosen as the most useful processing method for laser anemometry in this situation. Measurements obtained from engine component rigs using a counting system are presented together with measurements from several aero-engines obtained using photon correlation. All results were obtained using a 15-mW HeNe laser.

Nomenclature

x,y,z = Cartesian spatial coordinates
u,v,w = velocities in direction $\hat{x},\hat{y},\hat{z}$ or coordinates in velocity space
$\sigma_x,\sigma_y,\sigma_z$ = standard deviation of normally distributed velocity fluctuations in $\hat{u}$, $\hat{v}$, and $\hat{w}$
k_x,k_y,k_z = reduced parameters including σ, τ, and ℓ_0
ℓ = fringe spacing in $\hat{x}$ direction
ℓ_0 = dimension parameter of illuminated quadric
m = scaling factor on ℓ_0 in $\hat{z}$
y_0,z_0 = intersection points in $x \equiv 0$ of particle trajectory
r = fringe contrast
ϕ = phase of fringes in $\hat{x}$ at centroid of quadric
t = time
τ = correlation delay (pseudo time)
I = illumination intensity
S = receivable scattered signal
C = correlation function of S
$R(R_m)$ = reduced parameters in u, v, w, and m
$A_{(p)}$ = constant including scattering properties of particle
$p(u)$ = probability density of velocity u

Subscripts

x,y,z = quantities concerned are relevant to the Cartesian directions

Superscripts

$\bar{\ }$ = time mean value of a quantity
$\hat{\ }$ = quantity concerned is a unit vector in the direction shown

I. Introduction

THE great potential of laser anemometry to obtain the velocity of light-scattering aerosol (dopant) particles entrained in the flow has been apparent for several years (Refs. 1-11 and many others). The main advantages of such a system are that there is no probe to disturb the flow and that the technique can be applied in conditions were no probe material could survive. Accordingly, many researchers have developed laser anemometry systems, all based on obtaining velocity data from the laser light scattered by moving particles. Many of these systems have produced excellent results under controlled laboratory conditions and have provided a considerable amount of useful data.

In the development of aero-engines it is becoming increasingly necessary to obtain a more detailed understanding of the spatial distribution and time fluctuations of velocities within engine components. One area where such detailed knowledge is required is in the understanding of components of engine noise, such as the effect of transient flow distortions on fan noise and the effect of tailpipe and jet turbulence on 'excess' noise. Much could be learned of the detailed behavior of a combustion chamber if velocity and turbulence distributions could be measured at its operating condition. Similarly, measurements of flow fluctuations in blade rows could provide understanding of secondary flows and losses giving design feedback, which leads to increased efficiency.

Although much useful data can be obtained using more conventional instrumentation, such as pressure transducers and hot wire anemometers, there are many situations in rig and engine applications where a probe either significantly disturbs the flow or cannot be used, because of the high temperature or restrictions of space. In these cases laser anemometry becomes a promising technique.

Unfortunately many of the most useful applications produce severe difficulties both in engineering suitable optical systems, and in interpreting the results of measurements. Some of these difficulties include keeping windows clean, obtaining sufficient dopant in flows of up to 700 kg sec^{-1} and insuring that these dopant particles follow the required accelerations. In a complicated flow which may have velocities up to 500 msec^{-1}, these accelerations can be high in regions of interest. In addition to this, the system must be portable, conveniently traversable, and meet severe safety conditions. These requirements are far beyond the capabilities of commercial, or most laboratory, laser anemometry systems.

It has therefore been necessary to select the most suitable optical layouts and signal processing techniques and develop them to produce meaningful results in an aero-engine environment. The system cannot in most circumstances give the detailed waveform information available from a hot wire anemometer and from some laboratory laser anemometer

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Table 1 Selection of optical system

Optical input geometry	Condition of use
a) 'Real fringe'	Where the sample space contains no more than one significant particle at one time.
b) 'Reference beam'	Where the sample space contains many significant particles at all times.
c) 'Time of flight'	Advantages where excess flare from windows or walls tends to swamp the signal from small particles.

systems, but it has produced measurements of sufficient detail for many present engineering uses in situations where no alternative measuring system could be used. In this paper the choice and development of optical and signal processing systems appropriate to particular situations will be discussed and then some examples of the present uses of the system will be given.

II. Optical System

Many optical systems have been proposed[12-14] but these can be reduced to three for current aeroengine applications. These three are the 'real fringe' system, and 'reference beam' system, and the time of flight system proposed by Thompson.[15] In all our applications to date the first has been chosen. The main criteria which dictate system selection are summarized in Table 1.

In many cases it is not feasible to dope the flow in a situation from which measurements might be useful. Among these cases by far the most common is that pertaining to atmospheric air whose usual distribution of particulates is that of a smoothly declining number density with increasing size. Only when small particles are generated by combustion is there a tendency for more than one significant particle to be present in the sampling volume at any one time.

The scattered light signal from air moving through turbomachines tends to have a very high crest factor corresponding to large signal in the present of a particle and very little between these events. The optical system chosen and optimized looks like Fig. 1 with special emphasis on the detector geometry.

An illuminated ellipsoid is defined in space by the overlap of two Gaussian laser beams derived from the same source. Because these are coherent the volume will be filled with 'Young's fringes'. This 'real fringe' model is not a rigorous physical description but is quite adequate for many applications. More complete analyses may be found in standard texts on optics. Light scattered from particles in transit of this volume must be collected with highest efficiency, and all other sources of scattered light must be excluded. The trade off between these signals has decided the form of receiver system. Because photon correlation has been selected as the most

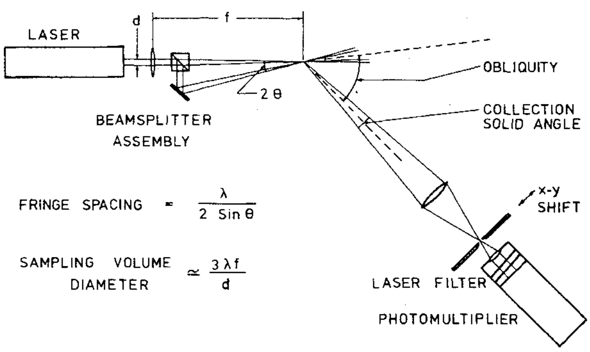

Fig. 1 Geometrical relationships for laser anemometer.

useful information retrieval technique in many present situations, the rejection of stray light is a marginally more important specification than the collection of every available photon scattered from the particle.

The important features of the receiver are a relatively high quality collection lens and a good geometrical aperture whose image can be placed exactly to include the whole, or a selected part, of the illuminated volume. If the observation direction is somewhat off the symmetry axis in a plane normal to the plane containing the incident beams, then the stay light rejection is much improved.

Although most of our work to data has been with a near forward scatter system, with the attendant mechanical inconveniences associated with access from both sides of rig or engine, it has been found possible to use a backscatter system when largish (2-3-μm) particles are available. The light scattered from this system is barely sufficient when using a HeNe laser of around 15 mW and even these sizes of particles do not follow with adequate accuracy the rapid accelerations in shear flow. This may be remedied by using a larger laser, but this has not been convenient for the following reasons. Typical more powerful lasers are bulky and fragile, require large power and/or water cooling supplies, are expensive, and a greater potential danger to people unfamiliar with optical radiation hazards. In the more usual forward collection mode a signal is perfectly obtainable from naturally occurring particles around 1-μm-diam and a small HeNe laser. The signal is still too small for conventional processing, which includes tracking and counting, but is quite suited to photon correlation.

Because of the rigorous environment in which the mechanical and optical components of the system must work the essence of design has been simplicity and the elimination of any components which were less than essential. The fringe projection unit is contained in a dry air purged flameproof steel box. The laser tube is by far the most vulnerable component but the claimed ruggedness of the Spectra-Physics 124A has been justified by several years of reliable use. The beam splitter and focusing lens or lenses have a wide range of possible configurations enabling fringe spacing, size of sampling region, and distance from sampling region to box to be varied to suit many diverse applications. Fringe spacings from a few microns to a few hundred microns have been used with systems of a few centimeters up to 5 m between transmitter and receiver. The fringe spacing must, of course, be tailored to the requirements of the intended processing apparatus and the nature of the flow.

The receiver box contains a lens assembly, photomultiplier, and power supply. For receiver lenses we chose to use those appropriate to 35-mm cameras because they are of acceptably high quality and cheap. An image of the sampling region is focused with suitable magnification onto a pinhole which is independently adjustable. Fig. 1 shows how the adjustment is retained in the receiver assembly to avoid small precise movements of a heavy unit. The photomultiplier, currently a Mullard 56 TVP, is wired so that it may be used for fringe crossing detection in an analog mode or, at a higher voltage, for single photon detection for use with the Malvern Correlator. The photomultiplier supply is controlled remotely by low voltage signal logic since access to the equipment is often not permitted during an experiment.

Where traversing has been required using a forward scatter system the boxes were strapped together and traversed as a complete unit. The position of the sampling volume must be measured at each station.

III. Signal Processing

Retrievable Information

When considering the type of signal processing that is most appropriate for a particular condition, it is first necessary to determine just what information is actually present in the detected signal. The basic limitation is the number of particles from which a usable scattered signal can be obtained. If a particle is too small, it does not scatter enough light to define the fringe crossing frequency. If it is too large, it does not follow the flow.

To obtain all the useful information about the velocity at a point it is necessary to sample it by suitable particles at a rate high compared with the highest frequency of turbulence present at that point. If particles were equally spaced in time it would be necessary only to sample at a little above the appropriate Nyquist frequency, which is twice the highest frequency of turbulence present in the flow. However, the random particle arrivals make a much higher rate necessary if all information is to be retained. If this condition is met, the full waveform of the velocity signal may be interpolated from the velocity samples.

If the effective samples of velocity come less often it is possible to obtain only time averaged statistics of the flow. For mean rates above an order below the Nyquist frequency, it is possible to obtain useful frequency information by autocorrelating the velocity samples and Fourier transforming so determine the velocity spectrum.[16,17]

When particles occur at lower rates, the samples are not close enough together to produce a useful spectrum and it is then possible to obtain only the particle velocity probability function and statistics derivable from this. These statistics include mean speed, rms turbulence, skew, and higher order moments where necessary.

Table 2 summarizes the retrievable information and shows some of the processing methods appropriate to each case. In typical aero-engine flows it is very rarely possible to supply particles to the flow artificially because of the high air mass flows. It is therefore necessary to accept the obtainable signal and choose the processing technique which will produce as much as possible of the required information.

Filtering

We have used several different methods of analyzing the detected signal. One of the simplest methods for a 'quick look' at the signal is direct frequency analysis either by sweeping the center frequency of a filter linearly through the frequency range or more expensively by using a bank of parallel filters.

Neither of these methods has given a real-time velocity signal nor a turbulence spectrum, but only some estimate of the velocity probability curve, although the latter is being developed with some recent success. With both methods used conventionally the result of the measurement will be severely weighted to the velocity of the largest particles, which may not follow the flow.

Even if the low frequency, or intensity fluctuation component of the spectrum, is excluded the spectrum of the total fringe crossing signal is measured, so that the signal is considerably broadened by the modulation envelope, the Doppler ambiguity. This is particularly serious when the ratio of fringe spacing to envelope must be increased because of high speeds, as in aero-engines. In this case there may be only ten or so fringes in the Gaussian envelope, and it becomes difficult to separate turbulence from the doppler ambiguity.

There is further difficulty in the case of swept frequency spectrum analyzers. This derives from the fact that only one frequency is present in the signal at any time, the frequency proportional to the speed at that time. Since the filter sweeps through the frequency range, there is an output only when the two frequencies are coincident, and that output depends, among other things, on the size of the particle passing through the sampling volume at that time. Only by summing the outputs at each frequency for a very long time is it possible to obtain a spectrum which is directly related to the velocity probability. Since data are accepted from the signal only when the signal and scanning frequency coincide, swept frequency analyzers are very inefficient and so can be used only when many scattering particles are present.[18]

A method which is much used for small-scale measurements where doping is possible overcomes this inefficiency by using a tracking filter, which effectively locks onto the frequency of the signal and follows it as it varies. The big advantage of this system is that it can be used to obtain a continuous analog of the velocity over a certain range of turbulence. However, it is usually necessary to supply a large quantity of dopant so that there is always sufficient signal to update the tracked frequency often enough to follow the turbulent fluctuations or, in another sense, avoid statistical biasing of the signal due to 'drop out'. If less particles are present it is possible only to interpolate between the signals that are available and eventually the tracking ability is lost. The accuracy, or meaning, of the output is brought into question somewhat before this point is reached.

Counting

The methods described so far are prone to frequency broadening caused by modulation of the fringe crossing frequency by the particle envelope function. In the case of frequency tracking this broadening need not be an error if the signal is large enough and the signal to 'noise' ratio is high. In practice the Poisson particle arrival rate means that the signal almost disappears from time to time and the biasing caused by this drop-out represents a nonlinear broadening in frequency space. That frequency tracking may acquire an error, rather than a mere reduction of sensitivity, has not always been stressed. If, however, the signal scattered from each particle can be separated, we can assume that it represents only one velocity, which may be obtained by measuring the rate of fringe crossing. This method is ideally suited to the situation where particles occur rarely and scatter sufficient light to form a continuous signal during transit of the illuminated volume. We therefore chose this approach for some aero-engine applications and a counter shown schematically in Fig. 2 was designed and built. There is the implicit condition that the transit time of the particle is shorter than the time taken for the velocity to change, or the reciprocal of the highest turbulence frequency.

The input signal is low-pass filtered to extract the envelope function and bandpass filtered at appropriate frequencies to extract the fringe crossing frequency component. The former is Schmidt triggered to provide a signal indicating that a particle is present, while the zero crossings of the latter are detected to provide a logic signal suitable for counting. The envelope signal starts two counters which produce pulses with widths proportional to the time taken for 14 and 7 fringe crossings. The widths of these pulses are compared and if they correspond to the same frequency within a given limit then the longer pulse is used in an analog circuit to produce a pulse with height inversely proportional to pulse width, and hence

Table 2 Dependence of output parameters on dopant level

Parameter	Very frequent particles[a]	Frequent particles[b]	Occasional particles[c]
Continuous signal	Yes (Tracking)	No	No
Turbulence spectrum	Yes (Spectrum analysis of tracked signal)	Possibly (autocorrelation)	
$p(u)$	Yes	Yes	Yes
$\bar{u}$ & σ_x	Yes	Yes	Yes

[a]Time between particles much less than period of highest frequency turbulence.
[b]Time between particles of same order as period of highest frequency turbulence.
[c]Time between particles much greater than period of highest frequency turbulence.

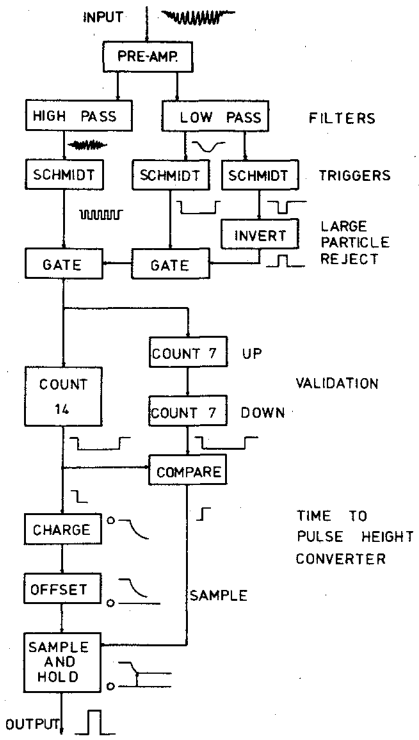

Fig. 2 Block diagram of counting system.

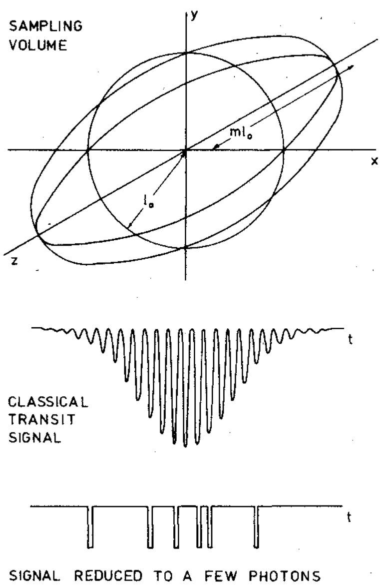

Fig. 3 Sampling volume geometry and signal from particle transit.

proportional to frequency. Processing with a pulse height analyzer gives the probability distribution of particle velocities. This counting system has a maximum frequency of 40 MHz which is covered in 12 ranges, with such overlap that for any center frequency a variation of $\pm 50\%$ can be accommodated in one range.

In common with other counting systems it is possible to obtain very frequent samples of the velocity when particles are plentiful. This permits a turbulence spectrum to be constructed via an autocorrelation function[17] or possibly even an interpolated real-time signal. However, insufficient particles have been present in any rig or engine tested so far to obtain frequency information in this way.

Photon Correlation

Since a reliable, safe and, portable system was required for rig and engine measurements, the laser power was restricted to around 20 mW. This means that at high speeds the particles that follow the flow do not scatter sufficient light to produce a signal which has a clear fringe crossing profile. In fact, the signal is often reduced to a few scattered photons per particle as shown in Fig. 3, even in nearly forward scatter. In this situation it is still possible to retrieve useful data from the signal using a photon correlation system.[19]

Although photons from the laser arrive at the sampling volume at random there is a higher probability of a photon being scattered and detected when the particle is passing through a light part of the fringe profile than when it is passing through a dark part. The probability of a photon being scattered is proportional to the intensity in the area through which the particle is passing. Thus, by correlating the times of arrival of photons, it is possible to retrieve fringe crossing information. It must be stressed that this is only a convenient conceptual model and the physical details are more complex. If we assume that the envelope of the intensity function in the sampling volume is Gaussian in all directions, with a longer scale in the direction bisecting the two beams, Fig. 3, the three-dimensional intensity function for constant laser power is given by

$$I \propto \frac{1}{\ell_0^2} \exp\left\{-\frac{1}{2\ell_0^2}\left[x^2+y^2+\left(\frac{z}{m}\right)^2\right]\right\} \left[1+r\cos\left(\frac{2\pi x}{\ell}+\phi\right)\right] \tag{1}$$

to an approximation adequate for this analysis. This Gaussian assumption is usually valid in the two directions perpendicular to the beam bisector but may be only an approximation in the z direction. If it is assumed for the moment that all particles pass through the volume in the same direction given by the velocity components u, v, and w, then the scattered analog signal is given by

$$S \propto \frac{A_{(p)}}{\ell_0^2} \exp\left\{-\frac{1}{2\ell_0^2}\left[u^2t^2+(vt+y_0)^2 + \left(\frac{wt+z_0}{m}\right)^2\right]\right\} \left[1+r\cos\left(\frac{2\pi ut}{\ell}+\phi\right)\right] \tag{2}$$

which has an autocorrelogram given by

$$C \propto \frac{A^2_{(p)}}{\ell_0^2\sqrt{R}} \exp\left\{-\frac{R_m\tau^2}{4\ell_0^2}\right\}\left[1+\frac{r^2}{2}\cos\frac{2\pi u\tau}{\ell} + 2r\exp\left\{-\left(\frac{\pi\ell_0}{\ell}\right)^2\right\}\cos\left(\frac{\pi u\tau}{\ell}+\phi\right) + \frac{r^2}{2}\exp\left\{-\left[\frac{2\pi\ell_0}{\ell}\right]^2\right\}\cos 2\phi\right] \tag{3}$$

when averaged over all possible paths through the sampling volume, where

$$R = u^2+v^2+w^2 \text{ and } R_m = u^2+v^2+(w/m)^2$$

This is the basic correlation function for a steady, laminar flow and the last two terms are negligible if there are at least a few fringes within the envelope.

The correlation function obtained in a fluctuating flow is the sum of the correlation functions obtained from the sampled particles, each with its appropriate velocity.

To proceed any further analytically, it is necessary to assume a probability function for the instantaneous velocity and then sum over all possible velocities. If a mean velocity vector with a Gaussian variation, independent in the three orthogonal directions, is chosen and corrected to give the par-

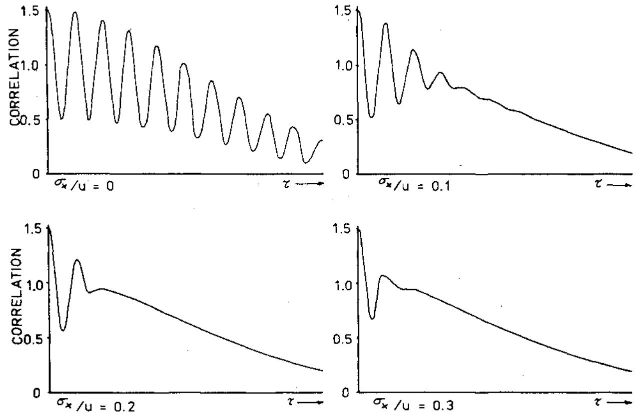

Fig. 4 Correlograms for $\sigma/\bar{u}=0, 0.1, 0.2, 0.3$.

ticle velocity probability function for incompressible flow, it may be integrated to give a correlation function of the form

$$C \propto \frac{\sum + A^2_{(p)}}{\ell_0^2\sqrt{k_x k_y k_z}} \exp\left[-\left\{\frac{\tau}{2\ell_0}\right\}^2 \cdot \left\{\frac{\bar{u}^2}{k_x}+\frac{\bar{v}^2}{k_y}+\frac{\bar{w}^2}{k_z}\right\}\right]$$

$$\left[1+\frac{r^2}{2}\exp\left\{\frac{-2}{k_x}\left[\frac{\pi\sigma_x\tau}{\ell}\right]^2\right\}\cos\left[\frac{2\pi\bar{u}\tau}{\ell k_x}\right]\right] \tag{4}$$

where $k_x = 1+(\sigma_x^2\tau^2/2\ell_0^2)$ etc. and σ_x is the standard deviation of the x component of velocity.

This function is shown in Fig. 4 for $\sigma_x/u=0$, 0.1, 0.2, and 0.3, for $\sigma_y=\sigma_z=0$ and it has three relevant features; an oscillating part with a frequency proportional to the fringe crossing frequency, a modulation decay function which depends on the turbulence intensity in the x direction and a center line droop which is a function of all velocity components, but is most strongly a function of the mean velocity magnitude. It is therefore possible to extract information about the flow by measuring the characteristics of these parts of the function. The frequency of the oscillation gives the mean speed and the rate of decay gives the turbulence.

The foregoing comments refer basically to the measurement of behavior of particulate clouds. The tacit assumption that the particles accurately reflect the fluid flow behavior is not truly justified by the mere guarantee that the particles should follow the flow to an accuracy specified by drag calculations. There exists the further, and tighter, condition[20] that the particle concentration shall not correlate with any component of the velocity field. The velocity biasing conventionally associated with such methods as counting is circumvented by photon correlation as although there are more particles to be observed at higher speeds there are fewer collected photons from each. The implicit correction is only of first order as it ignores three-dimensional and compressibility effects.

The assumption of Gaussian turbulence is not valid in many situations especially where the flow is sheared. However, all information concerning the full velocity probability curve is contained in the measured correlogram and it should be possible to extract it by a suitable transformation. Methods of processing this information are at present being developed and it appears that results of sufficient accuracy for most engineering uses can be obtained relatively simply.

IV. Applications to Aero-Engines

The counting and photon correlation systems described in the preceding have been used in a large number of component rig and aero-engine applications. The main uses have been to obtain some indication of the turbulence characteristics and mean velocity distributions for combustion, blade cooling, and noise studies. In many cases laser anemometry was the only system which could be used to obtain the required data, either because of the hostile environment or because of the requirement for undisturbed flow.

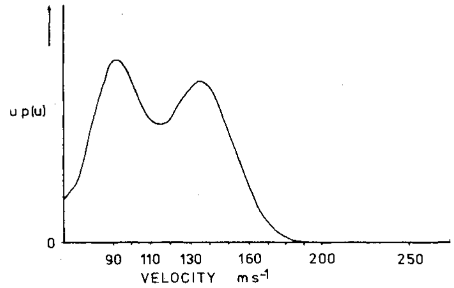

Fig. 5 Velocity probability behind a combustion annulus.

The first rig applications were made using the counting technique but, particularly in high speed rigs and engines, photon correlation was necessary to retrieve information from the light signal. In some situations it was also possible to obtain comparison of measured results with results from hot wire anemometers.

Early work on the measurement of the flow from a combustion chamber operating at atmospheric pressure showed the desirability of obtaining the velocity probability curve rather than just the turbulence intensity. A probability curve obtained at the outlet of the combustion annulus is shown in Fig. 5. This distribution is bimodal, showing either that the flow is pulsating or that it is oscillating laterally so that streams with two very different velocities are successively entering the sampling volume. A single figure of turbulence intensity would give approximately 28% on a mean velocity of 120 $msec^{-1}$ whereas in fact there are two components with mean velocities of 97 $msec^{-1}$ and 143 $msec^{-1}$ and turbulence intensities of 16% and 12%, respectively. Other measurements made within an atmospheric pressure combustion chamber have shown turbulence intensities between 7% and 21% at different positions but in parts of the recirculation zone turbulence has been so high as to be outside the range of the present methods. A system for producing continuously moving fringes may offer a possible solution to this problem. This may either increase or decrease the effective turbulence by superimposing a simulated velocity in either direction but the analysis and consequences are beyond the scope of this paper.

A similar distribution shown in Fig. 6a was obtained in the wake of a center body support strut of a research turbine. In this case the bimodal distribution was probably caused by vortices shed from the strut. An interesting feature of this curve is the central dip which is rather more pronounced than might be expected. We believe that it is due to depletion of particles in the vortex core and as such becomes a serious statistical biasing. At another position close to the duct wall a skewed single peaked distribution characteristics of shear flow was obtained as in Fig. 6b.

One of the first applications of photon correlation was in measuring the velocity distribution in a 38-mm-diam model jet rig used for noise studies. In this case the velocities were compared with those measured using hot wire anemometers and pitot probes. The comparison of mean velocities measured at an axial distance of six diameters from the nozzle is shown in Fig. 7. Near the center line the mean velocity was obtained from the modulation frequency of the correlation function, but at larger radii the turbulence intensity was so high that no sensible measure of mean velocity could be obtained in this way.

The remaining measurements were obtained from the center line curve of the correlation function, calibrated in the cen-

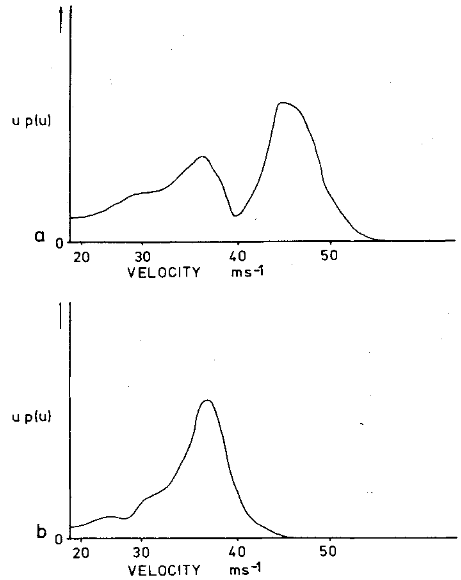

Fig. 6 Results behind a research turbine. a) In a strut wake. b) In boundary layer.

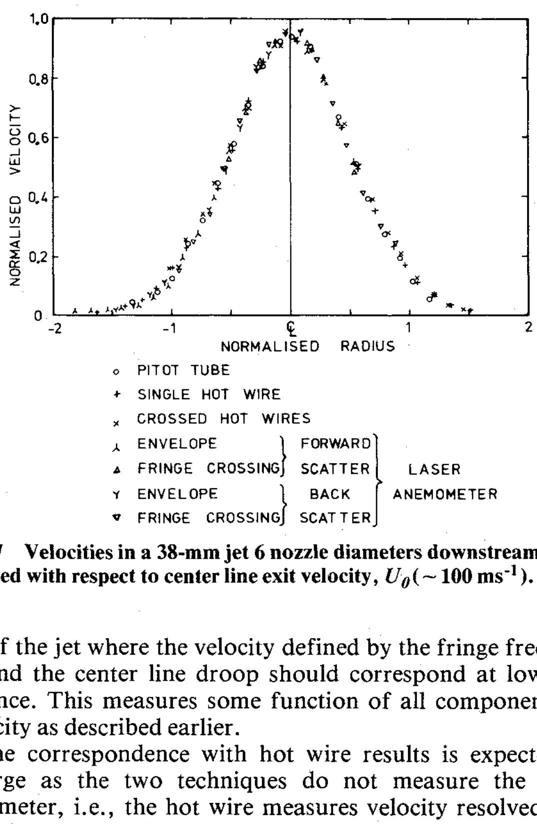

Fig. 7 Velocities in a 38-mm jet 6 nozzle diameters downstream, normalized with respect to center line exit velocity, $U_0(\sim 100 \text{ ms}^{-1})$.

ter of the jet where the velocity defined by the fringe frequency and the center line droop should correspond at low turbulence. This measures some function of all components of velocity as described earlier.

The correspondence with hot wire results is expected to diverge as the two techniques do not measure the same parameter, i.e., the hot wire measures velocity resolved into the plane perpendicular to a small filament and the laser device measures speed resolved into a specific direction. The exact quantitative consequencies of this depend in a rather complex manner on the detailed structure of turbulence. There is a further source of disparity which is much more evident at higher jet velocities; that is failure of particles to follow the flow immediately outside the potential core where there is a rapid deceleration into the mixing region.

More recent applications have been to the noise from complete engines. Measurements have been made aft of the turbine in three engines, the Olympus 593, the Viper, and the RB211, with various exhaust builds. In each of these applications the main problems were those of using sophisticated optical instrumentation in extremely hostile environments of high noise and vibration, with extreme heat from the jet pipe in one application. For reasons of rigging

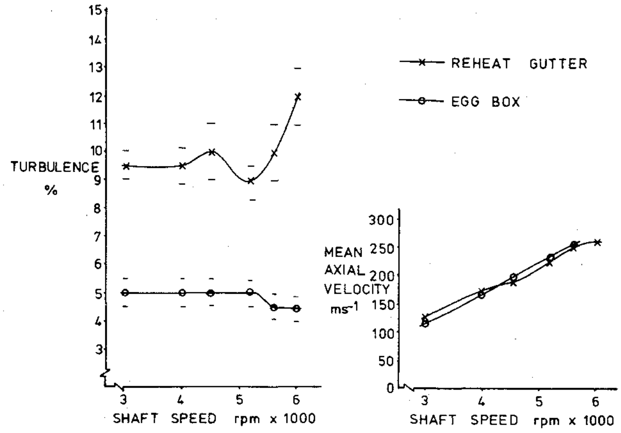

Fig. 8 Measurements at midradius of Olympus 593 jet pipe.

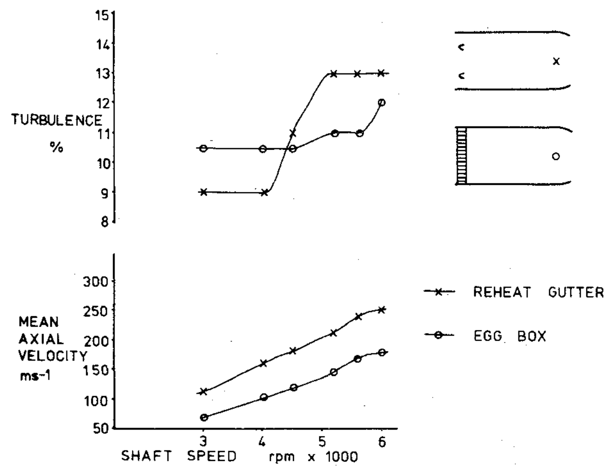

Fig. 9 Measurements on center line of Olympus 593 jet pipe.

and test stand use, it was necessary for the boxes containing optics to be left continually out of doors in sun, wind, rain, and, in one case, snow. The only problems on this account were thermal fluctuation of the laser, which reduced power output, but this may be overcome by holding the laser box interior at constant temperature.

In the case of the Olympus 593, measurements were made at fixed positions inside the tail pipe through quartz windows. These windows must have an acceptable optical finish; in particular the input window must not have the 'lemon peel' surface caused by too heavy or too rapid polishing, as this leads to 'scrambled fringes'. The windows were initially air cooled but this caused water, oil, and carbon particles to condense on the windows and contaminate them rapidly. Omission of cooling slowed the obscuration of the windows. Under these very harsh conditions the purging effect of the cooling air was quite inadequate at achievable flow rates. Using the forward oblique scatter system outlined earlier, deterioration of the window on the laser side of the rig is responsible for the most serious deterioration of fringe profile and hence signal quality. Contamination of the collector window reduces signal level but not quality.

Measurements in the tailpipe of the Olympus 593 were made at six positions, three just downstream of the reheat flame stabilizing gutter and three close to the final contraction of the tailpipe. In each case the mean speed and turbulence intensity were obtained over a range of engine conditions. Figure 8 shows the variation with engine shaft speed at a position near the exit plane for the standard build and also for a build which included an egg box flow straightener following the turbine. The result is a condsiderable reduction in the mainstream turbulence of the jet. A change of the mean velocity profile was also measured, consistant with a reduction of radial mixing in the tailpipe, Fig. 9.

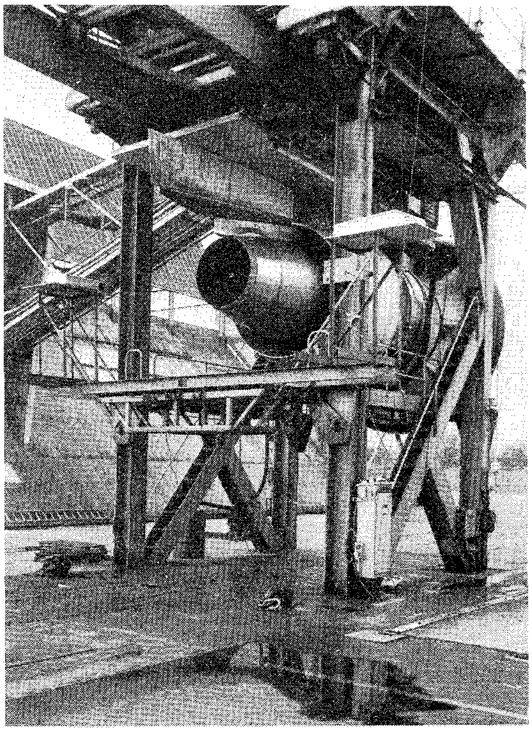

Fig. 10 Laser anemometer installed on RB211 test bed.

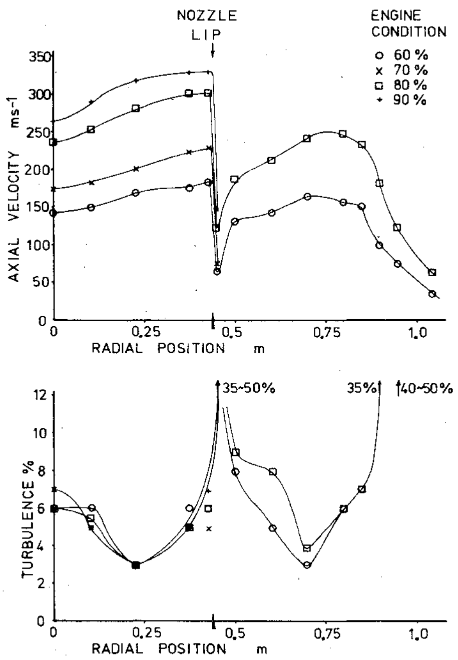

Fig. 11 RB211 exhaust survey results.

A complete traverse of the RB211 exhaust was made in a plane a few centimeters downstream of the engine section nozzle. Figure 10 shows a photograph of the laser anemometer installation to illustrate the typical layout. In this case the transmitter and detector boxes were rigidly bolted together on a beam mounted on electric hoists to facilitate the traversing of the complete system. Figure 11 shows typical results obtained from one build of this engine showing high turbulence and low velocity near the center line in the wake of the turbine hub. The turbulence is very much lower at midradius and increases greatly in the wake of the nozzle, as would be expected. At larger radii the profile of the fan jet is evident.

V. Conclusions

Laser anemometry has now reached a stage where it can be applied to both hot and cold flows in aero-engines and rigs without any serious difficulties. This has permitted us to measure mean velocity and turbulence levels which are useful in inderstanding the behavior of such flows, especially in connection with noise and combustion studies. The technique is particularly promising in hot flows where conventional instrumentation is least able to provide useful results.

No universal optical system seems possible and optimization and sometimes complete redesign is required for each application. In all our applications the low powered Helium-Neon laser has been used for convenience, safety, and portability of equipment.

It is necessary to select carefully the signal processing method according to the flow conditions, since for a particular flow speed and dopant level only a limited amount of information is available. It is usually not possible to change the dopant level in aero-engine types of flow, making it necessary to accept that in many cases only the statistics of the flow may be obtained. Fringe counting and photon correlation system have so far been used, yielding mean speed rms turbulence and the velocity probability curve. There is hope of extending the processing to produce turbulence spectra in some situations.

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