A 2D OPTICAL DISPLACEMENT TRANSDUCER TO MEASURE NANOMETRIC ERRORS IN PRECISION MACHINES

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Abstract

This work presents an innovative and portable optical measurement system based on a radial ESPI interferometer, capable to measure small displacements with a nanometric uncertainty. The system is fully automated, very portable and light weighted (~0.6 kg). Almost no surface preparation is required for 2D displacement measurement, what makes it very convenient for measuring directly on the work piece surface. In the current configuration, the system has a measurement range of ± 2 μm, and its calibration using a modified Michelson interferometer has showed an uncertainty U_{95} = ± 0.008 μm. The experiments revealed that the optical system is reliable and time efficient, having a strong potential to be applied in other situations where it is necessary to measure small displacements, with very low uncertainties. By combining three of those devices it is possible to measure all the six rigid body displacement and rotation components. Here, it is demonstrated its performance to measure the instalilities the the air bearings of a coordinate measuring machine. Its application to measure strain and stress in materials are also related in this work.

1. INTRODUCTION

Special machine tools and measuring machines must present very high positioning repeatability to assure that special parts (lenses, mirrors, …) and very accurate measurement can be obtained from these machines. In order to accomplish such tasks, the machines must present sub-micron repeatability that is influenced mainly by thermal factors, mechanic hysteresis, control limitations and, to some special machines, instabilities in the air bearings.

Air bearings are widely used in special machines when it is necessary to assure low friction, high stability and high displacement velocities. Ultra precision lathes for diamond turning and coordinate measuring machines are some examples of machines with air bearings. In these machines, the manufacturers expect that the bearings have a very good position stability to assure accurate parts and measurement results. Some manufacturers stand that a rotational and axial stability of 0,050 μm is achieved with air bearings and that this accuracy remains constant over time as there is no wear due to metal to metal contact between the rotating and static parts.

In order to assure such accuracy, the air bearing must be accurately designed, manufactured and installed on the machine. Under operation, it is necessary that air pressure is stable and that the bearing holes are clean to not block the air flow. Only under these conditions, its accuracy will be assured. To verify if the bearing is working properly it is necessary to measure its position stability and the measurement of air bearing stability is a very difficult task. Because of the very small displacements, it is necessary a measurement system with nanometer resolution and very low uncertainty to detect instabilities in the fluctuation of the machine parts over the air bearings. Classical instrumentation as mechanical gages, laser interferometers, etc., are not anymore suitable, because its uncertainty and operational limitations.

In this work, it is presented an innovative and portable system capable to measure nanometric displacements in moving parts, with very good time efficiency. The system, based on a radial interferometer, is very portable, light weighted and fully automated, having a resolution of 0,001 μm and an uncertainty of ± 0,008 μm. Its performance is demonstrated in the measurement of the instability of an air bearing of a coordinate measuring machine.

2. AN INNOVATIVE SYSTEM TO MEASURE SUB-MICRON DISPLACEMENTS

An innovative and portable optical measurement system based on a radial ESPI interferometer has been developed at the Federal University of Santa Catarina [1] to measure nanometric 2D displacements. The system can be seen in figure 3 and consists of an interferometer with conical mirrors to produce a double illuminated area from a single laser source. A diode laser and a CCD camera integrate the systems, that is fully automated and managed by a dedicated software

This double illumination makes possible to measure radial in plane displacements applying the principle of Electronic Holography or ESPI (Electronic Speckle Pattern Interferometry). The double illuminated area produces a speckle pattern that is acquired by the image processing system, producing a reference image. As the illuminated surface moves, the speckle pattern changes and new images are acquired and subtracted from the reference image, producing interference fringes and, after computer processing, phase maps. From these phase maps are measured the displacements of the illuminated region [2].

This innovative configuration made possible to build a compact measurement unit, capable to characterize in plane displacements in the illuminated surface, with metrological reliability, operational and economical advantages over classical methods.

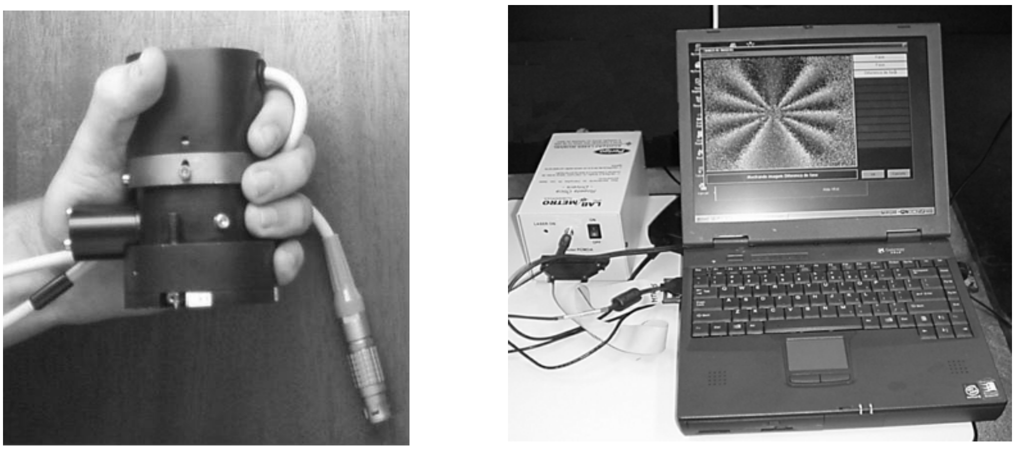
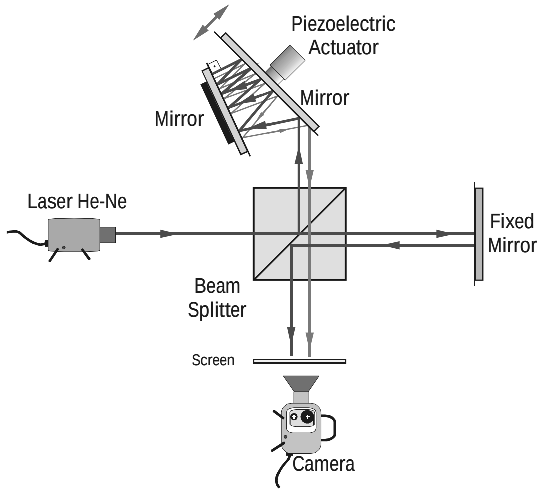


Figure 1 - Radial interferometer, drive control and software

The system was calibrated with an amplified Michelson interferometer using He-Ne laser and the results have a close concordance [3]. Some of then can be seen in figure 3. Its measuring range can be modified according the application. It the current configuration the system has a 2 μm range with 0,001 μm resolution. From this calibration, an uncertainty of ± 0,008 μm was estimated. Lower uncertainty can be obtained with a more accurate reference.



RUN	MICHELSON (μm)	SYSTEM (μm)
01	1.480	1.486
02	1.481	1.480
03	1.482	1.485
04	1.485	1.479
05	1.481	1.478
Mean	1.482	1.482
St Deviation	0.002	0.004

Figure 2 – Calibration with a modified michelson intereferometer

This same system can also be applied to measure stresses/strains and residual stresses in materials under load. For this operation, two dedicated and fully automated systems (***Optical Rousette*** and ***M-TRES***) were developed. Numerical and graphical results are obtained from the measurements enabling to know the stress state of mechanical components and structures in work conditions.

Comparisons with classical strain gages to measure stress and residual stresses have been done and the results were very close, but with ***Optical Rousette*** [4] and ***M-TRES*** [5, 6] systems this operation is done in 10% of the measurement time using strain gages and without the necessity of consumables. Figure 3 shows the ***Optical Rousette*** being applied to measure the stress in the rear suspension of a truck, after a 150 kg mass has been put over the vehicle. On the right side, there is an example of graphical and numerical result.

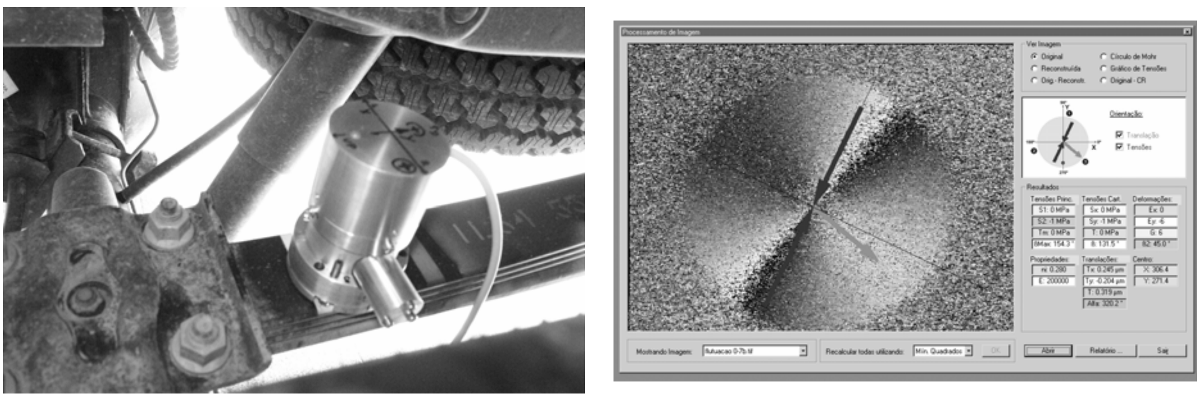


Figure 3 – Optical Rousette measuring the stress/strain in a truck suspension and a software result

3. MEASURING 2D DISPLACEMENTS OF AN AIR BEARING

As described in the introduction, air bearings are widely used in special machines when it is necessary to assure low friction, high stability and high displacement velocities. In these machines, the manufacturers expect that the bearings have a very good position stability to assure accurate parts and measurement results. In order to assure stability around 0,050 μm, the air bearings must be accurately designed, manufactured and installed on the machine. Under operation, it is necessary that the air pressure is stable and that the bearing holes are clean to not block the air flow.

In this work, the system was applied to measure the vertical bearing inslatibilty of an air bearing of a coordinate measuring machine (CMM). Under operation, the bearings of CMMs must present high stability to assure accurate results. Any instability will cause relative movement between the CMM touch probe and the workpiece to be measured.

In the experiments, the system was positioned in front of the right column of the CMM, 3 mm distant from the surface (figure 4). No surface preparation was done on the machine. The machine motors were turned off in order to measure movements only due to the air bearings. About 10 minutes after opened the air to the bearings, a first image was acquired and its phase map calculated. Other images were acquired with an interval of 1 minute between consecutive acquisitions. During the experiments, real time instabilities could be seen observing the real time fringes. This is as important tool to verify internal and external vibrations and/or quick variations in the bearings.

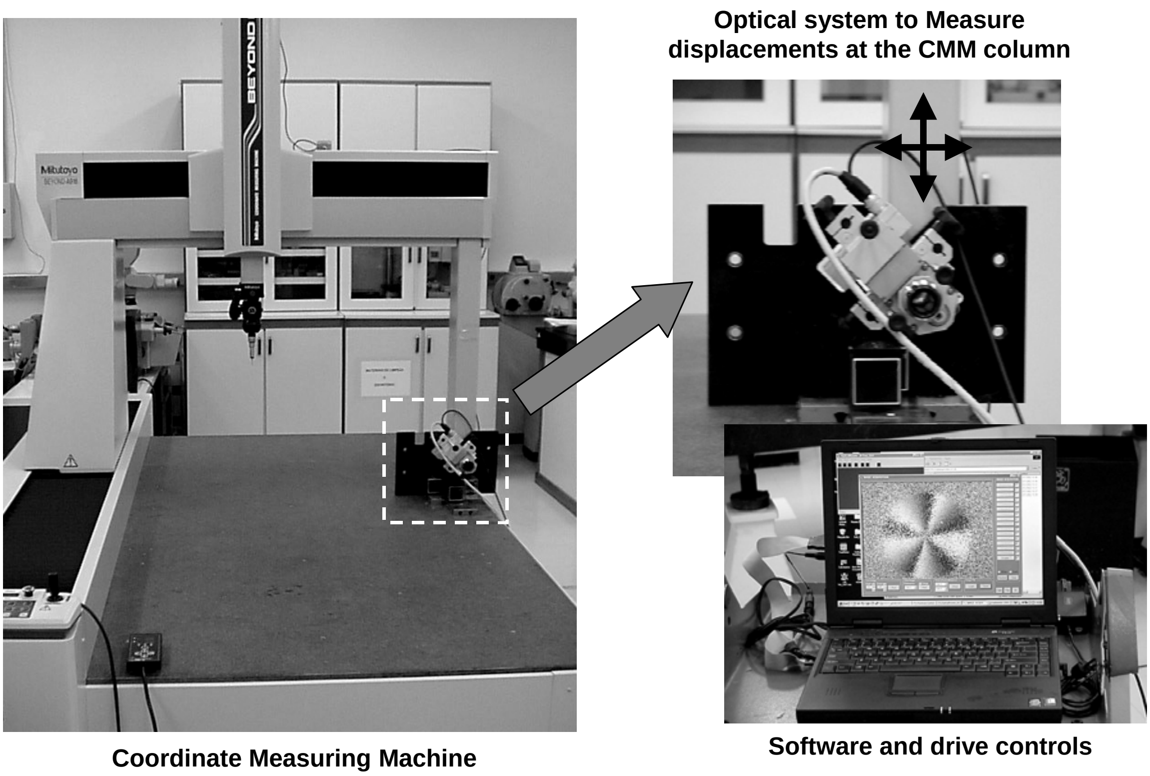


Figure 4 – Experimental setup to measure instabilities in the air bearing

The phase maps calculated for each image acquisition were combined and fringe patterns resulted, as a consequence of the displacementS caused by instabilities in the air bearing under the column of the CMM. The processing of these fringe patterns revealed the displacements. The image acquisition and processing is fully automated by software. The whole test was done in 25 minutes. Figure 5 shows some resultant images, as well as the bearing displacements along the period of test.

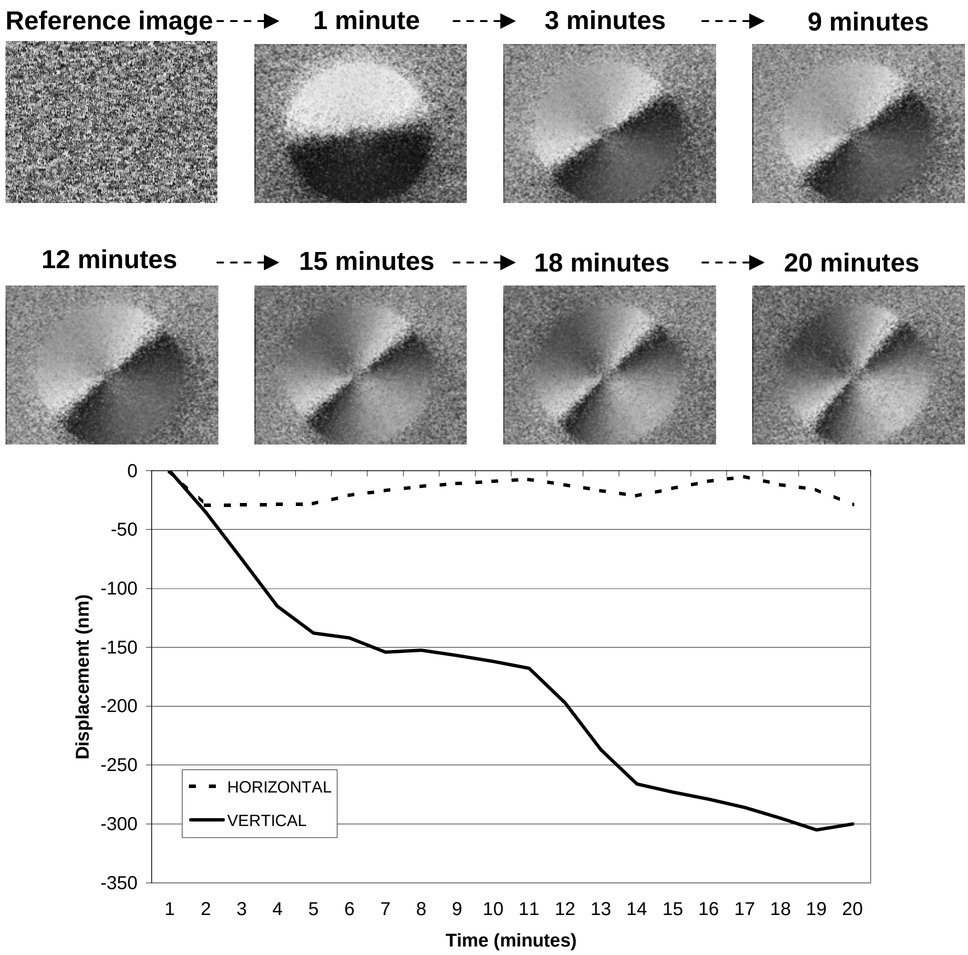


Figure 5 – 2D displacements measured on the CMM column

The results revealed that the air bearings had a vertical displacement of 0,305μm and 0,029μm horizontally, over a period of 20 minutes. Considering that the measuring uncertainty of this CMM starts from ± 3 μm, the bearing tested showed to be reliable to this application but for an ultra precision CMM this displacement level would be critical.

4. CONCLUSIONS

The konwledge of the performance of precision machines is a difficult task because it is necessary to measure very small errors with sub-micron uncertatinty. The measurement systems used to these experiments are usually very expensive or not reliable or have operational limitations.

This work presented an innovative and portable optical measurement system based on a radial interferometer using Electronic Speckle Pattern Interferometry, capable to measure very small displacements with a nanometric uncertainty. Based on this radial interferometer, different systems have been developed to test precision machines and also to measure stress/strain and residual stresses in materials.

For all these applications, an experimental setup is already complete. The radial interferometer, the diode laser and the CCD camera are integrated in one part. A control driver and a notebook complete the experimental setup, that it is configured and managed by a sofware test, making the system fully automated. These devices make the experiments to measure displacements, stress/strain and residual stresses very easy and quick.

Some evaluations comparing the ***Optical Rousette*** (stress/strain) and ***M-TRES (residual stresses)*** systems to classical instrumentation showed a similar uncertainty but strong operational advantages over classical systems [3]. Table 1 below shows one of these evaluations.

Cost [1]	Optical Rousette	Strain Gage
Man power [2]	US$ 1.50	US$ 22.50
Consumable	US$ 0.06	US$ 45.00
Total	US$ 1.56	US$ 67.50

[1] 1 measurement point [2] US$ 30.00/h

TABLE 1 – Economical comparison between Optical Rousette and strain gage for stress measurement.

The systems are very flexible and can be easily configured to specific applications. Developments have continuosly been implemented to make the systems even more reliable, time efficient and cost effective. All of them were developed at the Federal University of Santa Catarina and are produced and comercialized by Photonita - Photonical Instruments for Technical Applications – Inc (www.photonita.com.br).

5. REFERENCES

[1] Albertazzi, A. *Adequação de um interferômetro radial para a medição de tensões radiais por meio da holografia eletrônica.* **Brazilian Symposium on Experimental Stress Analisys – Brazil, 1995.**

[2] Albertazzi, A. *A robust hybrid phase unwrapping technique by block processing and sucessive approximation to a mathematical model*. **Fringe, 2001 – The 4th International Workshop on automatic processing of fringe patterns. Elsevier Science Publishers. Paris, 2001.**

[3] Willemann, D. Desenvolvimento de uma roseta óptica para a medição de tensões e deformações utilizando holografia eletrônica**. Master Program in Scientific and Industrial Metrology - Federal University of Santa Catarina – Brazil, 2002.**

[4] Willemann, D.; Veiga, C.; Albertazzi, A. *Desenvolvimento de um dispositivo interferométrico para a medição de tensões e deformações com holografia eletrônica.* **Brazilian Congress of Mechanical Engineering. Brazil, 2001.**

[5] Boettger, J. *Desenvolvimento de um sistema portátil para a medição de tensões residuais em campo utilizando a holografia eletrônica.* **Master Program in Mechanical Engineering - Federal University of Santa Catarina – Brazil, 1998.**

[6] Ronsani, M. *Otimização de um medidor portátil de tensões residuais.* **Master Program in Mechanical Engineering - Federal University of Santa Catarina – Brazil, 2000.**