Adaptive optics for IC-engine measurements *

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Abstract. The present paper is concerned with the development of miniaturized LDA-optical systems to produce small-size, optical velocity sensors that can be easily employed to measure flow velocities. Miniaturization is achieved by employment of graded index fibers to guide the incident laser beams to the optical head. The same sort of fibers are used to guide the collected scattered laser radiation back to the photodetector. In this way, the bulky parts of a conventional LDA-optical system can be placed and operated away from the test section. Small optical heads result that can be easily handled and traversed. Three different LDA-optical systems are described. Test measurements in pipe and channel flows are presented and first measurements in a fired internal combustion engine are provided to establish the correct functioning of the system.

1 Introduction

There has been a number of attempts to use glass fibers in laser-Doppler anemometry and the first phase of the development work concentrated on separating the photomultiplier from the main optical system by using glass fibers as guides for the scattered light. These first steps were followed by employing glass fibers to guide the laser beam to the transmission optics of an LDA-system. Further developments, aiming at the miniaturization of the optics, have resulted in devices to mount monomode fibers between the frequency-shift unit of an LDA-system and the focusing lens; e.g. see Buchhave and Knuthsen (1982).

For the present work graded index fibers were favoured. At the initial stages of the study, various optical configurations were tested and were shown to result in satisfactory LDA-signals both in the forward and the backward-scattered light mode when multimode fibers were used. A first account of this work was provided by Ruck and Durst (1983). The present work is a continuation of this study. First, various optical systems were built with the aim to be applicable for velocity measurements in different flow situations. The experience gained in this development work provided a basis for designing miniaturized LDA-sensors that operate at a distance from the laser light source, away from the major optical components and the photomultiplier. Three systems of this kind, operating in the backward-scatter mode are presented in this paper. Performance tests are described that were carried out in laminar and turbulent laboratory flows and it is shown that all optical systems work satisfactorily. One optical system was applied to a fired single-cylinder, four stroke engine and measurements described in this engine are shown as an example for results obtainable inside of internal combustion engines.

2 Development of miniaturized LDA-probes

2.1 General remarks

In the present work, the miniaturization of the optical heads was achieved by combining the small-sized optical components in the probe with glass fibers in order to guide first the light beams from the laser to the miniaturized optical head and subsequently to guide the collected scattered light back to the photodetector. Further miniaturization was achieved by mounting the beam splitter and the frequency shifter on the base of the laser source and taking the laser beams (after the frequency shifting unit) into glass fibers to guide them to the optical probe. Work along this line has been also reported by Buchhave and Knuthsen (1982), Ruck and Durst (1983), Neti and Colella (1983) and Ohba and Matsuno (1982). These optics differ from the present LDA-probes in one or more of the following characteristics:

- Graded index fibers were used to guide the incident light beam to the probe head and to bring back the collected scattered light.
- High power lasers (up to 5 Watts) were employed with the glass fiber probes.
In two of the cases, the incident light beams were guided through different graded index fibers to the miniature optical units, yielding a one- and a two-component LDA-optical probe.

The following paragraphs describe the basic properties of the graded index fibers and the design of the three, newly developed miniaturized optical systems.

2.2 Graded index fibers

Monomode fibers (Buchhave and Knuthsen 1982) have been favoured in laser Doppler anemometry and it is only recently that graded index fibers have been employed; e.g., see Ruck and Durst (1983). Experience shows that such fibers permit higher laser power to be propagated which is necessary for LDA-measurements in internal combustion engines or in other practical flows.

The light guiding properties of graded index glass fibers originate from the nearly parabolic variation of refractive index in the core of a graded index fiber. Unlike the case of step index fibers, the acceptance angle is not constant, but it varies with radius. It has its maximum on the optical axis and decreases with increasing core radius. To define this angle, however, the numerical aperture \( NA \) is defined as the sine of the maximum acceptance angle located at the center of a graded index fiber (Fig. 1).

\[
\sin \theta_c = n_e \sin \gamma_c = \sqrt{n_e^2 - n_M^2} = NA.
\]

For an ideal graded index fiber, one can write:

\[
\frac{\sin^2 \theta(r)}{NA^2} = 1 - \frac{r^2}{a^2}.
\]

The above Eq. (2) can be graphically represented in a phase-space diagram, see Geckeler (1983).

As far as laser-Doppler anemometry is concerned, the number of modes that propagate in a light fiber is shown by Grau (1981), Kleekamp and Metcalf (1978) to be dependent on the square of the parameter \( \nu \):

\[
\nu = \frac{\pi d}{\lambda} NA.
\]

The square of this characteristic fiber parameter, \( \nu^2 \), is proportional to the area in the phase-space diagram, shown in Fig. 2. If the \( \nu \)-value exceeds 2.4, multimode laser beam propagation occurs. From this value and the above Eq. (3) the diameter of monomode fibers can be computed to be approx. 2.5 microns if usual fiber materials and the green line of an Argon-Ion-laser are employed. Fibers of this diameter are difficult to handle and also possess severe limitations as far as the maximum propagated laser power is concerned. It is because of this that the authors decided to use fibers with larger diameters for their work and, considering the resultant advantages, accepted the occurring multimode operation.

Regarding the use of multimode glass fibers, experience shows that they also have limitations as far as their acceptable laser power is concerned. However, work carried out by the authors showed that the laser power needed for the LDA-measurements in internal combustion engines can be easily propagated through multimode glass-fibers to yield good LDA-signals with back-scattered light.

2.3 Miniaturized LDA-optical systems

In order to obtain optical access to the inside of internal combustion engines and to assure simplicity in handling an LDA-system for flow studies, it is required to have a small optical probe available that can also be attached to the engine. Successful spatial or temporal flow scale measurements in internal combustion engines require LDA-probes that can be operated at a distance from the laser source, the major parts of the transmission optics, and the photodetector. In order to achieve this final aim, the present development work was carried out in three phases:

- The transmitting optics and the photodetector were decoupled from the laser light source and the photodetector and measurements were obtained by traversing the transmission and receiving optics only.
- Two optical systems of reduced size were designed and manufactured. A system containing a rotating diffraction grating and an optical unit with small double Bragg cells for frequency shifting were designed and built.
- LDA-probes of very small dimensions for direction sensitive, one- and two-component LDA-measurements were developed and tested. First measurements in a fired internal combustion engine were carried out.

A summary of the development work and short descriptions of the various optical systems are presented below.