Influence of temperature in robotic joints

Roberto Pagani
DIMI Mechanical and Industrial Enginering dept.
University of Brescia
Brescia, Italy
r.pagani001@unibs.it

Giovanni Legnani
DIMI Mechanical and Industrial Enginering dept.
University of Brescia
Brescia, Italy
giovanni.legnani@unibs.it

Manuel Beschi
DIMI Mechanical and Industrial Enginering dept.
University of Brescia
Brescia, Italy
manuel.beschi@unibs.it

Monica Tiboni
DIMI Mechanical and Industrial Enginering dept.
University of Brescia
Brescia, Italy
monica.tiboni@unibs.it

***Abstract*—The estimation of the friction torque in joints transmissions is a crucial task in the robotics field. This work presents a model that describes the variations on friction that occur during the operations of an industrial robot due to thermal effects. The proposed technique is simple to implement and economically convenient. Possible applications are the improvement of the friction compensation algorithms used in control systems, the prediction of energy consumption and predictive maintenance.**

***Keywords*—Industrial Robotics, Friction, Temperature**

I. Introduction

In the field of intelligent machines, there are several advanced models used to obtain information on the internal status of the axis without using specific sensors. See for example [1], [2], [3], [4] [5]. As is knows, friction in an industrial robot prevents the end-effector from making accurate positioning and from accurately following an assigned trajectory. This phenomenon is always present between two mechanical parts in relative motion and it depends on many factors, including the dynamics of the contacts, the lubricants used and its condition, the types of surfaces, the contact geometry, the relative speed, the temperature, and so on. If we consider the energy aspect, it is evident that the study of phenomena related to friction and energy dissipation is always an interesting research topic and it is must be taken into account in any design procedure. Friction has been represented in different ways ranging from elementary models (e.g. Coulomb or viscous model) to more sophisticated models, see, for example, [6], [7]. Such models, however, do not consider the different sources that produce heat (friction, Joule effect, eddy currents) and correctly evaluate the thermal dissipation. This work provides a mathematical model based on heat exchange equations that predict the variations of friction by knowing the characteristics of the robot and its work cycle. An interesting aspect of the method here proposed concerns the possibility of making a reliable estimate of friction without using temperature sensors, which are often difficult to install inside an industrial robot.

II. Mathematical Formulations

The dynamic behaviour of an industrial robot is described by the following matrix equation:

$$\tau = M(q)\ddot{q} + V(q,\dot{q}) + G(q) + \tau_f - J^t F_e \qquad (1)$$

Where q , $\dot{q}$ and $\ddot{q}$ are the joint position, velocity, and acceleration vectors, respectively, τ is the vector of the driving actions applied to the robot joints, $M(q)$ the inertial matrix, $V(q,\dot{q})$ the matrix containing the centrifugal and Coriolis terms, $G(q)$ the gravitational term, J the extended Jacobian matrix, F_e the vector of the external forces, and τ_f the vector containing the frictional effects on the joints. The dependence of friction from the velocity is generally expressed in polynomial form by using the sign function (sign(x)=x/|x| for x≠0, and sign(x)=0 for x=0):

$$\tau_{fi} = a_i sign(\dot{q}_i) + b_i\dot{q}_i + c_i sign(\dot{q}_i)\dot{q}_i^2 + d_i\dot{q}_i^3 \quad (2)$$

Experience shows that the coefficients a_i, b_i, c_i, d_i depends on the temperature [8]. Fig. 1 shows the variation of the friction torque, the trend of the curves is increasing with the speed and, for a given speed value, the friction torque is lower when the transmission has been heated due to previously performed working cycles.

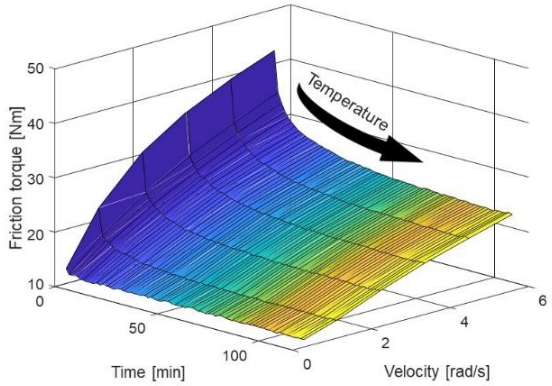

Fig. 1. *Friction vs speed during the warming up of the robot EFORT ER3A.*

III. Advanced model

The variation of the friction torque according to the temperature can be studied by means of a thermal balance. This approach was followed in previous studies by the authors [9], [10] do not consider the thermal losses due to the electricity. Electric actuators and devices dissipate part of the energy into heat mainly by Joule effect (copper losses) and eddy currents (Foucault's currents) in the ferromagnetic material. Fig. 2 shows the thermal power flows in the robotic joint; the symbols C_i ($i = 1,2,3$) and T_i indicate respectively the thermal capacities and the temperatures of zones 1, 2 and 3. In the first zone there is the generation of thermal power, which derives from two sources: W_f which is the friction component and W_e which is power dissipated in the electric motor (Joule effect and eddy currents).

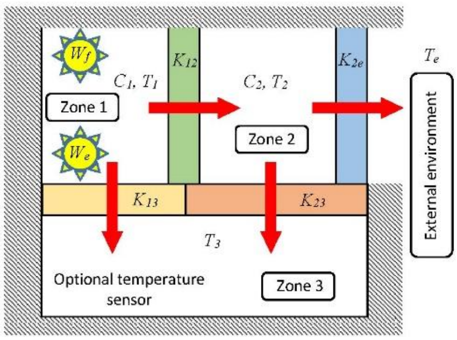

Fig. 2. *Scheme of the thermal flows in one robot joint.*

The coefficients of eq. (2) can be assumed linearly dependent with temperature:

$$a_i = a_{i0}[+\alpha(T - T_0) + \beta]$$

with $\alpha < 0$. The heat balance between zone 1 and 2 of the joint can be written in the following form:

$$\begin{cases} \dfrac{dT_1}{dt} = \dfrac{(aT_1+b)+W_e-K_{12}(T_1-T_2)-K_{13}(T_1-T_3)}{C_1} \\ \dfrac{dT_2}{dt} = \dfrac{K_{12}(T_1-T_2)-K_{23}(T_2-T_3)-K_{2e}(T_2-T_e)}{C_2} \end{cases} \quad (3)$$

with $W_{in} = \tau_f\,\dot{\vartheta}$, $\quad a = \tau_{fe}\,\dot{\vartheta}\,\alpha$, and $\quad b = \tau_{fe}\,\dot{\vartheta}\,(\beta - \alpha T)$

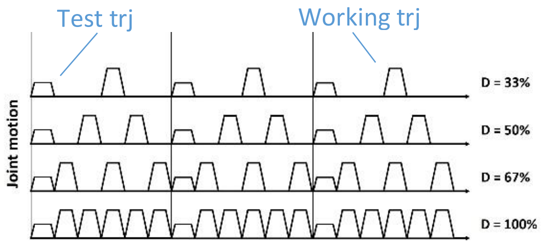

Fig. 3. Different duty cycles (33%, 50%, 67%, 100%).

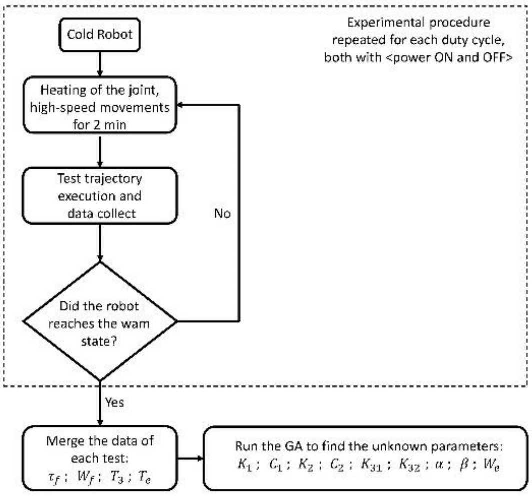

Fig. 4. *Experimental procedure flowchart.*

Fig. 5 shows, for example, the decrease in torque of a specific joint and its prediction during power ON and power OFF tests, i.e. starting the test from a completely cold state or after reaching the thermal regime of the motor due to the electrical dissipation. It is worth noting that the rise in temperature causes a significant decrement in the friction torque at the initial time, confirming the necessity to add a term dependent on electrical power in the model.

IV. Experimental verification

Experiments were performed on an anthropomorphic industrial manipulator Efort Model ER3A-C60, 23kg weight, 3kg payload. Heating experiments have been performed by alternating working cycles (high speed point-to-point movement) with a designed test trajectory with constant velocities intervals. Friction torque has been obtained by subtracting the dynamic and gravity effects (eq. (1)) from the measured motor torque. The tests were repeated with different duty cycles (Fig. 3) obtaining different transient responses and collecting enough data to estimate all the constant of the model using a genetic algorithm (see Fig.4 for clarifications).

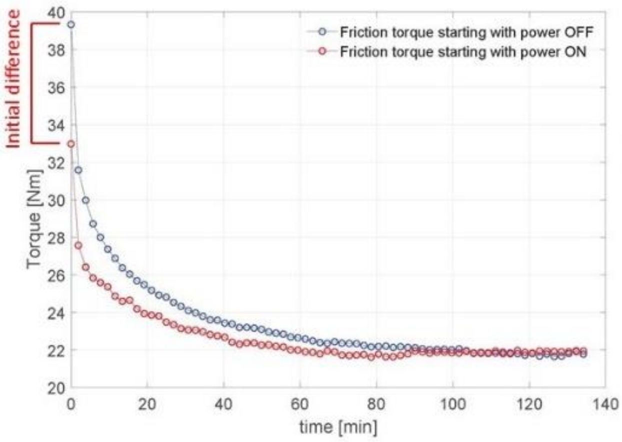

Fig. 5. *Friction torque vs time at 80% of maximum speed and D=100%, starting at power ON and OFF, Axis 4.*

Acknowledgment

The authors thank: Evolut Spa, BS (Italy), Robox SpA, NO (Italy) and Efort Intelligent Equipment Co. Ldt, for significant technical support during the experimental activity.

References

[1] M. Indri, S. Trapani and I. Lazzero, “Development of a Virtual Collision Sensor for Industrial Robots”. Sensors, vol. 17, 1148, 2017

[2] M. Indri, S. Trapani and I. Lazzero, "A general procedure for collision detection between an industrial robot and the environment," 2015 IEEE 20th Conf. on Emerging Technologies & Factory Automation (ETFA), Luxembourg, pp. 1-8, 2015.

[3] S. Haddadin, A. De Luca and A. Albu-Schäffer, "Robot Collisions: A Survey on Detection, Isolation, and Identification," in IEEE Transactions on Robotics, vol. 33, no. 6, pp. 1292-1312, Dec. 2017.

[4] Y. J. Heo, D. Kim, W. Lee, H. Kim, J. Park and W. K. Chung, "Collision Detection for Industrial Collaborative Robots: A Deep Learning Approach," in IEEE Robotics and Automation Letters, vol. 4, no. 2, pp. 740-746, April 2019.

[5] K. Suita, Y. Yamada, N. Tsuchida, K. Imai, H. Ikeda and N. Sugimoto, "A failure-to-safety "Kyozon" system with simple contact detection and stop capabilities for safe human-autonomous robot coexistence," Proceedings of 1995 IEEE International Conference on Robotics and Automation, Nagoya, Japan, vol.3, pp. 3089-3096, 1995.

[6] J. Y. Yoon and D . L. Trumper, “Friction modeling, identification, and compensation based on friction hysteresis and dahl resonance”. Mechatronics, vol. 24, pp. 734–741, 2014.

[7] M. Ruderman, “Presliding hysteresis damping of lugre and maxwell-slip friction models”. Mechatronics, vol. 30, pp. 225–230, 2015.

[8] L. Simoni, M. Beschi, G. Legnani and A. Visioli, “Friction modeling with temperature effects for industrial robot manipulators”. In Proc. of IEEE/RSJ Int. Conf. on Intelligent Robots and Systems IROS, pp. 3524–3529, 2016.

[9] G. Legnani, G. Incerti, R. Pagani, and M. Gheza, “Modelling and evaluation of the friction in robotic joints considering thermal effects”. In Proceedings of the ASME Design Engineering Technical Conference, Vol. 5A-2019.F, 2019.

[10] R. Pagani, G. Legnani, G. Incerti and M. Gheza, “Evaluation and modeling of the friction in robotic joints considering thermal effects”. Journal of Mechanisms and Robotics, 12(2). , 2020.