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# AN APPLICATION OF A SOLID STATE LDA TO HYDRODYNAMIC LUBRICATION

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## ABSTRACT

A Laser Doppler Anemometer employing a Laser Diode and Avalanche Photodiode is described. The laser diode's wavelength is in the visible region. Measurements of velocity were successfully obtained for flow in the 0.49mm gap of a hydrodynamic bearing.

## INTRODUCTION

Laser diodes and Photodiodes are widely employed in fiber optic communication systems and consumer products such as compact disk players. These solid-state components are cheap, very small, rugged and have low power consumption. A number of researchers (Shaughnessy and Zu'bi,1978), (Jentink et al, 1987) have demonstrated Laser Diode and Photodiode Doppler Anemometers. This paper describes the design of a Laser Diode/Photodiode LDA and its application to thin film flow. Firstly the design of the LDA is given with details on the laser source, receiver and optical components. Then the application of the LDA to thin film flow is described.

## DESIGN

The layout of the probe is shown in figure 1. The aim has been simple optical design with a minimum number of components. The optical layout of the LDA is based on the widely adopted Doppler difference technique fully described by Durst et al. (1981). The instrument operates in the backscatter mode. Further details of the design are given by Mackenzie et al. (1992b)

### Laser Source

This probe employs a visible wavelength laser diode which were first developed in 1985 (Kobayashi et al., 1985), (Ishikawa et al., 1986). These diodes operate at wavelengths in the 600nm region compared to infra-red diodes which operate at wavelengths above 700nm.

The lower wavelength offers a number of advantages for LDA over infra-red diodes. These are:

(1) Small measurement volumes are more easily obtained since the smallest focused spot size obtainable with a Gaussian laser beam is proportional to its wavelength.

(2) Better penetration of liquids. Figure 2 shows the transmission loss in water calculated for infra-red and visible diodes at working distances commonly used in LDA work. The transmission coefficients were obtained from Tyler (1978). The infra-red and visible diodes are assumed to operate at 780nm and 670nm respectively. The graph shows that at distances exceeding 100mm visible diodes have much greater penetration of water than infra-red diodes. (It should be noted that the probe described here has a working distance of 16mm. At this distance a visible diode has little performance advantage in terms of water penetration over an infra-red diode.).

(3) Easier positioning of the measurement volume and construction of the probe. (Infra-red diodes are of very low brightness or invisible to the human eye depending on the operating wavelength).

A disadvantage of Visible diodes is that photodiode detectors are generally slightly less sensitive in the 600nm band than in the infra-red region.

Furthermore infra-red diodes are favoured for certain applications such as measurements in the retina of the human eye (Petrig and Riva, 1991) and long range measurements in the vicinity of personnel (Mocker and Bjork, 1989).

### Receiver

A Mitsubishi PD1005 avalanche photodiode was chosen as the receiver. This particular diode has been proven in an LDA instrument before by Nishihara et al. (1982) and shown by Dopheide et al. (1988) to be as sensitive as a photomultiplier for LDA measurements at a wavelength of 633nm. The manufacturer's specifications of the APD indicate that it has a quantum efficiency greater than 80% for wavelengths between 600nm and 800nm with a peak efficiency of approximately 90% occuring at 700nm. The electronic design of the receiver is described by Mackenzie et al. (1992a).

### Optical Design

Collimation of the diverging beam from the laser diode package was achieved with a GRIN lens with a numerical aperture of 0.45 (MELLES GRIOT 06 GLC 009). This GRIN lens has a glass plate fitted to correct for wavefront aberration which occurs when the diverging laser beam passes through the window of the laser diode package (Kuntz, 1984). The beam dimensions after collimation perpendicular and parallel to the laser's emitting stripe were 3.3mm and 0.8mm respectively. The perpendicular beam was truncated by the collimator.

Beamsplitting is achieved with a cube beamsplitter and right-angled prism. Alignment of these components represents the only major difficulty as the beams must be parallel to a high degree of accuracy. This alignment was achieved with a fibre optic positioner originally intended for the launching of laser light into a fibre. The alignment method is similar to that presented by Burnett (1987).The beam spacing produced by the beamsplitter was 9.5mm. Investigations are currently under way to determine a more suitable beamsplitter and future systems may employ a diffraction grating (Oldengarm et al., 1975) or an optical flat (Mayo Jr, 1970).

The measurement region of the probe is required to be small to enable measurements in thin film flow produced in bearings. A small region has been achieved by using a short focal length transmitting lens. The focal length is 21mm and the lens diameter is 14mm. Spherical aberration is minimised by selecting an achromat lens. With this lens the measurement volume is 23mm x 97mm.

As well as producing a small measurement volume the optics of the LDA system were required to be suitable for measurements near walls. Measurements near walls with an LDA system are difficult. Firstly the velocity gradient increases as the wall is approached resulting in a broadening of the Doppler signal bandwidth and hence greater difficulty in removing the pedestal component. Secondly the scattered light from the wall reduces the effective SNR.

Velocity gradient broadening can be solved by a number of techniques such as frequency shifting and keeping the measurement volume small.

Mishina et al. (1979) has studied the effect of wall scattering on SNR and given guidelines for the design of LDA systems with microscopic measurement regions. The qualitative results of this study are that:

(1) the magnification factor of the measurement volume onto the receiver should be low (close to unity). (For the optical layout of this probe the magnification factor is given by the ratio of the focal lengths of the transmitting and receiving lens).

(2) the receiving lens aperture should be small. Note that a compromise needs to be reached since a high magnification allows easier alignment of the receiver and a large aperture allows higher SNR at distances far away from the wall. The receiving lens aperture (numerical aperture=0.3) and magnification factor (1/2) of this probe has so far proven to be adequate for measurements near walls.

Pin holes are normally used to reduce the effect of stray light such as that scattered from a wall. A pin hole should be matched to the size of the imaged measurement region. A pin hole has not been fitted to this probe because the small size of the pin hole required for this probe makes alignment extremely difficult.

## APPLICATION TO FLOW MEASUREMENT

### Poiseuille Flow

The probe was tested on laminar Poiseuille oil flow in a narrow rectangular channel (1mm X 30mm). The channel was carefully constructed so that only fully developed flow was measured.

Very low level signals were detected. These were estimated from the time domain signals (Figure 3) to be in the range of 20nW to 100nW. Figure 4 shows the frequency domain record of 100 Doppler Signals from a point near the centre of the channel. The velocity profile (Figure 4) was obtained across the 1mm gap at a Reynolds number (Re) of 700. The parabolic curve fitted the result with a regression analysis coefficient of 0.994.

The closest near-wall measurement obtained was at a distance approximately equal to the measurement volume length from the wall. Closer measurements were prevented by the pedestal component interfering with the signal component. (It should be mentioned that in a backscatter LDA system with a pinhole matched to the size of the measurement volume, the wall glare will begin to interfere with the signal at this distance (Gardavsky and Kleine, 1981)).

### Couette Flow

Application of the probe in turbulent flow measurements has been shown by Tieu et al (1992b) With this probe turbulent velocity profiles in a journal bearing have been measured successfully. In this case Couette flow occurs within the clearance space confined by the rotating shaft surface and the stationary outer housing. Two types of bearing were constructed. One was concentric to the bearing shaft with a radial clearance of 0.7mm whilst the other was offset by 0.21mm. The working medium was water. Figure 5 shows velocity profiles obtained in the journal bearing at a gap of 0.91mm and 0.49mm. The Reynolds numbers were 4655 and 2520 respectively. To our knowledge, this is the first time experimental velocity distributions in hydrodynamic bearings have been successfully measured by a solid state LDA system. Observations of these figures show excellent agreement between the measured and theoretical profiles. The theoretical profiles were obtained using the theory developed by Tieu and Kosasih (1992a) from extensive flow measurements with a conventional LDA system (Tieu et al., 1989) in the same narrow channel as the one described in the section above on Poiseuille flow. The results confirmed the applicability of the probe for velocity profiles in typical hydrodynamic lubrication situations.

## CONCLUSION

A simple, low cost Doppler anemometer is described. A solid-state laser in the visible wavelength region is employed. The probe proves to be a very useful device to measure velocity in small gaps (0.49 to 1.00mm) in hydrodynamic lubrication.

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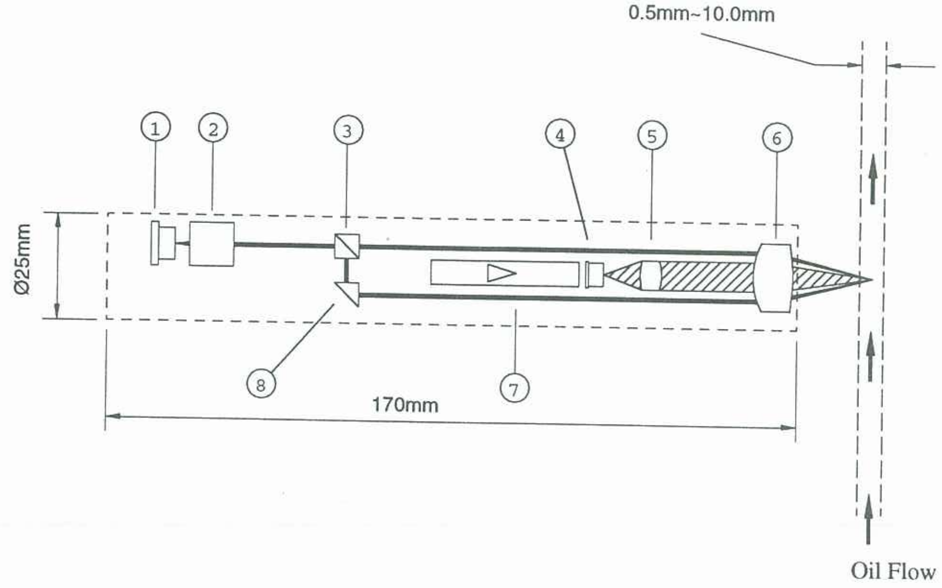


Figure 1. Schematic Drawing of Laser Doppler Anemometer probe designed for flow in narrow gaps.

1) Toshiba Visible Laser Diode (TOLD9215), 2) Collimator, 3) Beamsplitting cube, 4) Mitsubishi Avalanche Photodiode (PD1005), 5) Receiving Lens, 6) Front Lens, 7) Preamplifier, 8) Right-Angled Prism.

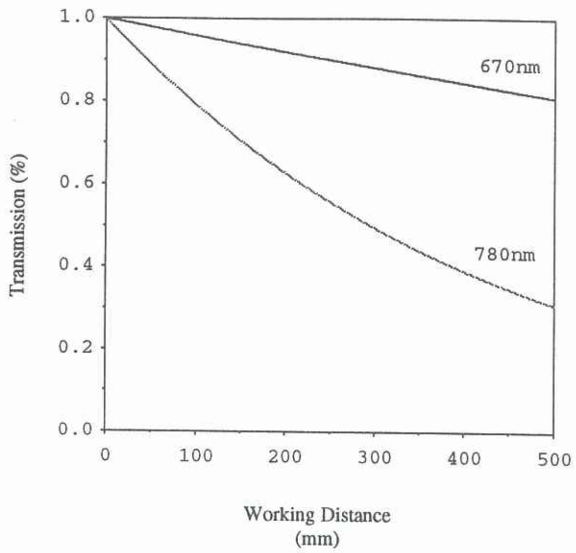


Figure 2. Penetration of water.

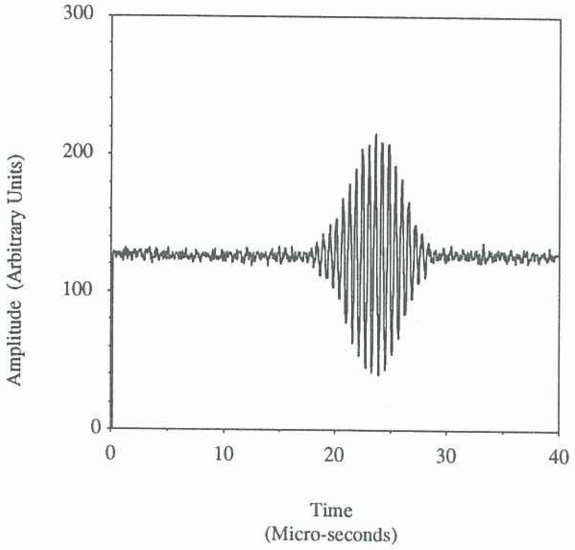


Figure 3. Filtered time domain signal.

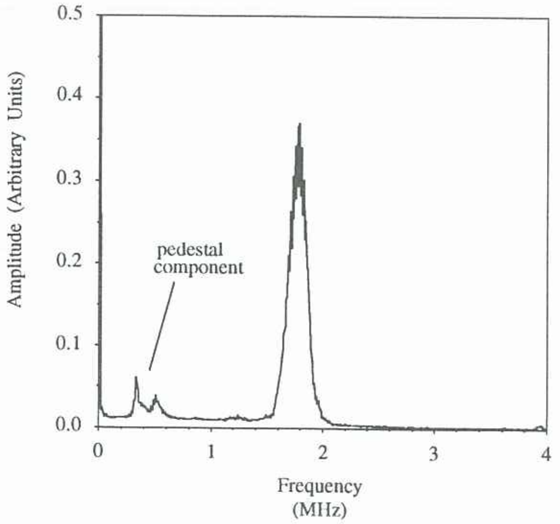


Figure 4. Fequency domain record from a point near the center of the channel

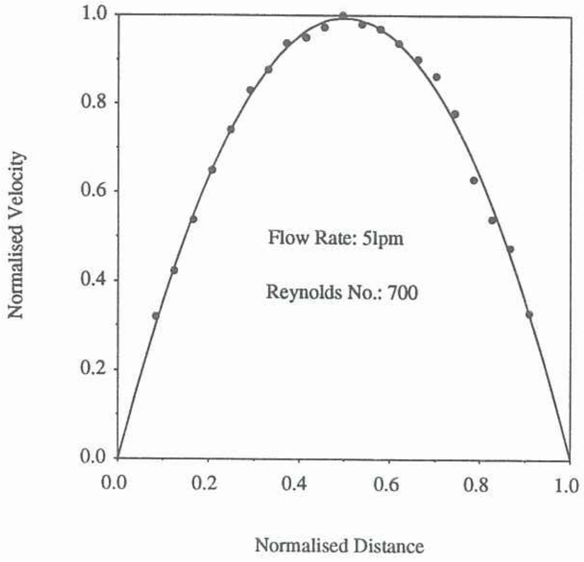
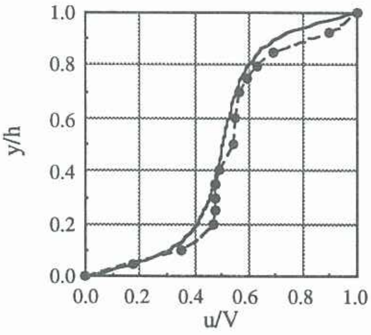
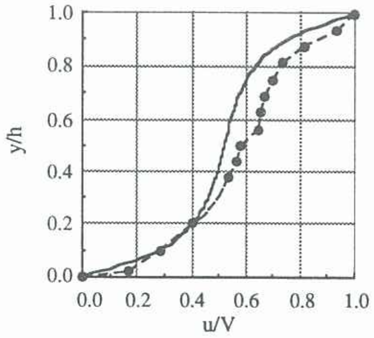


Figure 5. Laminar oil flow in 1mm channel.



(a) Rh=4655

eccentric case at maximum film thickness, gap=0.91mm



(b) Rh=2520

eccentric case at minimum film thickness, gap=0.49mm

Figure 6. Velocity profiles in journal bearing,
-●- present theory (Tieu and Kosasih, 1992a),
—— present experiment