

Dynamic Metrology Tool to measure the Elastic Deformation of Parallel Kinematics Machines

T. Cano ^{1,3}, R. Béarée ², P. Ray ¹, J.M. Lavest ³

¹ LaMI (Mechanical Engineering Research Group),
EA 3867 – FR TIMS / CNRS 2856, IFMA & Blaise Pascal University

² L2EP (Electronic Laboratory of Lille),
UPRES EA 2697,

³ LASMEA (Laboratory of Sciences and Materials for Electronics, and of Automatic)
UMR 6602 of CNRS, Blaise Pascal University

Abstract

The accelerations reached by the current machines prevent from regarding certain elements of the machine as rigid. We thus propose a tool adapted to the measurement of the elastic deformations of these elements during the real movements of the machine. This tool is based on the merging of heterogeneous data. It is built around a digital camera and accelerometers. After a description of the measurement system and the experimental bench used, we conclude by fixing, for the moment, the precision with $\pm 60 \mu\text{m}$ for a coverage of 300 millimetres.

Keywords:

Camera, accelerometer, machining movements, elastic deformations

1. INTRODUCTION

So as to increase productivity, the reductions of manufacturing duration have been closely studied. This reduction has been achieved partly thanks to an increase in dynamic capacities of manufacturing tools. This increase can have two origins. First an increase of the actuators performances enabled to build high speed serial machine. An other way was to design machines whose architecture favors high accelerations [1][2]. These architectures are those of parallel kinematics machines (PKM). The drawback of these high accelerations is higher elastic deformation and thus the tool path following is consequently deteriorated [3]. Then these deformations can no longer be neglected. Certain studies deal with these deformations by focusing on the design step. It is then possible to choose the materials that are going to favor stiffness or act on geometry to control the orientation of the elastic deformations. So it will be easier to compensate them by acting on the numerical control of the machine, this is called orthogonal mode design. Thus other studies deal with the numerical control. By integrating in the control model the elastic phenomenon it is possible to decrease their influence. Some of these works have already been taken into account by the machines builders. This permits to improve the dynamic behavior of high speed machine. Yet the tuning of the control parameters is highly fussy. To optimize this tuning and the use of the machine, we have to be able to identify in the best possible way the model parameters included elastic deformations.

The method currently used is modal analysis: it consists in measuring the deformation of the structure (with accelerometers) around a static position. Yet if this method obtains great results for a structure, it is less the case for a mechanism whose spatial configuration changes when used. Gagnol and al. [4] showed that modal analysis was not enough for the identification of high speed spindle natural modes. Indeed the rotation speed influences the values of natural frequencies. A single mode during zero speed identification can divide itself until the appearance of two distinct modes for a high rotation speed.

So we can truly think that the elastic deformation identification must be done during machining moves and not in a static position.

2. MAIN CONTRIBUTIONS

The main contribution of this paper is to propose a measurement tool for elastic deformations of a PKM during its rigid body movements. However it can be used for other kinds of machine if its accuracy is sufficient. To reach this objective without excessive cost, the paper proposes a combination of a digital camera and accelerometers.

The tool is firstly introduced and then the retained merging method is given. In a second time, the experiment made to evaluate the accuracy of this tool is described. Finally the results about accuracy are given before a justification of the accelerometers use.

3. TOOL MEASUREMENT DESCRIPTION

3.1. Experimental context

A priori, the most suitable tool for a deformation measurement is gauges. But the covered surface by this kind of tool is too small for our application. In fact the goal is to measure the deformation of several tens centimeter long elements which move in a volume around one cubic meter. These characteristics prevent us from using classical gauges. Specific long gauges built with optical fiber [5] can not be used too because the whole length of the element is not accessible. We can not use classical deformation field measurement for the same reason.

Actually we just need the relative displacement of particular points of the machine element, often the extremities. Laser interferometers are very accurate but if the movement is not in a straight line, no measurement is possible. The laser tracker solves this problem, and even if accuracy decreases, it is still sufficient. Leleu and al. evaluate the accuracy of a SMX laser tracker as equal to $5 \mu\text{m}$ in the worst direction [6]. But two problems remain. The laser must not be obstructed; and the number of

targets is limited to one. It is thus impossible to calculate a deformation between two points. Using a camera avoids these problems, but resolution is inadequate and the frequency is too slow. The first problem can be solved using a subpixel detector. The idea is based on a luminance model of the target. By using a standard target detector, the centre of the target is localized with a precision equal to about 1 pixel. A luminance model of the target is adjusted according to the luminance measured by the CDD sensor. With such a continuous model and an accurate calibration of the camera and lens [7], the centre of the target can be localized with a precision equal to about 0.02 pixel.[8] Nevertheless, the problem of frequency acquisition remains. A high speed camera can solve the problem of the frequency but its cost is prohibitive and the sensor quality is lower. The last way to obtain the position is to use accelerometers. The sampling frequency is very interesting but the double integration produces too important skew in data for our application.

Consequently we decided to build a specific hybrid sensor. This allows us to benefit from advantages of different kinds of sensors. A digital camera and its associate subpixel detector will give the special accuracy and accelerometers will give additional information to increase the sampling frequency.

3.2. Principle of the proposed hybrid sensor

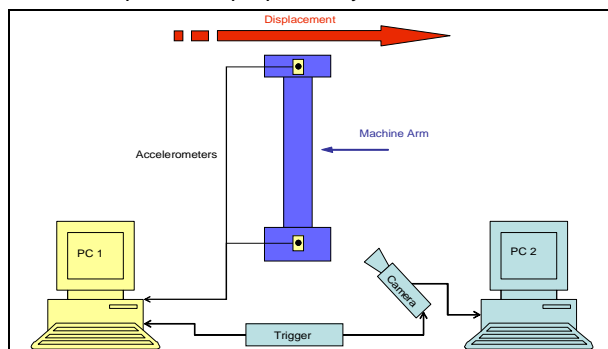


Figure 1: Principle of the measurement

The principle of the measurement is showed in Figure 1. A first computer records the acceleration of the interesting points and the camera watches the targets stuck on the same area. The second computer will calculate the position of the target later.

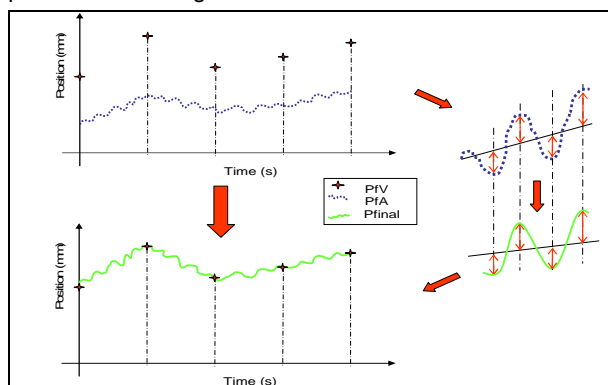


Figure 2: principle of data processing

The measurement system gives us two kinds of data: position from the vision system (PfV) and acceleration from the accelerometer. The acceleration is integrated twice to obtain the position from accelerometer (PfA). After this, the merged method can be processed. It is explained by the Figure 2:

- The error between PfV and PfA is calculated at the vision frequency,
- The error is extrapolated at the accelerometer frequency by a spline curve,
- The extrapolated error is added to PfA to obtain the final position curve (P final)

4. EXPERIMENT

Since it is about a new measurement tool, we have estimated necessary to compare it with a more conventional measurement system.

In a first time we have made a displacement with the help of a high speed milling machine and we have compared our measurement with the measurement of the machine [9]. The results were satisfactory but we consider that the movement was too smooth to reproduce the dynamic conditions of elastic deformation during high speed machining. So we have decided to use a mono-axis test bed built in the L2EP laboratory to generate the right motion. The test bed and the experiment are detailed before the study of the results.

4.1. The test bed description

The test bed is a single linear axis driven by an INDRAMAT LSP120C linear synchronous motor. In industry, this axis carried a robot arm for drilling operation. Such a system is submitted to vibrations limitations originating from the two main flexibilities of the robot arm. In order to reproduce the dynamic behavior of the production machine axis, two spring/mass systems were added in series on the table (primary part of the motor). The values of the masses and the stiffness have been chosen to reproduce the dynamic behavior of the initial machine. Three optical rules permit to measure the carriage and the masses displacement. A laser interferometer was able to realize accurately the measurement but the existing optical rules are accurate enough. The test bed has been initially built to study the influences of control on the masses vibration [10]. Figure 3 shows the carriage and the masses, the carriage optical rule is visible in the bottom of the picture.



Figure 3: the test bed

Concerning our application, this test bed allows us to make a movement with vibrations and to get a reference measurement of this movement. Thus we can compare our measurement with an industrial measurement to evaluate the accuracy of the proposed method.

4.2. Experimental Set-up

The Figure 4 shows the experimental set-up. For device reasons a strut is mounted to link the two masses. The accelerometer is mounted on the first mass, and targets are stuck on the first mass and the carriage. The targets stuck on the carriage allow us to quantify the influences of vibrations on the vision measurement by comparing the accuracy of the measurements of the carriage and the

first mass. The camera is installed on a tripod with its annular lighting. The camera covers a 300 mm width field with a focal equals to 6.5 mm. the shutter is set at 50 μ s to avoid motion blur and a variation of targets velocity. The stroke of the movement is equal to 200 mm. Several tests are made with different speed: from 25 m/min to 45 m/min.

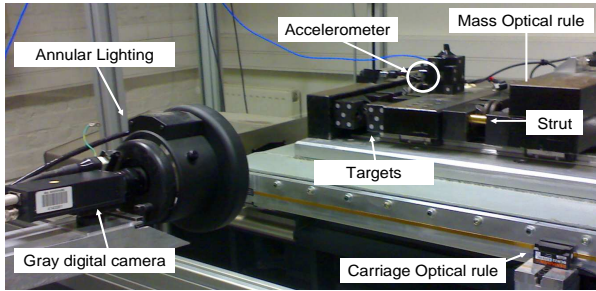


Figure 4: Experimental Set-up

4.3. Results

The aim of the experiment is to evaluate the accuracy of the proposed hybrid sensor but also to understand the origins of the errors. The movement of the carriage is smooth, without any vibration, because the elastic deformations of the load (spring/mass system) are too small to interact on the displacement of the actuator. The movement is smooth, with out vibrations, because it is directly generated by the numerical control.

Thus we can thereafter compare this accuracy measurement with the accuracy of the mass displacement measurement. This comparison gives us information about the influences of vibration on vision measurement. At last we focus on the accuracy of the hybrid sensor as a whole.

Measurement of the carriage displacement

Figure 5 shows the superposition of the measurement made by vision and the optical rule one. Points are the vision measurement which sampling frequency is 30 Hz and the curve is optical rule measurement which sampling frequency is 10 KHz.

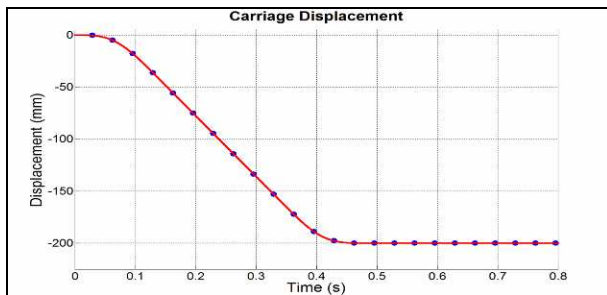


Figure 5: Carriage displacement

The error between the two measurements is given by Figure 6.

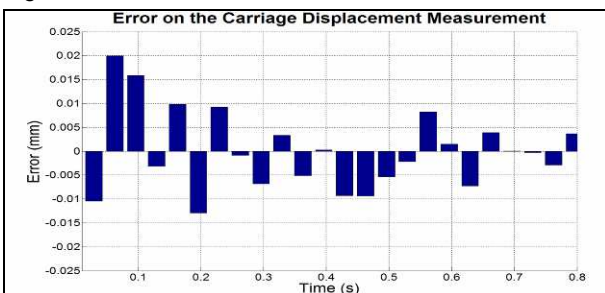


Figure 6: Error for the carriage displacement

The error is less than $\pm 20 \mu$ m. This value corresponds with the previous works [9]. The error in measuring the carriage displacement has the same order of magnitude for all tests. The final aim of the proposed tool is to measure few millimeters size deformations and the covered filed is 300 mm. In view of these parameters we estimate the accuracy as sufficient

Measurement of the mass displacement

As previously, we focus on the accuracy of the vision system for the time being. In fact the accuracy of the hybrid sensor should be fixed by the vision system. Figure 7 shows the error between the vision system and the mass optical rule.

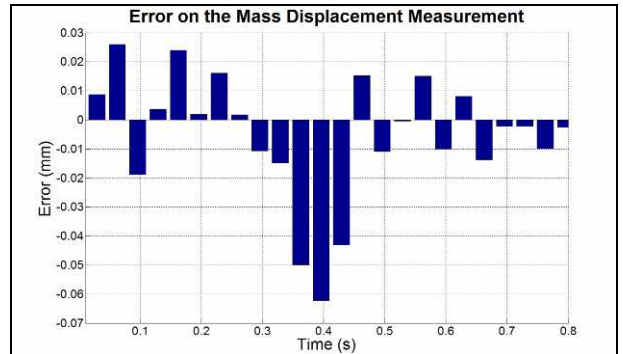


Figure 7: Error for the mass displacement

The error is greater for the mass displacement measurement than for the carriage one. Figure 8 brings together a zoom in the displacement curve of each element.

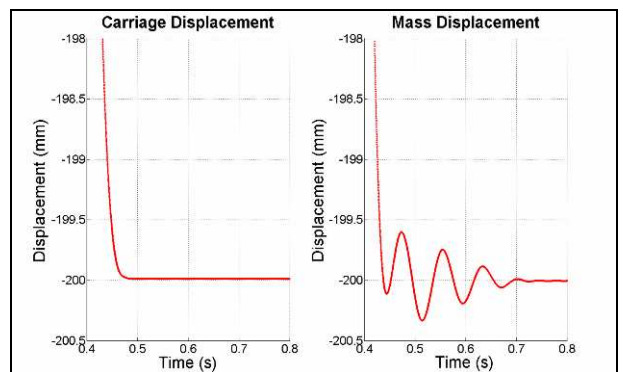


Figure 8: zoom in the displacement curves

A possible reason of the error increase is the appearance of vibrations in the movement. As the maximum error is multiplied by three, there must be another reason. In fact this peak of error is systematic for each test and at the same place on the curve. We notice in Figure 4 that the two measurements (vision and optical rule) are not made on the side of the mass. A rotation of the mass around a vertical axis can generate this kind of difference between the two measures. A new series of test is scheduled to confirm this argument.

For the time being we still consider an accuracy equal to $\pm 60 \mu$ m.

Measurement with the hybrid sensor

Until now we have only studied the vision measurement. But the sampling frequency of vision system equals to 30 Hz, and according to Shannon theorem this sampling frequency is too slow to observe phenomena whose frequency is of several tens Hz. This is the reason why we have added accelerometers to the vision system. The question is to know whether if the information given by the

accelerometers is coherent. Figure 9 shows the error made by the global hybrid system for the mass displacement measurement. This error is calculated at the sampling frequency of the optical rule which is inferior to that of the hybrid system.

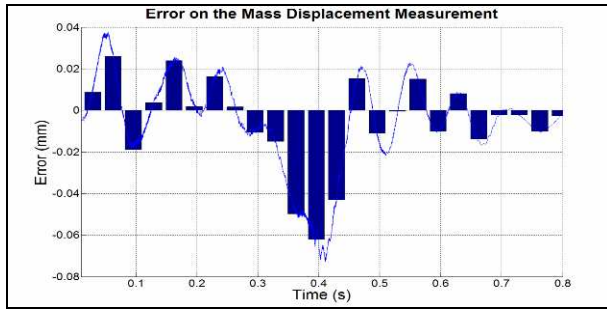


Figure 9: Error of hybrid sensor measurement

The curve represents the hybrid sensor error (at 10 kHz) and the bars that of the vision system alone. The difference is not significant.

To conclude, the accelerometer does give coherent information, which allows to over sampling the vision measurement.

5. LEGITIMACY OF THE ACCELEROMETER

We can now wonder if a mathematic method of interpolation won't have answered as well. So we are comparing here the hybrid sensor measurement to the vision measurement interpolated mathematically.

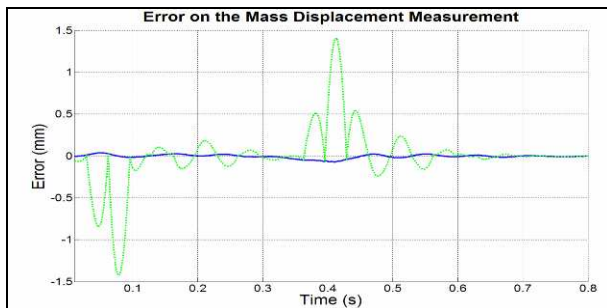


Figure 10: hybrid error and linear approximation error

Figure 10 shows the comparison between hybrid sensor and vision interpolated by linear approximation. The dashed curve represents the error between optical rule measurement and vision measurement interpolated. The other curve represents the error between optical rule and hybrid sensor. The gain made thanks to the accelerometer is huge, but it was predictable.

Figure 11 shows the comparison between hybrid sensor and vision interpolated the "spline" function of Matlab. Here the gain is less important, but yet it remains superior to three.

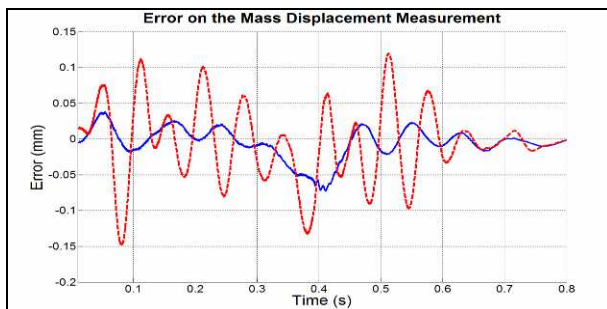


Figure 11: hybrid error and Spline approximation error

To conclude, only an extra real measurement can over sample the vision measurement.

6. CONCLUSION

The manufacturing machine evolution compels to take into account the elastic deformation of the mechanism. We propose a new tool adapted to in situ deformation measurement for real movements of the machine. After the measurement principle and the data merging method presenting, the experiment driven for the accuracy evaluation has been described. By now the retained accuracy is about $\pm 60 \mu\text{m}$ for a 300 mm covered field. In order to suppress detected parasite movements, a new test campaign is planned. We consider that the error should decrease till $\pm 30 \mu\text{m}$. we consider that accuracy as sufficient because beyond the machine will be considered as rigid. Our future experiments will concern the identification of industrial machine flexibilities.

7. ACKNOWLEDGMENTS

This paper was written within the framework of the TIMS Research Group, using grants from the Regional Council of Auvergne, the French ministry of research, the CNRS and the Cemagref.

8. REFERENCES

- [1] Tlustý, J., Ziegert, J., and Ridgeway, R., 1999, "Fundamental comparison of the use of serial and parallel kinematics for machine tools", *Annals of CIRP*, vol. 48, no. 1, pp. 331-356.
- [2] Weck, M. and Steumer, D., 2002, "Parallel Kinematics Machine tool – Current state and future potentials", *Annals of CIRP*, vol. 51, no. 2, pp. 671-681.
- [3] Barre, P.J. and Dumetz, E., 2002, "Dynamic behavior modeling and control of agile machine tool", *Mécanique & industries*, vol. 3, pp. 315-322.
- [4] Gagnol, V., Bouzgarrou, B.C., Ray, P., Barra, C., 2006, "Model-based chatter stability prediction for high-speed spindles", *International journal of Machine Tool and Manufacture*, in press.
- [5] Cumunel, G., Delepine-Lesoille, S., Argoul, P., 2006, "Continuously Attached long gage Fiber Optic Sensor (CA-FOS) as structural geometrical nonlinearity sensors.", *Vibrations Chocs et Bruit*, Lyon, France.
- [6] Leleu, S., David, J.M., Diolez, G, and Martin, P., 2002, "Evaluation of machine geometry, presentation of an innovative method with Laser Tracker", 4th International Conference on Integrated Design and Manufacturing in Mechanical Engineering, Clermont-Ferrand, France.
- [7] Lavest, J.M., Viala, M., Dhome, M., 1998, "Do we really need an accurate calibration pattern to achieve a reliable camera calibration?", *ECCV98*, pp. 158-174, Freiburg, Germany.
- [8] Shortis, M.R., Clarke, T.A., and Short, T., 1994, "A comparison of some techniques for the subpixel location of discrete target images", *Videometrics III*, vol. 2350.
- [9] Cano, T, Chapelle, F., Ray, P., Lavest, J.M., 2006, "Measuring the deformation of a Parallel Kinematics Machine under Dynamic Conditions, by Combining Video and Accelerometers", IROS, Beijing, China.
- [10] Béarée, R., 2005, "Prise en compte des phénomènes vibratoires dans la génération de commande des machines-outils à dynamique élevée", Phd thesis, ENSAM.