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Dynamic Identification of the Kuka LightWeight Robot: comparison between actual and confidential Kuka's parameters

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Abstract— **This paper deals with the dynamic identification of the Kuka LightWeight Robot *LWR4+*. Although this robot is widely used for research purposes by many laboratories, there is not yet a published dynamic model available for model based control or simulation. Because Kuka does not give any information about the dynamic parameters of the robot we propose to identify 2 sets of parameters using the usual off-line identification method which is based on the Inverse Dynamic Identification Model and linear Least Squares technique (*IDIM-LS*). The first set is obtained by the actual dynamic parameters of links and joints (inertia, gravity and friction parameters) which are identified from motor torques and motor positions data. The second set is obtained by the Kuka's inertial parameters of links, implemented in the controller for model-based control. This is a reverse engineering procedure which recovers the confidential manufacturer's data. The link parameters are estimated using the *IDIM-LS* method with the sampled data of the inertia matrix and the gravity torques computed by the controller. To complete the reverse engineering procedure we also identify the joint stiffness parameters used by Kuka to estimate the joint link side position using the joint torque sensors and motor positions data. A Comparison between the actual dynamic parameters and the Kuka's parameters allow concluding to a reliable data sheet. This is a strong and very useful result for future work of the scientific community on this very popular robot.**

I. Introduction

Recently, the Institute of Robotics and Mechatronics at German Aerospace Center (*DLR*) collaborated with Kuka Roboter to achieve manufacturing of a new generation of lightweight robot: the Kuka *LWR* (LightWeight Robot - *LBR*) [1][2][3]. This robot has been developed for different applications than classical and industrial robots. It is mainly designed for interaction with humans. Consequently, the robot is provided with torque sensor located after the gearbox of each actuated joint. They measure joint torques for collision and failure detection. The controller of robot estimates the joint position thanks to the measurements of joint torques, a priori joint stiffness values and motor positions.

The dynamic model of the robot is needed to control and simulate their motions with precision and reliability. The simulation of robot can be used to save cost and time because it allows to test some motions and applications before the experimentation on the robot.

Unfortunately, to our knowledge, only two publications are about the identification of the Kuka *LWR*4+ (future industrial version: Kuka *IIWA*) and the manufacturer don't give any information about dynamic parameters of the robot. In [3], the identification of rigid model of the robot is split into two parts. First the identification of the static parameters is performed. Second, the identification of the components of the inertia matrix is performed with the static parameters assumed know. But there is an accumulation of parameter errors between the two part and the identified static parameters are not given. Furthermore, the rotor inertia moment and frictions parameters are not identified because only the joint torques and joint positions are used. Whereas they are necessary to have the complete dynamic model of the robot. In [4], the identification of the robot is performed with joint torques and motor positions but no identified parameter is given.

In this paper, the parameter identification of the rigid model of the actual robot is performed. To complete this identification and for comparison, the manufacturer's gravity and inertias parameters are estimated from the inertia matrix and gravity torques given by the robot controller by a reverse engineering procedure. Finally the manufacturer's stiffness are identified from the estimated joint positions, motor position and measured joint torques. The identification process is based on the Inverse Dynamic Identification Model (*IDIM*) and Least Squares (*LS*) estimation. It has been performed on several robots with accurate results [5][6]. This method is used for the identification of the actual dynamic parameters of the robot and is adapted for the identification of confidential Kuka's parameters. This is to give to the international robotics community using the Kuka *LWR4+* the dynamic parameters of the robot for research purposes.

This paper is divided into five sections. Section II describes the modeling of robot. Section III presents the usual method for dynamic identification based on *IDIM-LS* method. Section IV is devoted to the modeling and experimental identification of the Kuka *LWR*. Section V is the conclusion.

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II. MODELING

A. Inverse Dynamic Identification Model of robot for actual parameters

The *IDM* of a rigid robot calculates the motor torques τ_{idm} as a function the motor positions, velocities and accelerations. It can be obtained from the Newton-Euler or the Lagrangian equations [7]. It is given by the following relation:

$$\tau_{idm} = M(q)\ddot{q} + H(q,\dot{q})\dot{q} + G(q) + \tau_f$$
$$\text{with } \tau_f = Fv\,\dot{q} + Fc\,\text{sign}(\dot{q}) + Off \tag{1}$$

where q, $\dot{q}$ and $\ddot{q}$ are respectively the (nx1) vectors of motor positions, velocities and accelerations; sign($\dot{q}$) is (nx1) vectors of sign of the motor velocities; the $M(q)$ is the (nxn) robot inertia matrix; $H(q,\dot{q})\dot{q}$ is the (nx1) vector of Coriolis and centrifugal torques. $G(q)$ is the (nx1) vector of gravity torques. Fv and Fc are respectively the (nxn) diagonal matrix of the viscous and Coulomb friction parameters. *Off* is the (nx1) vector of offset parameters. n is the number of moving links. All measurement and mechanical variables are given in S.I. unit on joint side.

The choice of the modified Denavit and Hartenberg frames attached to each link allows a dynamic model that is linear in relation to a set of standard dynamic parameters χ_{ST} [5][8]:

$$\tau_{idm} = IDM_{st}(q,\dot{q},\ddot{q})\chi_{st}$$
$$\text{with } \chi_{st} = \begin{bmatrix}\chi_{st1}^T & \chi_{st2}^T & \dots & \chi_{stn}^T\end{bmatrix}^T \tag{2}$$

where $IDM_{st}(q,\dot{q},\ddot{q})$ is the (nxNs) Jacobian matrix of τ_{idm}, with respect to the (Nsx1) vector χ_{st} of the standard parameters. χ_{stj} is composed of standard dynamic parameters of axis j:

$$\chi_{stj} = [XX_j \quad XY_j \quad XZ_j \quad YY_j \quad YZ_j \quad ZZ_j \quad MX_j$$
$$MY_j \quad MZ_j \quad M_j \quad Ia_j \quad Fv_j \quad Fc_j \quad Off_j]^T \tag{3}$$

where Ia_j is a total inertia moment for rotor and gears of actuator of link j (to simplify: it is named drive inertia moment) ; Fv_j and Fc_j are the viscous and Coulomb friction parameters of joint j ; Off_j is the motor current amplifier offset of joint j ; XX_j, XY_j, XZ_j, YY_j, YZ_j, ZZ_j are the six components of the robot inertia matrix of link j; MX_j, MY_j, MZ_j, are the components of the first moments of link j; M_j is the mass of link j; The maximum number of standard parameters is Ns=14xn.

B. Inverse Dynamic Identification Model for confidential Kuka's inertia and gravity parameters

An external computer can be connected to the Kuka *LWR* for receive measurements and send desired positions with a *C*++ program called Fast Research Interface (*FRI*) [2]. The *FRI* gives the (7x7) inertia matrix $M^{FRI}(q)$ and the (7x1) gravity torques $G^{FRI}(q)$. These measurements depends directly of *a priori* dynamic parameters of Kuka manufacturer, named confidential Kuka's parameters. Thus it is possible to identify these parameters to compare them with the actual dynamic parameters identified with (1).

The inertia matrix is symmetric so it can be defined with the following measurement, the "inertia matrix" torque containing its 28 (=(n^2+n)/2) independents terms:

$$\tau_M = [M^{FRI}(1,1) \quad M^{FRI}(1,2) \quad \dots \quad M^{FRI}(1,7) \quad \dots$$
$$M^{FRI}(2,2) \quad M^{FRI}(2,3) \quad \dots \quad M^{FRI}(2,7) \quad \dots \tag{4}$$
$$M^{FRI}(6,6) \quad M^{FRI}(6,7) \quad M^{FRI}(6,7)]^T$$

where $M^{FRI}(i,j)$ is the term of i^{th} line and j^{th} columns of $M^{FRI}(q)$. The measured gravity torque is defined:

$$\tau_G = G^{FRI}(q) \tag{5}$$

The concatenation of the torques (4) and (5) can be expressed in linear in relation to a set of standard dynamic parameters χ_{kcst}:

$$\tau_{FRIidm} = \begin{bmatrix}\tau_{Midm} \\ \tau_{Gidm}\end{bmatrix} = IDM_{kcst}(q)\chi_{kcst}$$
$$\text{with } \chi_{kcst} = \begin{bmatrix}\chi_{kcst1}^T & \chi_{kcst2}^T & \dots & \chi_{kcstn}^T\end{bmatrix}^T \tag{6}$$

where:

$$\chi_{kcstj} = [XX_j \quad XY_j \quad XZ_j \quad YY_j \quad YZ_j$$
$$ZZ_j \quad MX_j \quad MY_j \quad MZ_j \quad M_j]^T \tag{7}$$

We note that the manufacturer's drive inertia moments and friction parameters cannot be identified. Furthermore, only the motor positions are necessary to compute the *IDIM*.

C. Inverse Dynamic Identification Model for confidential Kuka's stiffness parameters

For each axis j, Kuka controller (*KRC*) estimates the joint position q_{aj} from the joint torque sensor measurement τ_{cj}, motor position q_j and an *a priori* stiffness value k^{ap}_j [9]:

$$q_{aj} = q_j - \tau_{cj} / k_j^{ap} \tag{8}$$

The equation (8) can be rewritten in linear relation to parameters for each axis with joint torque sensor expressed in function of the flexible degree of freedom *dof* q_{ej}:

$$\tau_{cj} = -k_j^{ap} q_{ej} \text{ with } q_{ej} = q_{aj} - q_j \tag{9}$$

III. *IDIM-LS*: INVERSE DYNAMIC IDENTIFICATION MODEL WITH LEAST SQUARES METHOD

Because of perturbations due to noise measurement and modeling errors, the actual torque τ differs from τ_{idm} by an error e, such that:

$$\tau = \tau_{idm} + e = IDM_{st}(q,\dot{q},\ddot{q})\chi_{st} + e \tag{10}$$

From (10), the following over determined system is built from the sampling of (10), while the robot is tracking exciting trajectories [10]:

$$Y = W_{st}\chi_{st} + \rho \qquad (11)$$

Where: Y is the (rx1) measurement vector, W_{st} the (rxN_s) observation matrix, and ρ is the (rx1) vector of errors. The number of rows is $r=nxn_e$, where the number of recorded samples is n_e.

When W_{st} is not a full rank matrix, the LS solution is not unique. The system (11) is rewritten:

$$Y = W\chi + \rho \qquad (12)$$

Where a subset W of b independent columns of W_{st} is calculated, which defines the vector χ of b base parameters [8][11]. The base parameters are obtained from standard dynamic parameters by regrouping some of them with linear relation [8][11].

ρ is assumed to have zero mean, be serially uncorrelated and be heteroscedastic, i.ie., to have a diagonal covariance matrix Ω partitioned so that [12][13]:

$$\Omega = diag\left(\sigma_1^2 I_{ne} \ldots \sigma_j^2 I_{ne} \ldots \sigma_n^2 I_{ne}\right) \qquad (13)$$

where I_{ne} is the (n_exn_e) identity matrix. The heteroscedasticity hypothesis is based on the fact that robots are nonlinear multi-input multi-output (*MIMO*).

σ_j^2 is the error variance calculated from subsystem j ordinary LS (OLS) solution:

$$Y^j = W^j\chi + \rho^j \qquad (14)$$

Thus, the Weighted LS (WLS) estimator is used to estimate χ. The WLS solution of (12) is given by:

$$\hat{\chi} = \left(W^T\Omega^{-1}W\right)^{-1} W^T\Omega^{-1}Y \qquad (15)$$

Usually, such weighting operations normalize the error terms in (12). Indeed, with:

$$\bar{\rho} = \Omega^{-1/2}\rho \qquad (16)$$

one obtains $\sum_{\bar{\rho}\rho} = E(\bar{\rho}\rho^{\mathrm{T}})=\Omega^{-1/2}E(\rho\rho^{\mathrm{T}})\Omega^{-1/2} = I_r$.

The estimated covariance matrix of WLS estimates is:

$$\sum_{LS} = \left(W^T\Omega^{-1}W\right)^{-1} \qquad (17)$$

$\hat{\sigma}_{\hat{\chi}(i)}^2 = \sum_{LS}(i,i)$ is the i^{th} diagonal coefficient of $\sum_{LS}$. The relative standard deviation $\%\hat{\sigma}_{\hat{\chi}(i)}$ of $\hat{\chi}$ (the i^{th} component of $\hat{\chi}$) is given by:

$$\%\hat{\sigma}_{\hat{\chi}(i)} = 100\hat{\sigma}_{\hat{\chi}(i)} / \hat{\chi}(i) \text{ with } \left|\hat{\chi}(i)\right| \neq 0 \qquad (18)$$

Calculating the LS solution of (12) from perturbed data in W and Y may lead to bias if W is correlated to ρ. Then, it is essential to filter data in Y and W before computing the WLS solution. Velocities and accelerations are estimated by means of a band-pass filtering of the positions (with Butterworth filter). More details about the adjustment of cut-off frequency of Butterworth filter can be found in [12] and [14].

To eliminate high frequency noises and torque ripples and to avoid that W and Y are statistically correlated with error terms, a parallel decimation (decimate filter) is performed on Y and on each column of W. To chose the cut-off frequency of the decimate filter, a Durbin-Watson test is performed [13], the dw value is computed with the following relation:

$$dw = \frac{\sum_{i=2}^{r}\left(\bar{\rho}(i)-\bar{\rho}(i-1)\right)^2}{\sum_{i=1}^{r}\bar{\rho}(i)^2} \qquad (19)$$

Where $\bar{\rho}(i)$ is i^{th} sample of $\bar{\rho}$. The dw value must be between 1 and 3 with ideal value at 2. The choice of the cut-off frequency of the decimate filter is a compromise between the minimization of $|dw\text{-}2|$ value and the conservation of the robot dynamics in W and Y.

Some base parameters have no significant contribution on the robot dynamics. These parameters can be cancelled in order to keep a set of essential parameters of a simplified dynamic model with a good accuracy, some details are given in [13].

IV. Experimental validation

A. Description of the robot and its kinematics

The Kuka *LWR* (see figure 1) robot has a serial structure with n=7 rotational joints. Its kinematics is defined using the Modified Denavit and Hartenberg (*MDH*) notation [15]. In this notation, the link j fixed frame is defined such that the z_j axis is taken along joint j axis and the x_j axis is along the common normal between z_j and z_{j+1}. The geometric parameters defining the robot frames are given in table I. The parameter σ_j=0, means that joint j is rotational, α_j and d_j parameterize the angle and distance between z_{j-1} and z_j along x_{j-1}, respectively, whereas θ_j and r_j parameterize the angle and distance between x_{j-1} and x_j along z_j , respectively. All *MDH* positions are equal to the motor position q_j given by the *KRC* controller of the Kuka *LWR.* The robot is provided with torque sensor located after the gearbox of each actuated joint (see figure 2). Each motor has encoder which measures the motor position q.

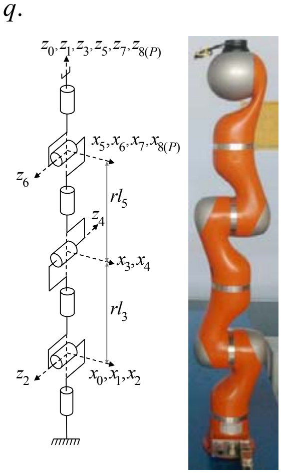

Figure 1. Link frame of the robot, picture of robot and picture of the payload

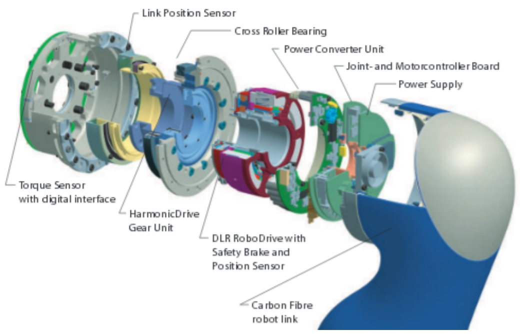

Figure 2. Exploded view of a joint of robot [1]

The rigid model of the Kuka *LWR* has $b = 69$ base parameters for the set of actual parameters, and $b = 48$ base parameters for the set of confidential Kuka's parameters. The regrouped parameters are detailed in appendix.

TABLE I. MDH PARAMETERS OF THE RIGID MODEL

j	σ_j	α_j	d_j	θ_j	r_j
1	0	0	0	q_1	0
2	0	$\pi/2$	0	q_2	0
3	0	$-\pi/2$	0	q_3	rl_3(= 0.400 m)
4	0	$-\pi/2$	0	q_4	0
5	0	$\pi/2$	0	q_5	rl_5(= 0.390 m)
6	0	$\pi/2$	0	q_6	0
7	0	$-\pi/2$	0	q_7	0

B. Data acquisition and exciting trajectories for robot identification

The *KRC* controller of the Kuka *LWR* provides motor positions, joint positions, motor current and joint torques using an internal special function called "*Recorder*" in S.I unit in joint side. The sample acquisition frequency for motor positions and motor torques is 1KHz.

The motor torque τ_j is computed by the *KRC* controller from the manufacturer's joint drive gain $g_{\tau j}^{ap}$ and the motor current I_j for each axis j:

$$\tau_j = g_{\tau j}^{ap} I_j \qquad (20)$$

For identification of the robot, the exciting trajectories *PTP* (Point-To-Point) consist of 44 points additional of start and stop positions chosen that make the robot moving in most of its workspace areas (see figure 3). The motion profiles are trapezoidal acceleration profiles and the total motion has duration of 90 seconds by trajectories.

The robot has severable possible control law: joint position control, joint impedance control, cartesian impedance control, cartesian force control. In this paper, only the joint position control is used with a decentralized feedback controller [1]. Unfortunately, the manufacturer does not give details on this controller.

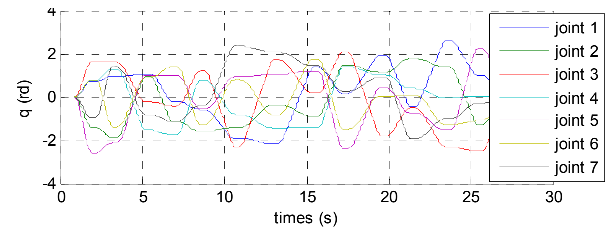

Figure 3. Measured motor positions

The cut-off frequency of the Butterworth filter is fixed at 10(Hz) . The cut-off frequency of the decimate filter is fixed at 0.8(Hz) and allows to have dw=1.7 .

C. Data acquisition and trajectories for identification of manufacturer's inertias and gravity parameters

The *FRI* provides motor positions, inertia matrix and gravity vector in S.I unit in joint side. For identification of manufacturer's values, the trajectories *PTP* (Point-To-Point) consist of 200 points that make the robot moving in most of its workspace areas. The sample acquisition frequency is 500Hz. Here, it is not necessary to have a special motion profiles because the accelerations and velocities are not necessary. Thus, only the positions at cross points are saved (see figure 4).

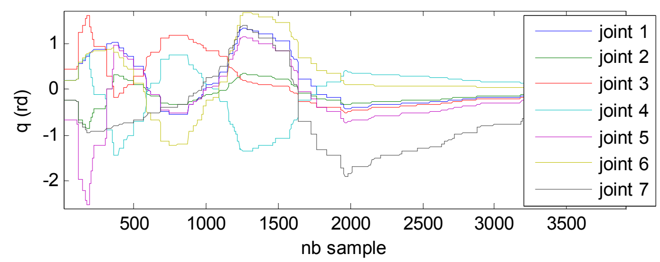

Figure 4. Measured motor positions

D. Identification of actual and confidential Kuka's parameters

The identification of actual and confidential Kuka's dynamic parameters are performed. The results are given in table II, the vector $\hat{\chi}$ contains the 28 actual essential parameters and the vector $\hat{\chi}^{ck}$ contains the 29 confidential Kuka's base parameters. The parameters with the subscript *R* stand for the regrouped parameters (see appendix).

The identification of confidential Kuka's parameters of the Kuka *LWR* is performed with *IDIM* (6) and the identification of actual parameters is performed with *IDIM* (2).

For actual parameters, the relative error between measured and reconstructed torques is 9.0%. The relative standard deviations are low thus the identification of the robot relevant. The measured and reconstructed torques are shown on figure 7.

TABLE II. *IDIM-LS* ACTUAL AND CONFIDENTIAL KUKA'S IDENTIFIED VALUES

Par.	$\hat{\chi}$	$\%\sigma_{\hat{\chi}}$	$\hat{\chi}^{ck}$	%e	Par.	$\hat{\chi}$	$\%\sigma_{\hat{\chi}}$	$\hat{\chi}^{ck}$	%e
ZZ_{1R}	**3.18**	2.6	-	-	Ia_4	**1.91**	4.3	-	-
ZZ_{1Rck}	-	-	**1.15 10^{-2}**	-	Fv_4	**11.9**	1.3	-	-
Fv_1	**14.3**	1.5	-	-	Fc_4	**8.42**	2.1	-	-
Fc_1	**12**	2.3	-	-	XX_{5R}	-	-	**3.95 10^{-3}**	-
XX_{2R}	**1.30**	11	**1.25**	**3.8**	YZ_5	-	-	**4.22 10^{-4}**	-
YZ_2	-	-	**-5.43 10^{-4}**	-	ZZ_{5R}	-	-	**6.33 10^{-3}**	-
ZZ_{2R}	**4.47**	4.2	-	-	MX_5	-	-	**-6.56 10^{-4}**	-
ZZ_{2Rck}	-	-	**1.25**	-	MY_{5R}	**0.049**	18	**4.07 10^{-2}**	**17**
MX_2	-	-	**1.35 10^{-3}**	-	Ia_5	**0.780**	3.4	-	-
MY_{2R}	**3.36**	1.6	**3.46**	**3.0**	Fv_5	**4.28**	1.8	-	-
Fv_2	**14.9**	2.7	-	-	Fc_5	**8.28**	1.4	-	-
Fc_2	**11.9**	3.3	-	-	XX_{6R}	-	-	**1.17 10^{-3}**	-
XX_{3R}	-	-	**6.36 10^{-3}**	-	YZ_6	-	-	**1.02 10^{-5}**	-
YZ_3	-	-	**7.26 10^{-4}**	-	ZZ_{6R}	-	-	**3.77 10^{-3}**	-
ZZ_{3R}	-	-	**1.08 10^{-2}**	-	MX_6	-	-	**8.35 10^{-4}**	-
MX_3	-	-	**9.45 10^{-4}**	-	MY_{6R}	**0.046**	15	**2.86 10^{-2}**	**37**
MY_{3R}	-	-	**-4.72 10^{-4}**	-	Ia_6	**0.394**	6.5	-	-
Ia_3	**2.01**	2.5	-	-	Fv_6	**2.22**	3.3	-	-
Fv_3	**6.54**	2.1	-	-	Fc_6	**4.78**	1.2	-	-
Fc_3	**9.01**	1.9	-	-	ZZ_7	-	-	**1.20 10^{-4}**	-
XX_{4R}	**0.372**	8.8	**0.413**	**11**	MX_7	-	-	**-2.98 10^{-4}**	-
YZ_4	-	-	**5.32 10^{-4}**	-	MY_7	-	-	**9.54 10^{-4}**	-
ZZ_{4R}	**0.501**	9.1	**0.418**	**17**	Ia_7	**0.398**	3.2	-	-
MX_4	-	-	**-3.50 10^{-3}**	-	Fv_7	**1.60**	2.3	-	-
MY_{4R}	**-1.36**	1.2	**-1.33**	**2.2**	Fc_7	**6.04**	0.98	-	-

For confidential Kuka's parameters, the identification is relevant because the norm of relative error between the measured gravity/mass torques and reconstructed gravity/mass torque is 10^{-13}. Therefore the identified values are the exact confidential manufacturer's parameters. But some base parameters are fixed at zero values by Kuka.

The relative error %e are computed between the actual parameters of the robot and the confidential Kuka's parameters. Some parameters are close and the relative error of the other are lower at $\%2\sigma_{\hat{\chi}_r}$.

The interest of the identification of the two set of parameters is to have the actual parameters of the drive chains (inertias and frictions parameters) and of the links, and to have also the confidential Kuka's parameters to complete the set of actual parameters. It allows to have a complete set of parameters for simulation and control.

E. Identification of manufacturer's stiffness parameters

To maximize the norm of flexible *dof* $|q_{ej}|$, the end-effector of robot is kept fixed with locking system (see figure 5). All motor positions vary up to the maximum admissible motor torques.

Figure 5. Robot with end-effector fixed and locking system

The identification of the *a priori* stiffness is performed on the Kuka *LWR* and the results are shown on table III.

TABLE III. IDENTIFIED CONFIDENTIAL KUKA STIFFNESS PARAMETERS

Par.	$\hat{\chi}_k$	$\%\sigma_{\hat{\chi}_r}$	Par.	$\hat{\chi}_k$	$\%\sigma_{\hat{\chi}_r}$
k_1^{ap}	**10000**	0.0014	k_5^{ap}	**10000**	0.0002
k_2^{ap}	**10000**	0.0004	k_6^{ap}	**7500**	0.0004
k_3^{ap}	**10000**	0.0012	k_7^{ap}	**7500**	0.0002
k_4^{ap}	**10000**	0.0002			

The relative error between measured and reconstructed torques is 0.001%. All *a priori* stiffness are very well identified because the same measurement are used to perform the identification and the computation of the joint position by the controller. The measured and reconstructed torques in function of the flexible *dof* are shown on figure 6.

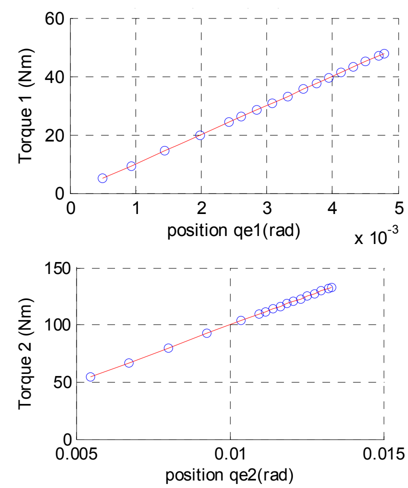

Figure 6. measure (blue circle) and model (red) of sensor torques 1 and 2

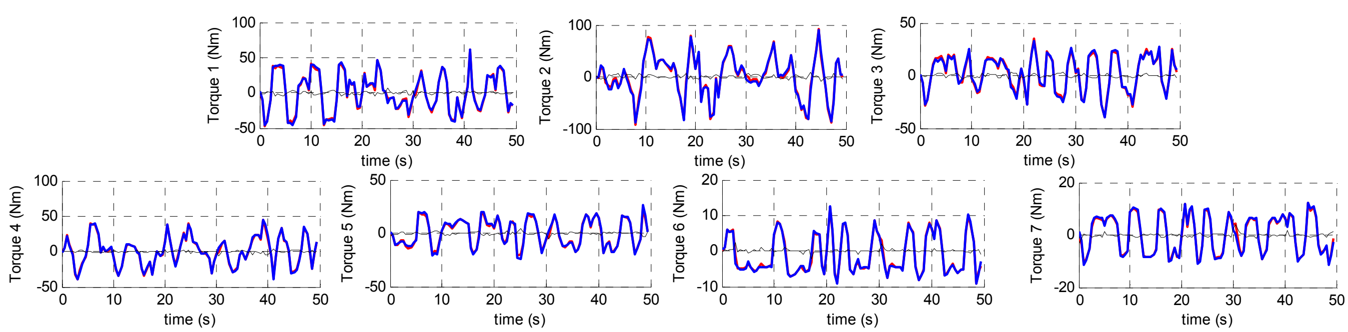

Figure 7. Measured (red) and reconstructed (blue) motor torque with error (black) for identification of actual robot

Unfortunately the real stiffness of the robot canno't be identified with *IDIM-LS* method because the actual joint positions are not given. But these *a priori* joint stiffness are identified precisely: $k_{1\ldots5}$=10000 Nm/rad and $k_{6,7}$=7500 Nm/rad.

The stiffness identified parameters can be used for simulation and control if the flexible model of the robot is necessary.

V. CONCLUSION

In this paper, the actual dynamic parameter identification of the Kuka *LWR4+* was performed and to complete this identification and for comparison, the confidential Kuka's parameters of gravity, inertias and stiffness are identified also. The identification process used is based on the *IDIM-LS* method which was adapted for the manufacturer's parameters identification. The manufacturer's and actual identified parameters are close. Futures works concern the identification of the actual flexible model of the robot.

APPENDIX: BASE PARAMETERS OF KUKA LWR

The regrouped base parameters [8][11] are given in table VI.

TABLE IV. REGROUPED BASE PARAMETERS

Set of actual parameters:
$\mathbf{ZZ_{1R}}=ZZ_1+\mathbf{Ia_1}+YY_2$
$\mathbf{ZZ_{2R}}=ZZ_2+\mathbf{Ia_2}+YY_3+2rl_3MZ_3+rl_3^2M_3+rl_3^2M_4+rl_3^2M_5+rl_3^2M_6+rl_3^2M_7$
Set of confidential Kuka's parameters:
$\mathbf{ZZ_{1Rck}}=ZZ_1+YY_2$
$\mathbf{ZZ_{2Rck}}=ZZ_2+YY_3+2rl_3MZ_3+rl_3^2M_3+rl_3^2M_4+rl_3^2M_5+rl_3^2M_6+rl_3^2M_7$
The two sets of parameters:
$\mathbf{XX_{2R}}=XX_2-YY_2+YY_3+2rl_3MZ_3+rl_3^2M_3+rl_3^2M_4+rl_3^2M_5+rl_3^2M_6+rl_3^2M_7$
$\mathbf{MY_{2R}}=MY_2+MZ_3+rl_3M_3+rl_3M_4+rl_3M_5+rl_3M_6+rl_3M_7$
$\mathbf{XX_{3R}}=XX_3-YY_3+YY_4$;
$\mathbf{ZZ_{3R}}=ZZ_3+YY_4$;
$\mathbf{MY_{3R}}=MY_3+MZ_4$
$\mathbf{XX_{4R}}=XX_4-YY_4+YY_5+2rl_5MZ_5+rl_5^2M_5+rl_5^2M_6+rl_5^2M_7$
$\mathbf{ZZ_{4R}}=ZZ_4+YY_5+2rl_5MZ_5+rl_5^2M_5+rl_5^2M_6+rl_5^2M_7$
$\mathbf{MY_{4R}}=MY_4-MZ_5-rl_5M_5-rl_5M_6-rl_5M_7$;
$\mathbf{XX_{5R}}=XX_5-YY_5+YY_6$
$\mathbf{ZZ_{5R}}=ZZ_5+YY_6$;
$\mathbf{MY_{5R}}=MY_5-MZ_6$;
$\mathbf{XX_{6R}}=XX_6-YY_6+YY_7$
$\mathbf{ZZ_{6R}}=ZZ_6+YY_7$;
$\mathbf{MY_{6R}}=MY_6+MZ_7$;
$\mathbf{XX_{7R}}=XX_7-YY_7$

The drive inertias moment of axis 1 and 2 are not present for the set of confidential Kuka's parameters so the regrouped base parameters are not equivalent to the set of actual parameters for $ZZ1_R$ and $ZZ2_R$.

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