Loughborough University

Laser and Optical Measurements

23WSD902

Semester 2 2024 | In-Person Exam paper

This examination is to take place in-person at a central University venue under exam conditions. The standard length of time for this paper is **2 hours**.

You will not be able to leave the exam hall for the first 30 or final 15 minutes of your exam. Your invigilator will collect your exam paper when you have finished.

<u>Help during the exam</u>

Invigilators are not able to answer queries about the content of your exam paper. Instead, please make a note of your query in your answer script to be considered during the marking process.

If you feel unwell, please raise your hand so that an invigilator can assist you.

Answer **ALL FOUR** questions.

All questions carry equal marks.

Use of a calculator is permitted - It must comply with the University's Calculator Policy for In-Person exams, in particular that it must not be able to transmit or receive information (e.g. mobile devices and smart watches are not allowed).

A range of formulae and tables likely to be of benefit in the solution of these questions is provided at the rear of the paper.

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1. A differential laser vibrometer is shown in figure Q1a).

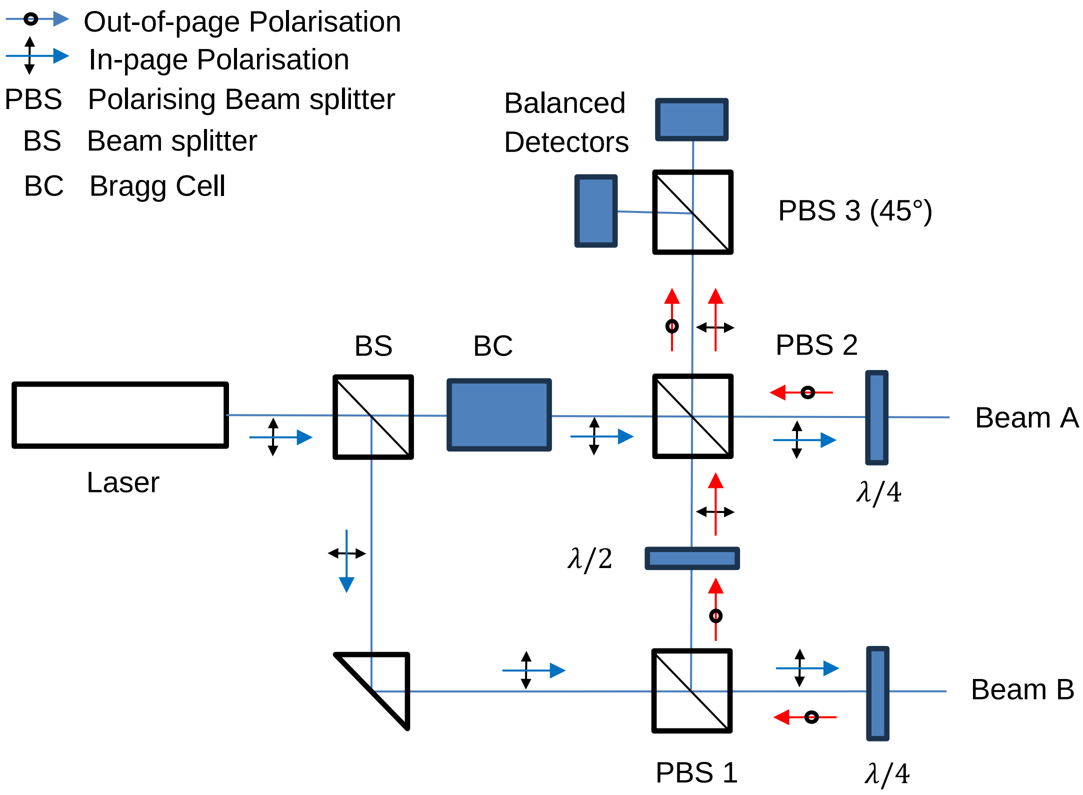

Figure Q1a)

a) Explain how the quarter-wave plates ($\lambda/4$) are oriented relative to the polarising beamsplitters (PBS 1, PBS 2) to redirect backscattered light toward the detector. [4 Marks]

b) What is the function of the half-wave plate ($\lambda/2$) between PBS 1 and PBS 2 and what is its orientation? [2 Marks]

c) Explain why balanced detectors are important and, in this configuration, why PBS 3 must be rotated by 45° to achieve balanced detection. [4 Marks]

d) Explain why it is generally important to include a frequency shifting device (Bragg Cell) and comment on the magnitude of the frequency shift required in practice. [3 Marks]

The differential vibrometer is applied to a speaker cone such that the beams are as shown in Q1b).

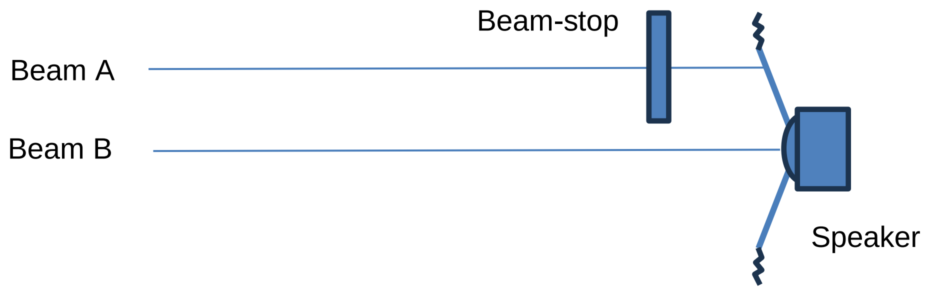

Figure Q1b)

Figure Q1c) shows the de-modulated output. Trace A is observed when driving the speaker at 100Hz with the beam stop in place. Trace B is also at 100Hz but with the beam stop removed, while trace C is a similar set-up to trace B but at 200Hz. The speaker is driven at the same amplitude throughout.

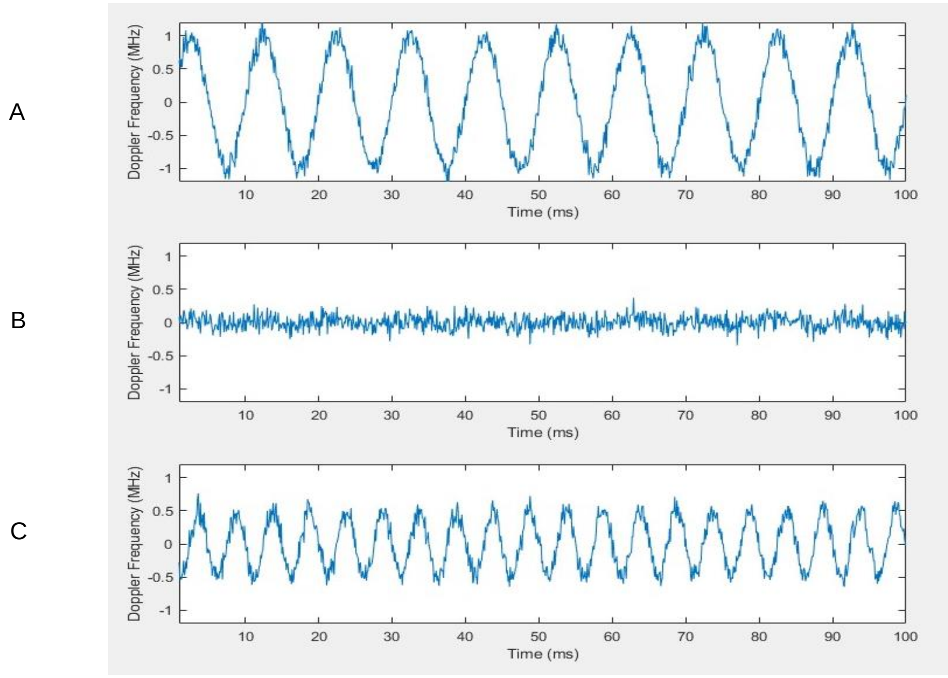

Figure Q1c)

e) If the laser wavelength is 632.8 nm, estimate the velocity of the cone from trace A. [4 Marks]

f) Explain why the differential measurement in trace B shows little vibration at 100 Hz. [4 Marks]

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g) Why might the amplitude of the differential measurement increase at a higher frequency (as in trace C)? [4 Marks]

2. An autocollimator is used to measure the quality of a rotary table using a precision polygonal mirror as shown in figure Q2.

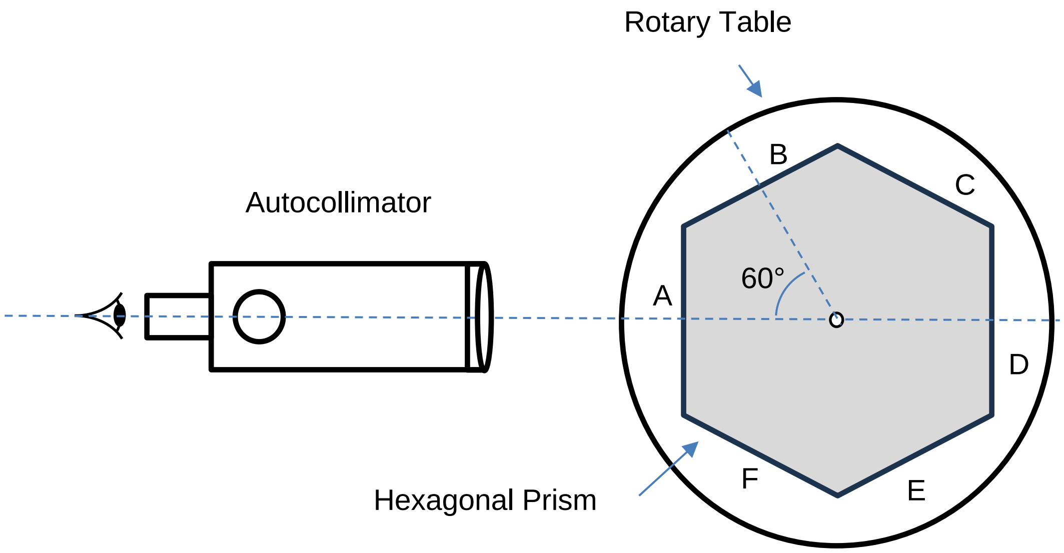

Figure Q2.

a) With reference to a diagram, explain what is meant by autocollimation and describe how the instrument can be used to measure the tilt of an external mirror. [5 Marks]

b) If the autocollimator has an objective lens of 300mm focal length and an eyepiece of 10mm focal length, what is its angular magnification? [4 Marks]

c) If the autocollimator has an objective lens of 50mm diameter and is diffraction limited, using a suitable wavelength, estimate the angular resolution of the instrument and the precision to which it can measure tilt. [6 Marks]

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The autocollimator was aligned such that the reticule position, θ_x, corresponded to tilt around the axis of the rotary table. Initially the instrument was aligned to face A of the hexagonal prism and the reticule position was zeroed. The table was then rotated in incrementally in 60-degree steps ($\theta_{step} = 60^\circ$) and the reticule positions θ_x and θ_y were noted. An inspection of the rotary table gained the data shown in table Q2.

	Measured Deviation (Degrees)						
	Face	A	B	C	D	E	F
outward	θ_x	0	-0.1	-0.102	-0.098	-0.101	-0.101
	θ_y	0	-0.0007	+0.0003	-0.0005	+0.0004	-0.0006
return	θ_x	+0.101	+0.099	+0.098	+0.098	+0.1	0
	θ_y	0	+0.0004	-0.0001	+0.0003	-0.0006	0

Table Q2.

d) Assuming that the prism is “perfect” and noting that these angles represent the difference from the nominal prism angle (i.e. $\theta_x = \theta_{step} - 60^\circ$), comment on:

i. Evidence of backlash in the table’s mechanism [5 Marks]

ii. Evidence of wobble around the table’s rotation axis [5 Marks]

3. A Michelson type displacement measurement interferometer is setup to measure the axial positioning of a milling machine table with a nominal range of motion of 1.0m. The light source is an un-stabilised He-Ne laser with wavelength $\lambda = 632.8\,nm$ and a frequency stability $\frac{\Delta\nu}{\nu} = 0.5\,ppm$. Fringe counting is based on in-phase/quadrature detection and measurements are performed in environmental conditions (T, P, RH, concentration of CO2) at which the refractive index of air is $n_{air} = 1.000271373$.

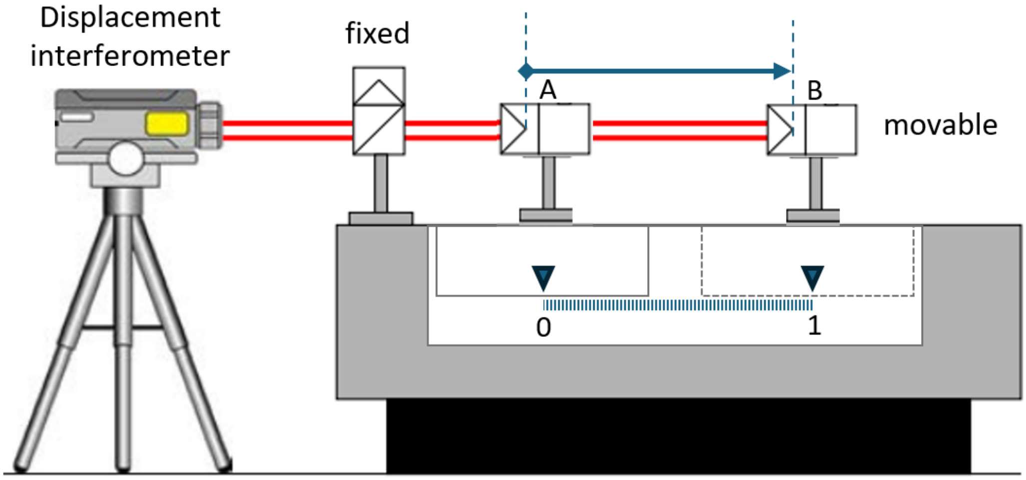

Figure Q3.

a) Determine the coherence length of the laser source. [5 marks]

b) When moving the table between the 0 and 1m marks, the instrument counts 3,161,001 fringes (to the nearest integer). Determine the mechanical displacement that this fringe count corresponds to, to the nearest micrometer. [5 marks]

c) A storm is approaching, and the pressure drops by 10mbar. The refractive index of air changes 1 ppm for every 3mbar of pressure change. Determine the change in the fringe number count that you would expect for a table displacement of 1 m (express the result to the nearest integer). [5 marks]

d) If the minimum phase change that the interferometer can measure is 1/100th of a fringe, determine the displacement resolution (i.e. the minimum displacement that can be distinguished). Take the refractive index of air as $n_{air} \sim 1$ and express the result in nm. [5 marks]

e) The He-Ne displacement interferometer in Figure Q3 (page 6) is replaced by a frequency scanning interferometer based on a tunable laser with a tuning range from 1260nm to 1360nm and a sweep rate of 100,000 scans per second (assume linear scans, sawtooth profile). Show that the frequency of the interference signal when the target distance is 1m from the datum will be greater than ~10 GHz, requiring expensive data acquisition boards with high sampling rates. [5 marks]

4. In 1970, J. A. Leendertz proposed an interesting configuration to reduce the sensitivity of out-of-plane speckle interferometers. Both illumination beams are on the same side of the z-axis and inclined at angles θ_1 and θ_2 to the observation direction, as shown in Figure Q4(a).

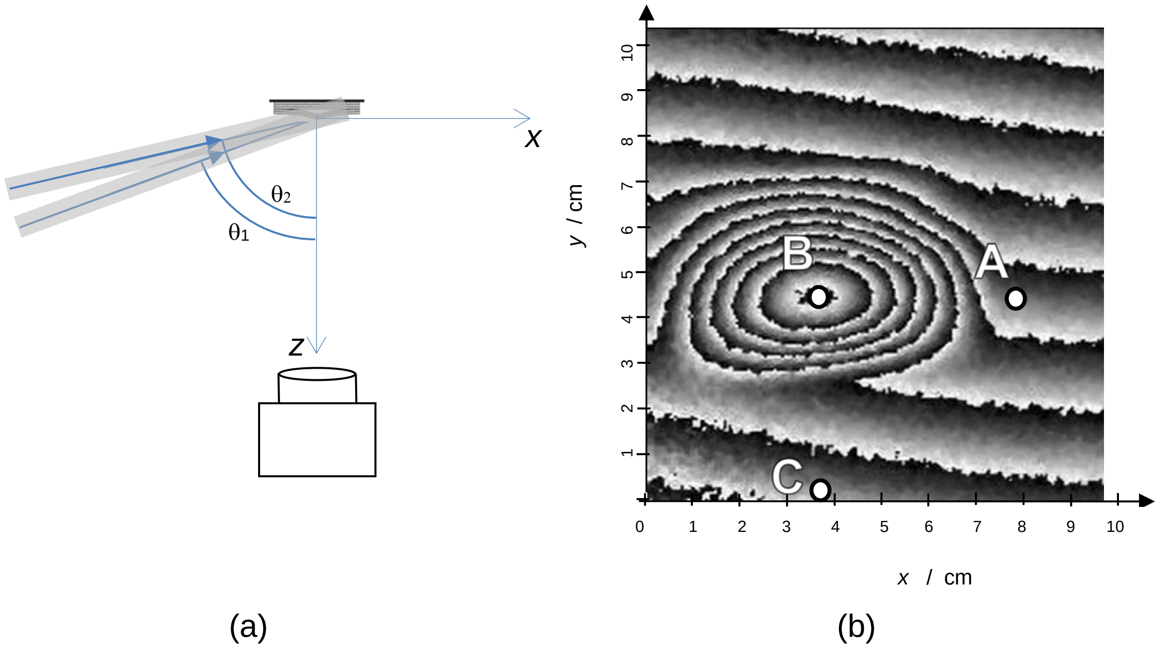

Figure Q4.

a) Draw a vector diagram and find the sensitivity vector, **K**. [4 marks]

b) Show analytically that a displacement *w* in the *z* direction results in a phase change given by [4 marks]

$$\Delta\varphi_{def} = \frac{2\pi}{\lambda} w(\cos\theta_2 - \cos\theta_1). \qquad (1)$$

c) What adjustments would you make to the interferometer geometry to reduce the out-of-plane sensitivity even more? [2 marks]

Figure Q4(b) shows a wrapped phase map obtained with the interferometer in Fig. Q4(a) (page 7) using a laser with wavelength $\lambda = 532\ nm$ and illumination angles $\theta_1 = 80°$ and $\theta_2 = 85°$. It corresponds to a composite panel with an internal delamination expanding due to a change in ambient pressure. The straight parallel fringes correspond to a rigid body tilt of the composite plate.

d) Using Equation (1) above, evaluate the out-of-plane displacement corresponding to one fringe. [2 marks]

e) Given that the wrapped phase values at points A, B and C are 0, -π and 0, respectively, evaluate the relative displacement between points A and B, A and C, and B and C. Assume that there are no in-plane displacements. [4 marks]

f) Draw a diagram of the unwrapped phase along a line at $x = 4\ cm$ and for y between 0 and $10\ cm$. [4 marks]

g) For similar detection of delamination defects in tyre manufacturing, the low stiffness of rubber requires only small out-of-plane sensitivity. Maintaining the wavelength at $\lambda = 532\ nm$, recommend suitable values of θ_1 and θ_2 to have a displacement per fringe value w_f that corresponds to $100\ \mu m$ per fringe. [5 marks]

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