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DEVELOPMENT OF AN LDA-MEASUREMENT-HEAD FOR THE USE ON THE INTERNATIONAL SPACE STATION

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Abstract

A compact fiber-based LDA-measurement-system is under development as a multi-user tool for the Fluid Science Laboratory (FSL) on the International Space Station (ISS). The first use of the measurement system is planned for the micro-gravity GEOFLOW experiment. We investigated the optical properties and the feasibility of the measurement head of the system, which has been realized as a first step for one velocity component in respect to the experiments planned on the ISS. The Doppler signals have been obtained in backscattering mode. A measurement volume with an averaged fringe-spacing variation of 3 % within the length of 600 µm has been realized, which will be improved further to meet the requirement for the measurement head.

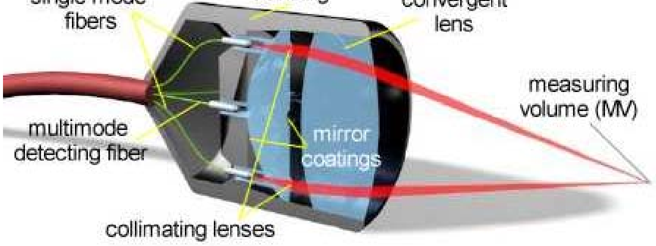

Fig. 1: Design of measurement head (© ZARM)

1. Introduction

Thermally driven flow trapped between two concentric, coaxially rotating spherical shells is an important model for fluid mechanics, astrophysics and geophysics. It exhibits a variety of different types of instabilities, which depend on parameters, e.g. rotation rate, temperature gradient, the width of the gap between the shells, flow materials, etc. The main objective of this project is to investigate the stability, pattern formation and transition to turbulence of the geophysical fluid flow (GEOFLOW) under microgravity. It will give a deep insight into geophysical and astrophysical phenomena such as convective flow in the outer core of the earth or atmospheric flows of gas planets.

In order to exclude the gravity effect, the experiments are planned to be conducted within the FSL at the ISS under microgravity conditions. Great efforts are needed for a better understanding of these flow phenomena by experiments as well as by numerical simulations done by Egbers et al (1999) and Travnikov et al (2002). The GEOFLOW experiment will investigate the silicon-oil flow within a gap between two concentric spherical shells, which can be rigidly rotated at different speeds as described in Egbers et al (2003). In the experiment each shell can be heated with different temperatures. A high voltage field can be applied in between the inner and outer shell to create a central force field.

Flow visualization techniques as well as other optical measurement techniques like differential interferometry will be used as described by Sitte and Rath (2003). Spatially resolved measurements of velocity distributions under different flow conditions can be realized by the technique of Laser Doppler Anemometry (LDA). The LDA technique has been widely used for the flow velocity measurement with the advantage of non-intrusive and relatively high spatial resolution compared to other flow diagnostic techniques (Albrecht et al 2002). In general, the spatial resolution is determined by the size of the measurement volume. However, it can be enhanced by using two wavelengths (Czarske 2001, Czarske et al. 2002, Büttner and Czarske 2003) or multimode fibers (Büttner and Czarske 2001).

The LDA system is required to measure two velocity components in back-scattering mode. It must be capable of measuring a velocity range from 0.1 mm/s to 100 mm/s with a spatial resolution of better than 100 µm in the direction of the optical axis. In view of cost reduction aspects the launching weight of the diagnostic system components has to be minimized. The LDA system should also consist of a compact, lightweight measurement head. Therefore several different concepts were made for meeting these conditions (Fechtmann et al 2001, Fechtmann and Immohr 2003). In the present work a specially designed optical measurement head (Fig. 1) is used for meeting the necessary conditions for the compact fiber-optic LDA system. The path of the scattered light is folded inside the measurement head so that the length of the head does not exceed the maximal length of 50 mm. The system is designed as a cost-effective, monolithic fiber-optic system, which is flexible for several different flow experiments on the ISS.

In this paper we present the first step of the development of the measurement-head, which was designed for the use on the ISS experiment. Before the measurement-head is used for a real flow experiment, laboratory experiments are necessary to examine the feasibility. First, an overview of the optical design together will be given with the requirements in the application. Then the fabrication quality of the optical components will be examined, which is followed by the experiments for evaluating the properties of measurement-head with a laboratory set-up.

2. Design of the measurement-head

The measurement head (Fig. 1) is designed for measuring two lateral velocity components in a backscattered-light collection mode. Due to the limited space conditions within the Experiment Container (ETC) at the FSL the measurement-head has to be lightweight and small with a maximum length of about 50 mm. However, it also should be capable of supporting working distances in the range of 30-200 mm by using different front lenses or different measurement heads.

For the flexibility of the traversing as well as for separating the driving units from the measurement head, both the sending and detected light are guided by optical fibers. Two pairs of single-mode fibers will be used to deliver the light to the probe and to create the measurement volume (MV), while a multi-mode fiber delivers the backscattered light from the MV to the detectors when two wavelengths are used. To estimate the Doppler-burst frequency by adequate signal processing a small versatile burst-processor has been developed using field programmable gate arrays (FPGA). For this different algorithms (e.g. counter, FFT or wavelet transform) have been developed, which can be remotely updated to the FPGA (Fechtmann 2002, Fechtmann 2003, Fechtmann et al 2004).

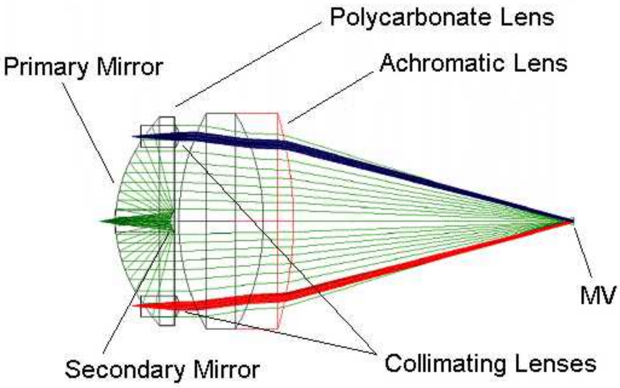

Fig. 2: The working principle, showing the multifunctional optical element, with the collimating lenses, the primary and secondary mirror as well as the achromatic lens and the light paths

The measurement head has a length of about 45 mm and an outer diameter of 30 mm, containing two elements: A commercial achromatic lens, which defines the working distance of the probe, and a highly integrated, monolithic, multifunctional optical element (Fig. 2), which is created by an injection molding process using a precision, diamond tuned tool.

As can be seen in Fig. 3 a/b the multifunctional element integrates four aspherical collimating lenses on the frontside and five tubes for alignment and holding the fibers on the backside. The backscattered light is guided into the central fiber by a folded, mirror based beam path, consisting of the metal coated aspherical surface on the backside of the element and in the middle of the front surface. The four lenses on the front of the polycarbonate element collimate the light delivered by singlemode (SM) fibers. Afterwards the collimated beams are focussed by the achromatic lens to create the MV. The backscattered light from the MV is first collected and collimated by the achromatic lens. The primary mirror on the backside of the optical element directs the light towards a secondary mirror placed in the middle of the front surface, from where it is focused into a multimode (MM) fiber positioned within the central fiber holder tube.

Depending on the wavelengths used the coating of the mirrors have been done with Al (Fig.3a) or Au (Fig. 3b). For the tests described here, the mirrors were coated with gold to increase the detecting efficiency at the laser wavelength of 980 nm. Nonetheless, the detection system is achromatic due to the use of mirrors and a small curvature of the front surface offsetting the chromatic aberration of the flat surface in the fiber holder. Therefore, it can be used over a wide range of wavelengths. The transmitting efficiency of the mirror design is expected to be better than 50 % of the backscattered light from the MV into the MM fiber.

Fig. 3a: The backside view of the injection molded monolithic polycarbonate lens, with five tubes for guiding the optical fibers (Al-coated for 532 nm)

Fig. 3b: The frontside view of the injection molded polycarbonate lens, with four integrated collimating lenses on the surface and a secondary centric mirror inside (Au-coated for 980nm).

3. Laboratory Experiments with Results

Beam quality analysis with CCD camera and beam profiler

For the first step only one pair of beams was used. A fiber-coupled laser-diode (wavelength: 980 nm, coherence length: 7.9 mm) was utilized for the following experiments. The laser-diode was already coupled into a SM fiber with the maximum output power of 300 mW. The light from the SM fiber was equally divided into two SM fibers using a 1x2 fiber coupler. Each of the SM fibers is fixed on top of an *x-y-z* mechanical traversing stage as shown in Fig. 4 guiding the laser beams into their respective tubes. For the tests an achromatic lens with focal length of 50 mm was placed in front of the polycarbonate element to create the MV. Both the monolithic optical element and the achromatic lens are placed inside the measurement head housing as depicted in Fig. 1.

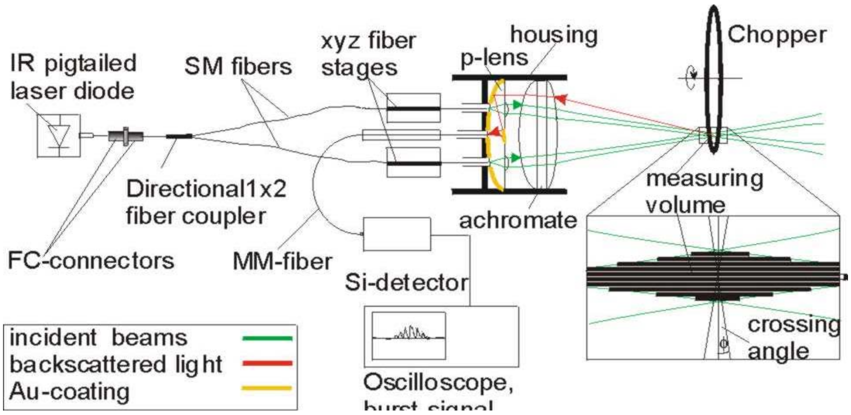

Fig. 4: Experimental setup for the Doppler signal measurement.

The position of each SM fiber was carefully adjusted by the *x-y-z* stage, constantly monitoring the position of the two beams with a CCD camera which was placed at the crossing point, when focusing the two beams to create the MV. Referred to Miles (1996), for reducing non-uniformity of the fringe-spacing inside the MV, it is important to adjust the crossing point to coincide with each respective beam-waist position.

The quality of the beams and the position of their waists is the key factor for generating a highly uniform interference pattern in the MV. The quality of components can be evaluated by comparing the beam quality in front of and behind the lens. For the evaluation of the beam quality two methods are available: observation by a CCD camera and measurement with a beam profiler, both detected after the passage through the achromatic lens. Each of the beams was scanned by a beam profiler to detect the beam diameter of e^{-2} width of Gaussian beam in the distance of the MV after passing the achromatic lens.

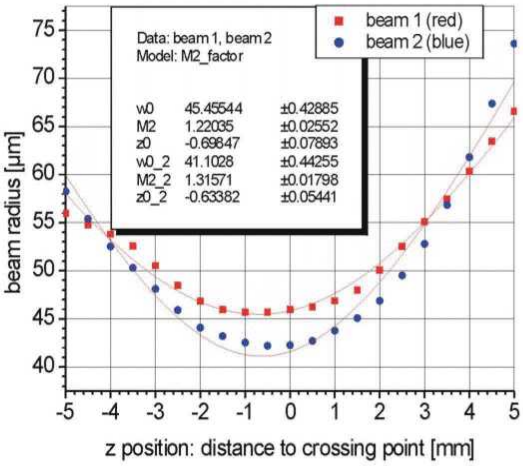

Fig. 5: Beam radius profile along the optical axis

Fig. 5 shows the result of the beam-radius measurement along the optical axis with calculated M^2-value and beam-waist position for each beam. As seen in the Fig. 5, the beam waists were set approximately into the same position with a deviation of 65 µm. This deviation was considered to be small compared to the length of the MV of about L(MV) = 600 µm. In the future a MV with a length lower than 100 µm will be generated e.g. by stronger focussing the beams.

The image of the irradiance profile was also observed with a CCD camera for both beams. Using an alignment laser coupled into the other side of the multimode fiber to mark the optical axis of the head, the system shows the crossing point in Fig. 6a and a position 2 mm behind it in Fig. 6b. This alignment optimize the in-coupling efficiency of the collecting optics.

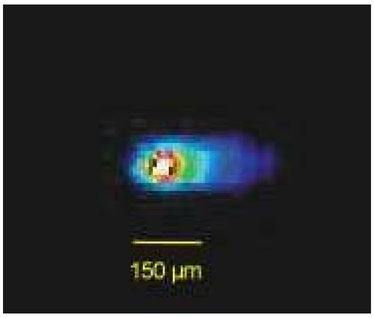

Fig. 6a: CCD image of the beam irradiance profile of coinciding two laser beams and alignment laser in focus position (MV) at z = 0.

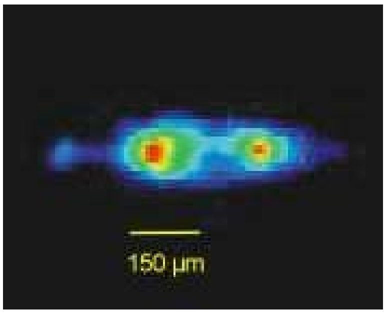

Fig. 6b: CCD image of the alignment laser (middle) and MV-lasers at z = 2 mm behind the MV

Doppler signal detection and fringe-spacing measurement

The Doppler-burst signal was detected and the fringe spacing was calculated from the measured Doppler frequency using a tungsten wire with a diameter of 4 µm as a scattering object. The wire was attached on an optical chopper on a motorized stage. An example of the observed Doppler burst signal is shown in Fig. 7. The signal shows a low visibility of

V = 0,3 which can be caused by a slight misalignment of fibers or a tilt of the wire passing through the MV.

The Doppler frequency was estimated for each of the burst signals by a fast Fourier transform (Fig. 8). The fringe spacing was then calculated from the measured Doppler frequency and the known velocity of the wire. Fig. 9 depicts the fringe spacing variation along the optical axis. The average fringe spacing was measured as d_m = 2.50 µm, which is almost constant along the optical axis with a relative variation of 3 % in the MV of about 600 µm length. This agrees well with the theoretically calculated value of d_t = 2.50 µm from the half-crossing angle of φ = 11.3° and the wavelength of the laser λ = 980 nm. However, the relative variation of the fringe spacing along the optical axis should be less than 1 % for the required accuracy of the flow experiments in the ISS. The requirement is only achieved in the center part of the MV of 300 µm. This will be improved by adjusting the position of the fibers as well as removing any residual tilt between the different optical elements.

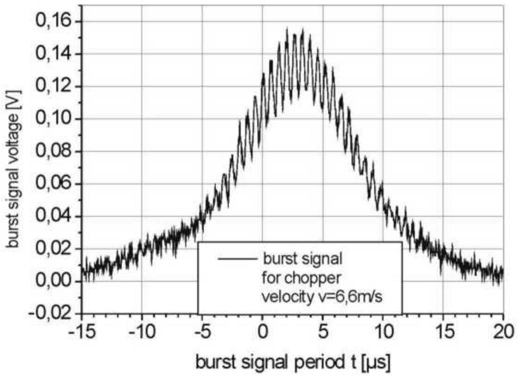

Fig. 7: Detected Doppler-burst signal.

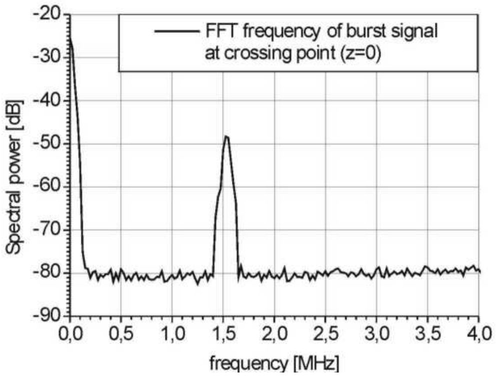

Fig. 8: Power spectrum of a Doppler-burst signal.

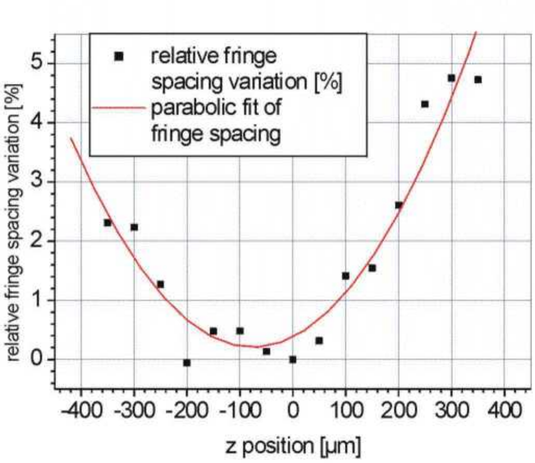

Fig. 9: Relative fringe spacing variation

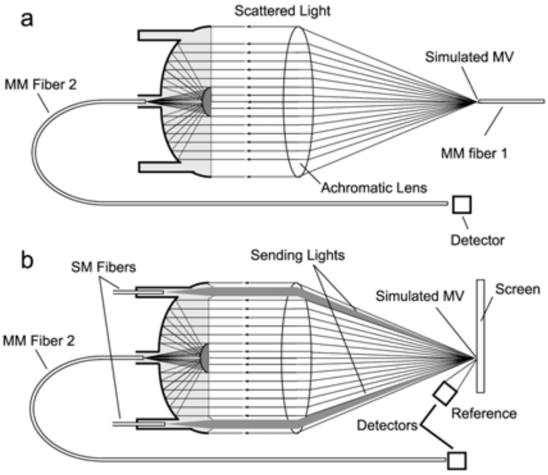

Fig. 10: Setup for mirror efficiency evaluation

Evaluation of the mirror detecting efficiency

For the evaluation of the detecting efficiency of the mirrors inside the polycarbonate element, light from an MM fiber (MM fiber 1 in Fig. 10a) was placed at the MV for simulating the backscattered light from the MV. Another MM fiber (MM fiber 2 in Fig. 10a) with low numerical aperture (NA) was set to the center of the backside of the polycarbonate element to collect the light from the simulated MV. The detecting efficiency was derived as the ratio of detected light power and emitted light power at the simulated MV (MM fiber 1). The optical detection efficiency was roughly 0.1 % of the incoming beam creating the simulated MV. Then another method was utilized as shown in Fig. 10b, since the backscattered power is not identical to the entering power. MV was created on a screen by lights from two SM fibers as used for flow measurement. A part of the backscattered-light power was measured as a reference at a point inclined to the optical axis and 20 mm apart from the screen. Assuming the uniform distribution for the backscattered light and taking account of the aperture of the detector the efficiency (the ratio of detected power and estimated total backscattered-light power) turned out to be about 3 % of the backscattered light.

4. Conclusion and Future Work

A compact fiber-based LDA-measurement-system with a specially designed integrated monolithic optical element is being developed as a multi-user measurement-system for the ISS. Before applied to a real flow measurement, basic properties as well as the feasibility of the measurement head were examined in a laboratory set-up. Fabrication quality of the optical components were investigated and a measurement head for one velocity-component measurement with backscatter mode was realized as a first step. The Doppler signals were detected and the fringe spacing in the MV was measured. The resulting fringe spacing agreed well with the expected value from the optical configuration. However, the fringe spacing variation inside the MV along the optical axis was 3 % through the MV of 600 µm length. The variation of less than 1 % which is required for the accuracy of the flow experiments in the ISS was obtained only in the center part of the MV of 300 µm. This will be improved with more refined adjustment and fixing. The function of the monolithic component was confirmed for the detection of the signals with backscatter mode.

The realized measurement head is now enabled to satisfy with the requirements and will be characterized more precisely by rotating glass plate in the PTB in a way according to Müller et al. (2001). A test measurement with the measurement head will be conducted in a flow in the BTU-LAS.

Acknowledgements

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