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Design and performance of a high-resolution dual-channel heterodyne laser velocimeter

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Abstract

We describe a dual-channel laser velocimeter based on a single laser source and a single set of carrier wave generation optics. The apparatus is intended for simultaneous vibration measurements on several points of instable objects, such as biological specimens or micro electronic mechanical systems, so that instantaneous phase relationships and amplitude ratios can be determined. Our instrument presently allows measurements on two points of interest which can be arbitrarily chosen. The optical design allows expansion to at least four independent channels. At a maximal velocity amplitude of $52\,\mathrm{mm\,s^{-1}}$, the velocity resolution and the detection limit equal $2.6\,\mu\mathrm{m\,s^{-1}\,Hz^{-1/2}}$. Even with object points less than 0.4 mm apart, channel cross-talk is less than −78 dB at all frequencies.

Keywords: Multipoint; Vibrometry; Cross-talk

1. Introduction

Laser vibrometry is an important technique for research on the acoustic behavior of complex and delicate systems, such as the eardrum and the middle ear ossicles. Experimental investigation of these objects requires non-contact measurements spanning the entire audible frequency range. Interferometric vibrometers meet these requirements, but presently systems fall in one of four categories: (1) systems addressing one spatial point at a time only [1–3], (2) multipoint systems restricted to low vibration frequencies [4], (3) multipoint systems restricted to time-averaged measurements [5] or (4) multipoint systems restricted to a regular array of spatial points [6]. The inherent instability of in vivo biomedical specimens, due to physiological changes, implies that repeated measurements do not necessarily yield the same results, which makes successive or time-averaged measurements at several, spatially separated points difficult to interpret. This restriction is overcome by an instrument which allows for simultaneous acquisition of measurements at several points in space. For unambiguous interpretation, the system needs to provide both amplitude and phase of the vibration at each measurement point.

We are developing an interferometric vibrometer which is able to perform such measurements – presently at two measurement points – for application in our research on the mechanics of hearing. Obviously, such an instrument will be useful in any area where vibration measurements need to be made on instable structures, for instance integrated micro electronic mechanical systems (MEMS). In these systems, the moving parts are not only reduced to tiny dimensions but often are manufactured exactly alike to a very high degree of

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precision. Mechanical vibrations are then easily transmitted from one element to another due to resonant acoustic coupling. Furthermore, small changes in (spurious) electrical charges on the elements can drastically alter their resonance behavior, which makes simultaneous measurements on several points useful.

An interferometer can be used to study such instable objects when the object is at least a few microns wide, since focusing the laser beam onto the object using completely filled, high-aperture lenses yields a spot size of the order of the wavelength. The heterodyning principle assures that even very low intensities within the retro reflected beam can be measured [7], ensuring that the light itself will not become a disturbing factor.

The easiest way to realize a multiple beam vibrometer simply is to use as many interferometers as there are measurement points required. This implies the use not only of multiple laser sources but, in case of classical heterodyne interferometry, also the use of multiple (sets of) acousto-optic modulators (AOMs) needed to generate the heterodyne carrier frequency as well as all other optics required to build the interferometer. We designed a classical multipoint interferometric system based on a single laser source and a single set of AOMs with as much as possible of the interferometer optics shared among the different beams.

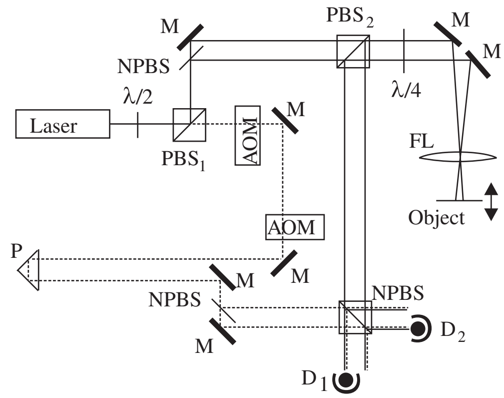

Fig. 1. Optical design of the dual-channel heterodyne interferometer. The half-wave plate ($\lambda/2$) and polarizing beam splitter (PBS_1) allow adjustment of the intensities in the reference beam (dashed) and the object beam (solid). The reference beam is frequency shifted by means of two acousto-optic modulators (AOM) before doubling the beam by means of a combination of a non-polarizing beam splitter (NPBS) and a mirror (M). The prism (P) allows for path length adjustment. An NPBS recombines reference and object beams. The quarter-wave plate ($\lambda/4$) and polarizing beam splitter (PBS_2) redirect retro reflected light towards the NPBS. Measuring positions on the object(s) can be adjusted by altering the direction of the beams through the focusing lens (FL) or by directing each beam through its own lens. The signals are detected by photodiodes (D).

2. The dual-channel heterodyne interferometer

2.1. Optical design

The interferometer, shown schematically in Fig. 1, is based on the well-known Mach-Zender design. The combination of the $\lambda/2$ plate and the first polarizing beam splitter (PBS_1) creates the reference and object beams from the linearly polarized He–Ne laser. The object beam is then split into two parallel beams and passed to the object through a second polarizing beam splitter (PBS_2) and a $\lambda/4$ plate, thus ensuring that retro reflected light is reflected by PBS_2. The reference beam first is frequency shifted, then split into two parallel beams and finally directed towards the beam combining beam splitter. This optical design offers some interesting features.

First, note that the retro reflected beams are necessarily (almost) perfectly coincident with the incoming beams. Light entering a neighboring channel through scattering travels a substantial distance (>1 m) before reaching the beam combining beam splitter. Scattered light will therefore always be angularly separated from the beam itself and only at very small angular separation it is able to reach the detector. Optical cross-talk is thus expected to be minimal. Optical cross-talk might become significant, however, when both channels are directed to overlapping measurement spots, because then reflected light from one channel can be launched exactly coincident into the other channel. Focusing light on the same spot from different directions can be used to measure different directional components of a vibration. This, however, is not the purpose of our present design.

Secondly, the optical design is easily extended to a fourfold heterodyne interferometer. The beam doubling optics are presently oriented in a horizontal plane and clearly can be replaced by a pair of beam doublers, one oriented horizontally, the other vertically.

Finally, the number of optical elements within each object beam is kept to a minimum, so as to minimize intensity losses within these beams. This is important when objects of low reflectivity [8] are studied.

Though in Fig. 1 we have depicted both object beams to be directed to the object surface through a common focusing lens, this setup is by no means necessary. It is equally well possible to direct each beam through separate focusing lenses or lens systems, or to launch each beam into a fiber.

2.2. Signal processing

All measurement signals are identically processed according to the scheme given in Fig. 2. The frequency