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LASER INTERFEROMETRY APPLICATIONS

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I. INTRODUCTION

The first report¹ ever of laser operation was in 1960 using a ruby crystal. Continuous maser oscillation in the infrared using a mixture of helium and neon was reported² in 1961. In 1962³ continuous maser operation in the visible range was reported. The laser, an acronym for Light Amplification by Stimulated Emission of radiation, is an ideal light source for optical systems. Basically a laser is a light source inside a Fabry-Perot interferometer. The advantages of a laser light source over conventional light sources is the fact that a laser provides extreme spatial and temporal coherence. Spatial coherence means that all points along the wave front are exactly in phase which one would expect from a point source at infinity. Temporal coherence has to do with the laser's extremely narrow bandwidth. Since both temporal and spatial coherence are satisfied, long path interferometry is possible. Conventional light sources have both the size of the aperture and lack of monochromaticity as limitations to the distance that can be measured with an interferometer. A two beam interferometer is used principally for measuring distance or displacement. An interferometer uses a beam splitter to divide a beam of light into two beams with a definite phase relationship between them. The combination of these two beams produces interference fringes. Workers at Sandia Corporation, Livermore Laboratories⁴ reported the first use of a laser as the light source for an interferometer in 1963. Another AEC plant at Oak Ridge reported⁵ the development of a laser interferometer in 1964.

II. INSTALLATION ON A MEASURING MACHINE

As part of the development of laser interferometers, the Y-12 plant at Oak Ridge developed a miniature interferometer. Two miniature laser interferometers were purchased from the

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Y-12 plant to be installed on a measuring machine. (Figure 1) shows the set up on the measuring machine including the single frequency laser, beam splitter, and longitudinal axis interferometer. (Figure 2) shows both interferometers for the two axis measuring machine. The beam splitter allowed both interferometers to be operated by a single light source. (Figure 3) shows the set up to evaluate the accuracy improvement realized when using the laser interferometer rather than the lead screw. An 18 inch step gauge was used as the master in this test. A commercially available laser interferometer was used as an aid in making the evaluation.

(Figure 4) is a plot showing the accuracy improvement. The interferometer system improved the accuracy from 3 parts per million to 1 part per million. The initial downward trend of both interferometer plots is caused by cosine error. A systematic error caused by making the temperature correction is responsible for both interferometer plots going up at long distances. Abbe offset error could account for part of the discrepancies. The conclusion is that the accuracy of the measuring machine was improved. With more time and effort it is believed that the systematic errors can be greatly reduced. As far as precision or repeatability is concerned, the pooled standard deviation of the interferometer system was 5 microinches compared to 8 microinches using the lead screw.

III. EVALUATION OF COMMERCIAL LASER INTERFEROMETER SYSTEM

The announcement⁶ of the first commercially available automatic length measuring laser interferometer system was made in 1964. Also in 1964 it was reported⁷ that OPTOmechanisms Incorporated had breadboarded an automatic laser interferometer system. The Rocky Flats Division purchased an OPTOmechanisms system shortly after it was placed on the market as the lowest of three bids. The OPTOmechanisms system consists of a laser, interferometer, fringe counter, inch computer, and correction computer. (Figure 5) is a photograph of this laser interferometer system mounted⁸ on a measuring machine to check the accuracy of the interferometer system. The lead screw of the measuring machine was checked with the interferometer. The calibration data were in close agreement with the factory acceptance data performed on the measuring machine with a step gauge. Each of the four input sensors in the environmental correction computer was found to be accurate separately to 0.1 parts per million. The maximum velocity of travel of the movable reflector without losing count of the interference fringes was found to be 1.3 inches per second. The repeatability obtained when traversing the total length of travel on a large machine tool slide of 88 inches was within 10 microinches. Therefore as a result of these and other tests it was concluded that the system is capable of an accuracy of 1 part per million in measuring displacement.

IV. APPLICATIONS OF LASER INTERFEROMETER

The laser interferometer system is used⁹ to improve and verify the accuracy of machine tools. The most accurate numerically controlled machine tools presently available have correction cams to compensate for lead screw error. (Figure 6) is a comparison of the curve connecting data points at every inch displacement with the curve connecting data points at every 0.1 inch increments. All data were taken dynamically with the laser interferometer. This comparison is instructive because the usual evaluation of machine-tool slides is accomplished by a step gauge at one inch increments. (Figure 7) is a comparison of the least squares polynomial fit of the 0.1 inch increment data with the curve connecting the average error in inch increments. (The one inch increment curve would be used to fabricate the correction cam if the uncorrected machine tool slide was evaluated with a step gauge.) In this case the correction cam was made from the least squares polynomial fit of the 0.1 inch increment data. It is apparent that some rapidly changing error could not be compensated for by the correction cam due to the finite size of the cam follower. (Figure 8) is a plot comparing the predicted error after the correction cam was installed to the actual error of one measuring run.

The laser interferometer, when measuring displacement on-the-fly, is very useful in machine tool trouble shooting. (Figure 9) is a graph depicting gear slop in a resolver gear train when a machine tool slide was moved very slowly. The peaks with a period of 0.002 inches demonstrate clearance or

nonlinear angular transmission between the first pair of gears. The peaks with a period of about 0.0004 to 0.0005 inches are probably caused by gear tooth composite error between the second pair of gears in the resolver gear train. The laser interferometer was very useful in repairing a machine tool slide that was accidentally knocked out of alignment.

The Numerical Control (NC) Committee of the National Machine Tool Builders Association (NMTBA) has defined¹⁰ accuracy and repeatability for NC machine tools as: $\Delta x \pm 3\sigma$. The mean, $\bar{x}$, is plotted at each measured point along with $\bar{x}+3\sigma$ and $\bar{x}-3\sigma$. About 99.75 percent of all probable values are covered by ± 3 standard deviations from the mean at each measured point. The data are then adjusted so that the highest value of $\bar{x}+3\sigma$ is equal in magnitude to the lowest value of $\bar{x}-3\sigma$ shifting the zero error line. For a set of measurements on a machine tool, one number can be used to describe both accuracy and precision, namely $\pm(\Delta x+3\sigma)$. The NMTBA recommends, however, that the machine slide be at rest for 1 to 10 seconds before making accuracy-repeatability checks.

A certain machine slide was checked using this criteria with the resultant accuracy and precision being ± 30 microinches. The machine slide was also checked on-the-fly using a laser interferometer. (Figure 10) is a plot of $\bar{x}$, $\bar{x}+3\sigma$, and $\bar{x}-3\sigma$ for this evaluation. The maximum value of $\bar{x}+3\sigma$ is 286 microinches at the 6.5 inch position. The lowest value of $\bar{x}-3\sigma$ is 299 microinches at the 11.1 inch position. Therefore,

the accuracy and precision of this machine slide is ± 292 microinches when checked dynamically. Hence, it was discovered that the servo system controlling the slide position was oscillating or underdamped.

V. ANALYSIS OF A LASER INTERFEROMETER

(Figure 11) is a schematic of a typical early model commercial laser interferometer system. An analysis¹¹ of this system revealed that the principle involved was the combination of linear polarized light with circular polarized light. The light that traverses the corner cube prism, is reflected off the mirror, and returns to the beam splitter thru the corner cube prism is converted from circular polarized light to linear polarized light. Total internal reflection in a prism causes a phase change. Another example¹² of this phenomenon is the Fresnel rhomboid prism which converts circular polarized light to linear polarized light or vice versa. It was discovered by accident that a corner cube made of fused quartz instead of borosilicate crown degraded the operation of this interferometer system. The phase change experienced by light in total internal reflection is proportioned to the index of reflection. Analyzing the phase change experienced by two passes thru the corner-cube reflector confirmed the fact that a corner-cube of higher index more closely converts the circularly polarized light to linearly polarized light. Results of this study were used to make improvements in an interferometric gauge head.

VI. INTERFEROMETRIC GAUGE HEAD

(Figure 12) is a sectional view of the miniature interferometric gauge head developed at Rocky Flats. The first report¹³ of this gauge head was made in 1968. The gauging stylus is surrounded by air thus forming an air bearing. Longitudinal motion of the stylus is accomplished by air pressure. A mirror is cemented to the rear of the stylus which forms the movable mirror for the laser interferometer.

(Figure 13) shows the set up using two interferometric gauge heads to measure spherical shells.

(Figure 14) is a photograph of the complete prototype system used for evaluation.

An improvement in the operation of the gauge head was realized when the polarized light principle was incorporated that is similar to most commercial interferometer systems. Several of these gauging machines have been set up, each with a digital computer for automatic inspection of machined contours.

VII. TRANSVERSE INTERFEROMETER

The Köster's double image prism forms an important element in several types of interferometers¹⁴ and is the heart of the alignment interferometer¹⁵. The Kösters prism is made from two identical 30-60-90 degree prisms with very accurate angles. The alignment interferometer uses division of wavefront instead of division of amplitude as is used in most two-beam interferometers. (Figure 15) illustrates the division of wavefront in the alignment interferometer. Consider a wide beam of collimated light entering the Köster's prism with a width of $4 d \cos \alpha$. If the 45-90 degree prism (or porro prism) is shifted transversely a distance d then light from both sides of the beam are combined in the beam splitter surface of the Kösters prism. Since these two beams of light are traveling in the same direction and came from the same source interference is possible when $4 d \sin \alpha = n \lambda$. If n is changed by one integer it is seen that $d = \lambda / 4 \sin \alpha$. This indicates that the value of one fringe is dependent on the entrance angle. The value of one fringe becomes smaller as the entrance angle is increased. (Figure 16 and Figure 17) illustrate this limitation of the alignment interferometer. In (Figure 16) the porro prism is close to the Köster's prism. In (Figure 17) the porro prism has been displaced. The combined beam in (Figure 17) has shifted to the apex of the Kösters prism. If the porro prism was displaced any further, part of the beam would be blocked. Using a laser as the light source for the alignment interferometer was suggested¹⁶ in 1968. The design of a practical alignment interferometer system requires a wide laser beam and large optical elements. A prototype system was developed at

Rocky Flats using a fringe value of 320 microinches. Using a four inch Kösters prism and porro prism the system is capable of measuring deviation from straightness on slides of 15 inch travel. (Figure 18) is a photograph of the transverse interferometer system mounted on a measuring machine. An electronic fringe division system¹⁷ is used to divide the fringes into 32 parts. Therefore, each count of a fringe counter is worth 10 microinches. In a preliminary test the system was able to repeat all measurements within 10 microinches taken every inch along 15 inches of travel of the measuring machine slide.

VIII. CONCLUSION

In conclusion the Rocky Flats plant uses laser interferometers routinely in evaluating machine tools and gauging production parts. Future plans include the use of laser interferometers as the position sensing devices for machine tools during machining operations.

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