

Dual-drive gantry stage decoupling control based on a coupling model

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Abstract: A Dual-Drive Moving Gantry Stage Robot can be modelled as a square MIMO system. However, it is usually considered as two independent SISO systems: classical industrial gantry control is achieved by two independent position controllers. This control structure does not take into account the mechanical coupling between the two actuators and leads to a reduction of the overall performances of the system. In this paper, a physical lumped parameters model of an industrial robot is proposed and experimentally identified. It is based on a structural, modal, and Finite Element Method analysis. Then, a physical model-based control structure is deduced. The solution is finally simulated and implemented on an experimental test bench. Results are compared to the performances of the initial industrial control and show an improvement of the overall performances.

Keywords: Dual-drive gantry robot, Mechatronics, Physical modelling, Decoupling motion control.

1. Introduction

Dual-drive gantry systems are commonly used in many industrial processes where high-dynamic and/or high-precision Cartesian movements are required (printed circuit board assembly, precision metrology or laser/water-jet cutting machines). In this configuration, two motors, which are mounted on two parallel rails in the x direction, move simultaneously a beam (Fig. 1). The head assembly on the beam moves in the y and z directions. The studied industrial dual-drive moving gantry stage developed by ETEL Company (Switzerland) [1] is equipped with permanent magnet linear synchronous motors (PMLSM).

Linear drives can reach high acceleration and high velocity values. In dual drive gantry systems, such dynamical demands generate high strains in the mechanical coupling between the two motors. The performances of the system are mainly limited by the induced vibrations which increase the settling time.

Indeed, during a movement, the mechanical structure undergoes a strain due to the synchronous error x_1-x_2 between the two actuators. The potential energy thus stored during the movement is dissipated when the gantry stops, leading to mechanical vibrations. The aim is consequently to minimize as much as possible the synchronous error between the two actuators during the whole movement.

Many synchronous controllers are based on disturbance observers [2]-[5]. The main idea is thus to use first order models for both parallel motors and to consider the mechanical coupling effect as a disturbance to be rejected. However, the parameters of the model are often far from the physical structure of the system and are consequently difficult to identify.

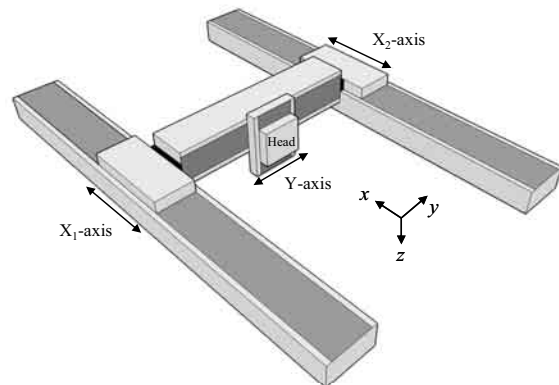


Fig. 1 - Dual-drive gantry stage

This paper presents a decoupling control strategy based on a physical dynamic model of a gantry stage robot.

First of all, a lumped parameters model of the gantry stage is proposed and experimentally identified. A model-based decoupling control is then deduced. Finally, an experimental validation is carried out and experimental results show that the proposed decoupling control yields to better performances than the initial industrial control.

2. Physical modelling of the gantry

The present objective is to establish a control-oriented model of the machine, based on its physical mechanical parameters.

Finite Element Method analysis of the overall mechanical structure combined to a deep structural and modal analysis with an impact hammer have led to the conclusion that joints between the beam and the motors are mainly responsible for the dominant vibratory behaviour of the system. The beam is thus initially considered as a rigid element. This leads to the lumped parameters model presented in Fig. 2. The masses of the beam and of the head assembly are concatenated in a single equivalent mass, so called m_{eq_b} . The rotational inertia I_{eq_b} of the equivalent beam is thus related to its mass through relation (1). As both joints are subjected to the same angle, they can be modelled by a single equivalent spring with stiffness k and damping ratio μ .

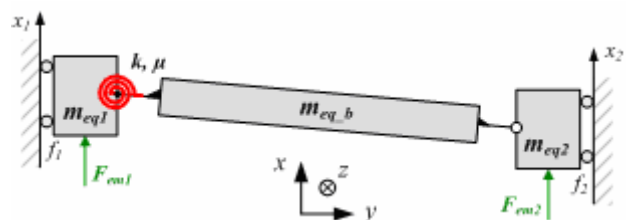


Fig. 2 - Equivalent lumped parameters model of the x -axis of the gantry stage

$$I_{eq_b} = \frac{m_{eq_b} \cdot L^2}{12} \quad (1)$$

$$\Sigma_{eq_i}: \frac{v_i}{F_{emi} - F_{b/i}} = \frac{1}{m_{eq_i} \cdot s + f_i}; i=1,2 \quad (2)$$

$$\Sigma_{eq_b}: \begin{cases} F_{b/1} = \frac{m_{eq_b}}{2} \cdot \frac{a_1 + a_2}{2} + \frac{I_{eq_b}}{L^2} \cdot (a_1 - a_2) + \left(\frac{\mu}{L^2} + \frac{k}{L^2 \cdot s} \right) \cdot (v_1 - v_2) \\ F_{b/2} = \frac{m_{eq_b}}{2} \cdot \frac{a_1 + a_2}{2} - \frac{I_{eq_b}}{L^2} \cdot (a_1 - a_2) - \left(\frac{\mu}{L^2} + \frac{k}{L^2 \cdot s} \right) \cdot (v_1 - v_2) \end{cases} \quad (3)$$

Applying Newton's laws of motion to each equivalent mass of the lumped parameters model, the system can be described by (2) and (3). v_1 and v_2 are the speeds of equivalent masses m_{eq1} and m_{eq2} , a_1 and a_2 are the corresponding accelerations, and L is the length of the beam. F_{em1} and F_{em2} are the electromagnetic forces generated by the two PMLSMs. $F_{b/1}$ and $F_{b/2}$ are the reaction forces of the mechanical coupling, respectively on the two equivalent axes. This set of equations respects the integral causality. The corresponding schematic representation is given in Fig. 3.

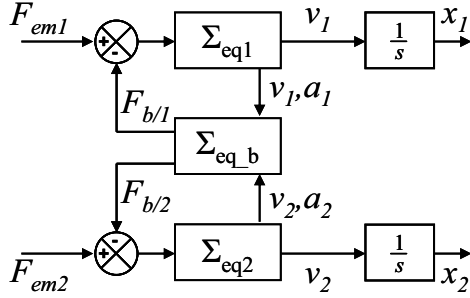


Fig. 3 - Schematic representation of the model

The first vibratory mode of the x -axis of the gantry is modelled thanks to a set of five modal parameters: m_{eq1} , m_{eq2} , m_{eq_b} , k and μ . The rigid body motion is also represented with the masses and the two viscous friction coefficients f_1 and f_2 .

The experimental identification of the five modal parameters is based on a measurement of the two direct mechanical transfer functions, $(v_1/F_{em1})|_{F_{em2}=0}$ and $(v_2/F_{em2})|_{F_{em1}=0}$. Assuming (1), the gantry stage can be described as the square MIMO (Multiple Input Multiple Output) system (4):

$$\begin{pmatrix} v_1 \\ v_2 \end{pmatrix} = G(s) \cdot \begin{pmatrix} F_{em1} \\ F_{em2} \end{pmatrix}; G(s) = \begin{pmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{pmatrix} \quad (4)$$

G_{11} (5) and G_{22} (6) are the two direct mechanical transfer functions, while G_{12} and G_{21} (7) are identical transfer functions representing the mechanical cross-coupling.

$$G_{11}(s) = \frac{v_1}{F_{em1}} \Big|_{F_{em2}=0} = \frac{\frac{k}{L^2} + \left(\frac{\mu}{L^2} + f_2 \right) \cdot s + \left(m_{eq2} + \frac{m_{eq_b}}{3} \right) \cdot s^2}{Den(s)} \quad (5)$$

$$G_{22}(s) = \frac{v_2}{F_{em2}} \Big|_{F_{em1}=0} = \frac{\frac{k}{L^2} + \left(\frac{\mu}{L^2} + f_1 \right) \cdot s + \left(m_{eq1} + \frac{m_{eq_b}}{3} \right) \cdot s^2}{Den(s)} \quad (6)$$

$$G_{12}(s) = \frac{v_1}{F_{em2}} \Big|_{F_{em1}=0} = G_{21}(s) = \frac{v_2}{F_{em1}} \Big|_{F_{em2}=0} = \frac{k/L^2 + (\mu/L^2) \cdot s - (m_{eq_b}/6) \cdot s^2}{Den(s)} \quad (7)$$

$$Den(s) = \frac{k}{L^2} \cdot (f_1 + f_2) + \left(\frac{k}{L^2} \cdot m_t + f_1 \cdot f_2 + \frac{\mu}{L^2} \cdot (f_1 + f_2) \right) \cdot s + \left(\frac{\mu}{L^2} \cdot m_t + \frac{m_{eq_b}}{3} \cdot (f_1 + f_2) + f_1 \cdot m_{eq1} + f_2 \cdot m_{eq2} \right) \cdot s^2 + \left(m_{eq1} \cdot m_{eq2} + \frac{m_{eq_b}}{3} \cdot \left(m_{eq1} + m_{eq2} + \frac{m_{eq_b}}{4} \right) \right) \cdot s^3 \quad (8)$$

where $m_t = m_{eq1} + m_{eq2} + m_{eq_b}$ is the total mass of the system.

Fig. 4 shows the good agreement between Bode diagrams of measured and calculated direct mechanical transfer functions v_1/F_{em1} and v_2/F_{em2} . Experimental transfer functions have been obtained by white noise excitation of the linear actuators. These identification methods are provided by ETEL industrial position controllers [7].

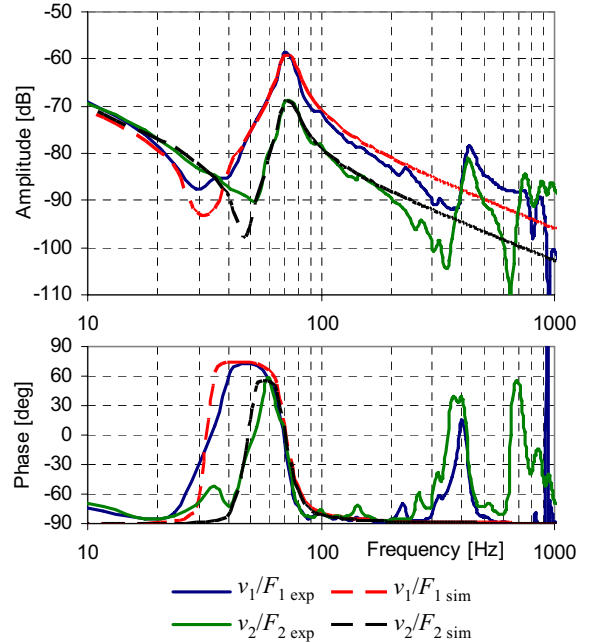


Fig. 4 – Experimental and calculated Bode diagrams of G_{11} and G_{22} direct mechanical transfer functions

In this paper, the position of the head assembly is assumed to be constant. Otherwise, a different set of modal parameters is necessary for each y position.

3. Model-based decoupling control

Industrial gantry control is usually performed by two independent PID position controllers, with identical position references. The gantry system is thus considered as two independent SISO (Single-Input-Single-Output) systems, and the mechanical coupling between the two parallel actuators is ignored.

Fig. 5 shows the cross-coupling and direct transfer functions. As DC gains are similar, both axes are in fact highly coupled. This invalidates the assumption of two independent SISO systems.

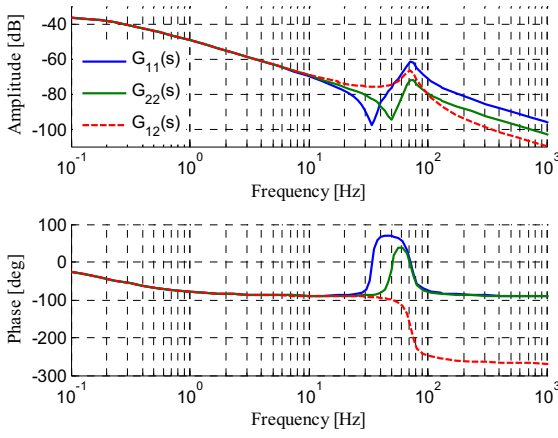


Fig. 5 - Bode diagram of the direct (G_{11} and G_{22}) and cross-coupling transfer functions ($G_{12} = G_{21}$)

Reduction of the mechanical coupling effect is generally done by the means of a decoupling algorithm based on a state space control of the process [5] and tuned thanks to the minimization of a coupling criterion [4].

A systematic design methodology of the control law, based on two complementary principles of inversion (direct and indirect) and leading to a state control structure, has been presented in [6]. This methodology has been applied to the modelled gantry stage. By this way, the mechanical coupling between the two parallel axes is logically taken into account in the gantry control. The decoupling control thus obtained is represented in Fig. 6.

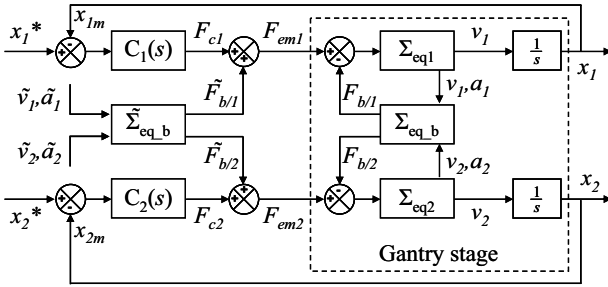


Fig. 6 - Decoupling control strategy based on a physical mechanical modelling

x_1^* and x_2^* are the position references whereas x_{1m} and x_{2m} are the corresponding measured positions. Each equivalent axis is controlled by a PID controller ($C_1(s)$ and $C_2(s)$).

The model of the mechanical coupling, described in (3), is used as a coupling thrust estimator to decouple the two equivalent axes. On linear systems, the position information is often measured thanks to accurate incremental linear encoders. Hence, the speeds can be estimated (\tilde{v}_1 and \tilde{v}_2) using the positions time derivative. \tilde{a}_1 and \tilde{a}_2 are the corresponding estimated accelerations. These ones can also be directly measured on each actuator.

This decoupling control respects the integral causality and can be directly introduced as extra thrust terms, $\tilde{F}_{b/1}$ and $\tilde{F}_{b/2}$, to be added to the thrust references of the industrial classical controllers.

4. Experimental validation

The previously proposed model and control structure have been experimentally validated.

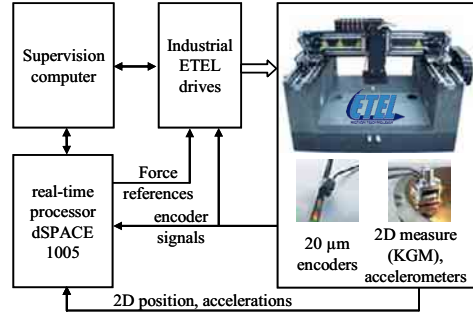


Fig. 7 - Experimental test bench configuration

The laboratory test-bench, presented in Fig. 7, is composed of an ETEL dual-drive gantry robot equipped with linear actuators and their industrial position controllers. According to the reference and measured positions, a dSpace DS1005 real-time digital control card generates the force reference for each axis to be controlled.

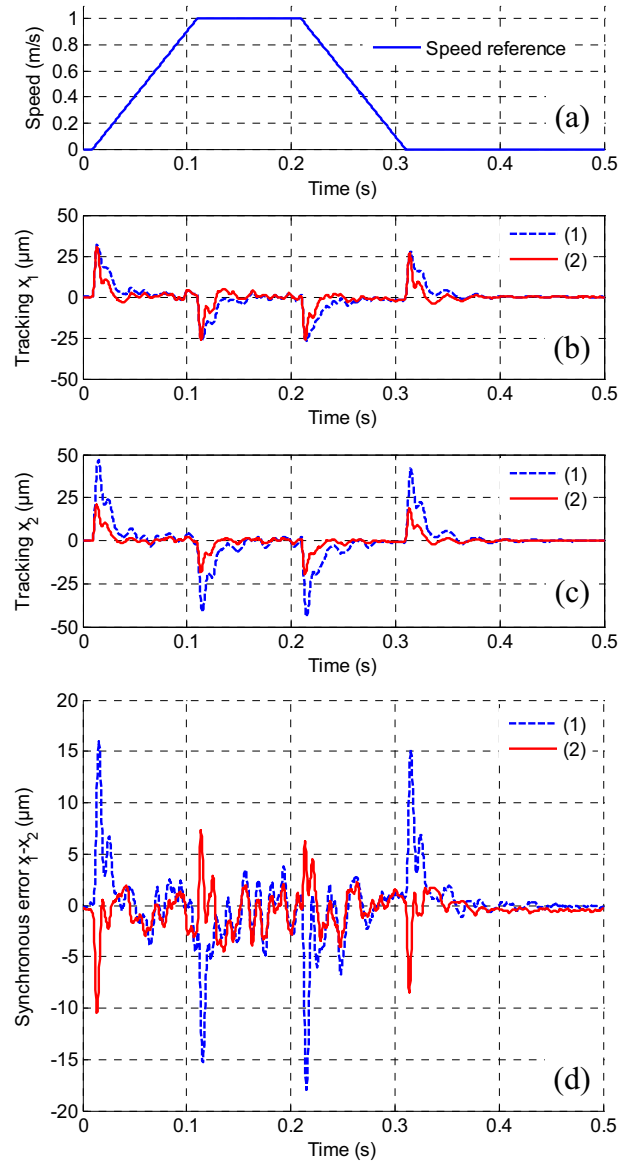


Fig. 8 - Experimental results: Speed reference profile (a), x_1 and x_2 tracking errors (b) and (c), and Synchronous error $x_2 - x_1$ (d), with the initial independent axis control (1) and the proposed decoupling control strategy (2)

The experimental results presented in Fig. 8 are obtained with a trapezoidal speed reference profile. The initial independent axis control is compared to the proposed decoupling control.

The maximum of the absolute value of the synchronous error is about 40% lower with the proposed decoupling control than with the initial independent axis control. In the same way, the tracking error of the x_2 -axis is decreased in about 50% thanks to the additional acceleration compensation provided by the coupling thrust estimator, while the tracking error of the x_1 -axis remains quite unmodified in this configuration. Finally, the global stabilization time under a 1 μm precision is also decreased, leading to a shorter cycle time.

We note that the experimental validations have been conducted only considering the beam displacement. If we now consider multi-axial movements, the modal parameters variations related to the position of the head assembly have to be taken into account. Robustness of such algorithm will be investigated in further works.

5. Conclusion

This paper presents a decoupling control of an industrial dual linear drive moving gantry stage based on a physical dynamic model of the machine.

The proposed lumped parameters representation models the first vibratory mode as well as the rigid body motion of the x -axis. The experimental identification of the modal parameters is carried out and the model behaviour is compared to real measurements.

This control oriented model is then used to deduce a gantry controller including a coupling thrust estimator. The two extra thrust terms are added to the thrust references of the industrial classical controllers.

Finally, experimental results from an industrial gantry stage controlled with a real-time control system show the effectiveness of the proposed control structure: the synchronous error between the two actuators and the stabilization time are decreased.

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References

- [1] <http://www.etel.ch>
- [2] Heung-Keun Park, Sung-Su Kim, Jin-Moo Park, Tae-Yeon Cho, Daehie Hong, "Dynamics of dual-drive servo mechanism", IEEE International Symposium on Industrial Electronics 2001, Proceedings. ISIE 2001, vol. 3, pp. 1996-2000, June 2001.
- [3] Teo C.S., Tan K.K., Huang S., Lim S.Y, "Dynamic modeling and adaptive control of a multi-axial gantry stage", IEEE International Conference on Systems, Man and Cybernetics, 2005, vol. 4, pp. 3374-3379, Oct. 2005.
- [4] Sungsoo Kim, Baeksuk Chu, Daehie Hong, Heung-Keun Park, Jin-Moo Park, Tae-Yeon Cho, "Synchronizing Dual-Drive Gantry of Chip Mounter with LQR Approach", Proceeding of the 2003 IEEE/ASME International Conference on Advanced Intelligent

Mechatronics (AIM 2003).

- [5] Yu Dongmei, Guo Qingding, Hu Qing, "Study on synchronous drive technique of biaxial linear servo motor based on decoupling control and internal model control with two-degree-of-freedom", Sixth International Conference on Electrical Machines and Systems, 2003, ICEMS 2003 Proceedings, vol. 2, pp. 541-543, Nov. 2003.
- [6] R. Béarée, J-P. Hautier, P-J. Barre "Control structure synthesis for electromechanical systems based on the concept of inverse model using Causal Ordering Graph", IEEE-IECON'06, Paris, November 2006.
- [7] M. Mathia, V. Very, "Method for analysing a drive system", ETEL patent EP 1 467 266 B1, September 2006