

Parameter Identification of a single degree of freedom haptic interface

Flavia Khatounian, A. Janot, Sandrine Moreau, C. Bidard, Eric Monmasson,

M. Gautier

► To cite this version:

Flavia Khatounian, A. Janot, Sandrine Moreau, C. Bidard, Eric Monmasson, et al.. Parameter Identification of a single degree of freedom haptic interface. 14th IFAC Symposium on Identification and System Parameter Estimation, Mar 2006, Newcastle, Australia. pp.249-254, 10.3182/20060329-3-AU-2901.00034. hal-04069088

HAL Id: hal-04069088 https://hal.science/hal-04069088

Submitted on 31 May 2023 $\,$

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers. L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

PARAMETER IDENTIFICATION OF A SINGLE DEGREE OF FREEDOM HAPTIC INTERFACE

F. Khatounian⁽¹⁾, A. Janot⁽²⁾, S. Moreau⁽³⁾, C. Bidard⁽²⁾, E. Monmasson⁽³⁾, M. Gautier⁽⁴⁾

 ⁽¹⁾ HAPTION Virtual Touch – Atelier relais de Soulgé sur Ouette, route de Laval, 53210 Soulgé sur Ouette, France, flavia.khatounian@haption.com
 ⁽²⁾ CEA/LIST, 92265 Fontenay-aux-Roses Cedex, France, alexandre.janot@cea.fr, catherine.bidard@cea.fr
 ⁽³⁾ SATIE – CNRS UMR8029 – Université de Cergy, rue d'Eragny, 95301 Cergy-Pontoise, France, sandrine.moreau@univ-poitiers.fr, eric.monmasson@iupge.u-cergy.fr
 ⁽⁴⁾ IRCCyN – CNRS UMR6597 – Université et école centrale de Nantes, BP92101, 44321 Nantes Cedex 3, France, Maxime.Gautier@irccyn.ec-nantes.fr

Abstract: A haptic system consists in an articulated mechanical structure with motors and position sensors, as well as embedded electronics allowing force feedback. It is driven by a haptic interface, which enables the user to interact with an image in a virtual reality application, through the sense of touch. This paper presents a protocol allowing the identification of both electrical and mechanical parameters using inverse models and least-squares techniques, in order to achieve a robust control strategy of the overall system in terms of transparency and stiffness. *Copyright* [©] 2006 IFAC

Keywords: least-squares identification, haptic interface, synchronous machine, viscous and Coulomb friction, electrical parameters.

1. INTRODUCTION

A haptic interface is a computer device, which enables its user to interact with the image in a virtual reality application or model, through the sense of touch. Users can experience feelings of touch and movement thanks to this technology that optimizes human communication with machines and intensifies a human's immersion in a virtual world. Such systems are in growing demands for applications such as mobile robotics, force feedback remotecontrol systems for extreme environment, manmachine interaction and training in professional operating procedures (Colgate, et al., 1993; Millman, et al., 1993). They consist in an articulated mechanical structure with motors and position sensors, as well as embedded electronics. The user holds the end-point of the structure in his hand, and can move it around, both in the real and in the virtual world on the computer screen (Fig. 1). Whenever his

virtual hand makes contact with a digital object, a force value is sent to the motors, which simulates a real contact (Khatounian, et al., 2005).

The proposed system (Fig. 2) is based on brushless Permanent Magnet Synchronous Machines (PMSM). The objective of the study is to obtain a torque regulation with the best dynamic behavior and without ripples in order to have the best stiffness and transparency of the system. Therefore, an accurate dynamic model of the system is required to control or simulate virtual motions. These models depend on the geometric parameters of the interface (length of links, angle between joint axis...) which are supposedly known and on the dynamic electrical and mechanical parameters (permanent flux, stator windings resistance and inductance, inertia, friction...). This paper establishes a simple protocol allowing the identification of the dynamic parameters using inverse models and least squares techniques.



Fig. 1. Articulated mechanical structure for haptic interfaces (VIRTUOSE).

Section 2 presents the explicit electrical and mechanical models of the overall system. Section 3 describes the least-squares technique used to identify the desired parameters. Section 4 gives the experimental protocol for data measurements and filtering necessary to the identification. Results prove the feasibility of the protocol by comparing constructor or expected parameters with the identified ones.

2. EXPLICIT ELECTRICAL AND MECHANICAL MODEL OF THE SYSTEM

2.1 Electrical model of the synchronous machine

The PMSM electrical model, in the Park synchronous reference frame (Leonhard, 1985; Vas, 1990) is described in Eq. (1) and (2). *R* is the stator winding resistance, L_d and L_q the direct and quadrature axis inductances, whereas V_d , V_q , I_d and I_q are the direct and quadrature axis voltage and current components. φ_f is the permanent magnet flux, *p* the number of poles and Γ the electromagnetic torque.

$$\begin{cases} V_{d} = R.I_{d} + L_{d} \frac{d}{dt} I_{d} - \omega L_{q} I_{q} \\ V_{q} = R.I_{q} + L_{q} \frac{d}{dt} I_{q} + \omega L_{d} I_{d} + \omega \varphi_{f} \end{cases}$$
(1)

$$\Gamma = \frac{2}{3} p \left(\varphi_f - \left(L_q - L_d \right) I_d \right) I_q$$
⁽²⁾

In this case, the chosen PMSM is symmetrical with a non-salient rotor. The direct and the quadrature stator inductances are equal and Eq. (2) is simplified as follows:

$$L = L_d = L_q \tag{3}$$

$$\Gamma = \frac{2}{3} p.\varphi_f . I_q = K_c . I_q \tag{4}$$

where K_c is the torque constant.



Fig. 2. Experimental single degree of freedom haptic interface.

In order to use the least-squares identification method, the \mathbf{q} axis system described in Eq. (1) is written as an inverse linear model.

$$V_{q} = R.I_{q} + L\left(\frac{dI_{q}}{dt} + \omega.I_{d}\right) + \varphi_{f}.\omega$$

$$V_{q} = \sum_{j=1,N_{pc}} W_{j}X_{j}$$
(5)

The electrical parameters to identify are the stator windings resistance *R*, the stator windings inductance *L* and the permanent flux φ_{i} .

2.2 Mechanical model of the haptic system

The inverse dynamic model of a rigid system gives the motor torque as follows:

$$\Gamma = J\ddot{q} + \frac{\partial U}{\partial q} + \Gamma_f \tag{6}$$

where q and \ddot{q} are respectively the joint position and acceleration, J is the global inertia of the system, U its potential energy and $\partial U/\partial q$ the gravitational torque. The friction torque Γ_f is measured according to the method developed by Spetch and Isermann (1988). It consists in measuring the torque at different constant speeds and eliminating all transient modes. Fig. 3 shows that the friction model can be considered at non-zero velocity as the following, where sign (\dot{q}) is the sign function of the velocity \dot{q} , and f_c , f_v respectively denote the Coulomb and viscous friction coefficients.

$$\Gamma_f = f_c sign(\dot{q}) + f_v \dot{q} \tag{7}$$



Fig. 3. Friction torque.



Fig. 4. Frames and joint variables of the haptic device at the handle and pulley.

An inverse dynamic model is obtained. It is linear to a set of N_p minimum dynamic parameters (Gautier, 1990; Khalil and Dombre, 2002):

$$\Gamma = J\ddot{q} - M_X g\cos(q) + M_Y g\sin(q) + f_v \dot{q} + f_c sign(\dot{q})$$

$$\Gamma = \sum_{i=1,Np} W_i X_i \tag{8}$$

where $\begin{bmatrix} M_X & M_Y \end{bmatrix}^t = m \begin{bmatrix} X_G & Y_G \end{bmatrix}^t$, *m* is the mass of the handle and X_G, Y_G are the coordinates of the center of gravity G of the rotating body (Fig. 4), in the body-fixed frame (O, x₁, y₁).

Finally, the set of mechanical parameters to identify is (J, M_X, M_Y, f_v, f_c) .

3. LEAST-SQUARES IDENTIFICATION TECHNIQUE

3.1 Least-squares method

Generally, ordinary least-squares (LS) technique is used to estimate the minimum dynamic parameters solving an overdetermined linear system. This system is obtained from a sampling of a dynamic model along a given trajectory (z,\dot{z},\ddot{z}) (Gautier and Khalil, 1988; Gautier, et al, 1995). **z** is a rx1 vector, which represents for example the current vector $\mathbf{I}_{\mathbf{q}}$ in the electrical parameters identification or the joint position vector **q** in the mechanical parameters identification. (\dot{z},\ddot{z}) are the first and second order derivatives of **z**. The system is described as follows:

$$Y = WX + \rho \tag{9}$$

where **X** is the optimal parameters vector to identify, **Y** the measurements vector, **W** the observation matrix and $\mathbf{\rho}$ the vector of errors.

The L.S. solution \hat{X} minimizes the 2-norm of the vector of errors ρ . The singularity of \hat{X} depends on the rank of the observation matrix **W**.

In order to avoid the problem of structural parameters identifiability and/or the problem of optimal measurements and in order to decrease the sensitivity of \hat{X} to errors in **Y** and **W**, we consider the minimal set of parameters and the conditioning of **W**. If the trajectory is sufficiently exciting, then the condition number of **W** will be close to one. **W** is a rxN_p full rank and well conditioned matrix obtained by tracking an exciting trajectory.

Standard deviations $\sigma_{\hat{x}_i}$ are estimated using classical results from statistics. The matrix **W** is supposed to be deterministic and ρ a zero-mean additive independent noise, with a standard deviation such as:

$$C_{\rho\rho} = E(\rho^T \rho) = \sigma_{\rho}^2 I_r \tag{10}$$

E is the expectation operator and $\mathbf{I}_{\mathbf{r}}$ the rxr identity matrix. An unbiased estimation of σ_{ρ} is:

$$\hat{\sigma}_{\rho}^{2} = \frac{\left\| Y - W\hat{X} \right\|^{2}}{r - Np} \tag{11}$$

The covariance matrix of the standard deviation is calculated as follows:

$$C_{\hat{X}\hat{X}} = E\left[\left(X - \hat{X}\right)\left(X - \hat{X}\right)^{T}\right] = \sigma_{\rho}^{2}\left(W^{T}W\right)^{-1} (12)$$

 $\sigma_{\hat{x}i}^2 = C_{\hat{x}\hat{x}_{ii}}$ is the ith diagonal coefficient of $C_{\hat{x}\hat{x}}$. The relative standard deviation $\%\sigma_{\hat{x}_{ii}}$ is given by:

$$\%\sigma_{\hat{X}_{i}} = 100 * \frac{\sigma_{\hat{X}_{i}}}{\hat{X}_{i}}$$
(13)

However, in practice, **W** is not deterministic. This problem can be solved by filtering the measurement matrix **Y** and the columns of the observation matrix **W** as described in Gautier (1997) and Pham (2002).

3.2 Data filtering

Vectors **Y** and **z** are samples measured during an experimental test. The derivatives \dot{z} and \ddot{z} are obtained without phase shift using a centered finite

difference of the vector z. Knowing that z is disturbed by high frequency noises which will be amplified by the numeric derivation, a lowpass filter with an order greater than 2 is used. The choice of the cut-off frequency ω_f is very sensitive because the filtered data $(z_f, \dot{z}_f, \ddot{z}_f)$ must be equal to the vector (z, \dot{z}, \ddot{z}) in the range $[0, \omega_f]$, in order to avoid distortion in the dynamic regressor. The filter must have a flat amplitude characteristic without phase shift in the range $[0, \omega_f]$ with the rule of thumb $\omega_f > 10 * \omega_{dyn}$. ω_{dyn} represents the dynamic frequency of the system. Considering an off-line identification, this is easily achieved with a noncausal zero-phase digital filter, by processing the input data through an IIR lowpass butterworth filter in the forward and reverse direction. The measurement vector Y is also filtered. A new filtered linear system is obtained:

$$Y_f = W_f X + \rho_f \tag{14}$$

There is no more signal in the range $[\omega_f, \omega_s/2]$, where ω_s is the sampling frequency. Vector $\mathbf{Y}_{\mathbf{f}}$ and matrix $\mathbf{W}_{\mathbf{f}}$ are re-sampled at a lower rate after lowpass filtering. One sample over n_d samples is kept, in order to obtain the final system to identify:

$$Y_{fd} = W_{fd} X + \rho_{fd} \tag{15}$$

$$n_d = 0.8 \frac{\omega_s}{2.\omega_f} \tag{16}$$

4. PARAMETER IDENTIFICATION

4.1 Parameter pre-estimation

On the long term, the objective of this study is to identify the electrical and mechanical parameters of the system without previous knowledge of them. In order to validate the proposed method and to compare theoretical values with estimated ones, the nominal values of the electrical parameters given by the PMSM manufacturer are considered (Table 1).

The mechanical parameters J, M_X and M_Y are calculated from nominal values. The global inertia J is determined as:

$$J = J_s + N^2 J_m \tag{17}$$

where J is the global inertia of the system, J_s the experimental structure inertia, N the ratio of the reductor and J_m the motor inertia. M_X and M_Y are calculated assuming that the center of gravity G is aligned with the handle axis X_1 . M_X is deduced from the classic mechanical rules and M_Y is close to zero. Friction coefficients were estimated from the specific identification test described in section 2.2.

Table 1 Pre-estimated electrical and mechanical parameter values

Electrical	Nominal	Mechanical	Nominal
parameters	values	parameters	values
$R(\Omega)$	0,65	J (kg.m ²)	$1,45.10^{-3}$
L (H)	$2,55.10^{-4}$	$M_X(kg.m)$	$2,5.10^{-3}$
ϕ_{f} (Wb)	0,027	M _Y (kg.m)	0
• • •		f _v (Nm.s.rad ⁻¹)	$2,3.10^{-3}$
		f _c (Nm)	6.10^{-2}

4.2 Identification of the electrical parameters

The electrical model of the permanent magnet synchronous machine given in Eq. (1) can be written as the following linear system. It allows the identification of the three electrical parameters.

$$Y_e = W_e X_e \tag{18}$$

where Y_e , W_e and X_e are respectively the electrical measurement vector, observation matrix and parameter vector.

$$\begin{cases} Y_e = V_q \\ X_e = \begin{bmatrix} R & L & \varphi_f \end{bmatrix}^t \\ W_e = \begin{bmatrix} I_q & (\dot{I}_q + \omega I_d) & \omega \end{bmatrix} \end{cases}$$
(19)

Quadrature tension V_q , direct and quadrature currents I_d and I_q and the electrical speed ω were measured, with a sampling period of 60µs. A trapezoidal current reference is used. This trajectory was chosen because it allows an easy derivation thus, a good excitation of all parameters including the inductance *L*. Vector \dot{I}_q was derived from the current vector I_q , and all data were filtered as described in section 3.2.

Table 2 Estimated and nominal electrical parameter values

Electrical parameters	Nominal values	Estimated values	$\%\sigma_{\hat{\mathrm{X}}_\mathrm{r}}$
$R(\Omega)$	0,65	0,76	0,11
L (H)	$2,55.10^{-4}$	$2,8.10^{-4}$	1,96
$\phi_{f}(Wb)$	0,027	0,02	0,7
	Cond(W)=29		

The parameters obtained with the least-squares technique are given in Table 2 and compared to the constructor values. In order to obtain the best results, different tests and identification were realized. Each one gives a new set of parameters which are all close to each others. The average value of all tests has been presented in the table which shows that the differences between constructor values and estimated values are small.

Figure 5 shows the trapezoidal waveform of the current \mathbf{I}_q used as the identification trajectory, the measured and estimated quadrature voltage \mathbf{V}_q and the voltage estimation error obtained after identification. The obtained voltage error is less than 10% relatively to the measured voltage. In addition to the previous comparison made between constructor and estimated values, this figure validates our procedure concerning the electrical parameters identification.

4.3 Identification of the mechanical parameters

The mechanical model of the haptic device given in Eq. (8) can be written as the following linear system. It allows the identification of the five mechanical parameters.

$$Y_m = W_m X_m \tag{20}$$

where Y_m , W_m and X_m are respectively the mechanical measurement vector, observation matrix and parameter vector.

$$\begin{cases} Y_m = \Gamma = K_c \cdot I_q \\ X_m = \begin{bmatrix} J & M_x & M_y & f_v & f_c \end{bmatrix}^t \\ W_m = \begin{bmatrix} \ddot{q} & -g \cdot \cos(q) & g \cdot \sin(q) & \dot{q} & sign(\dot{q}) \end{bmatrix} \end{cases}$$
(21)

Quadrature current $\mathbf{I}_{\mathbf{q}}$ and joint position and velocity \mathbf{q} and \dot{q} were measured with a sampling period of 240µs and using a trapezoidal speed reference. This trajectory was chosen because it is equivalent to a rectangular trajectory for the joint acceleration. It allows the estimation of the inertia term due to the change of the acceleration sign, of the gravitational and viscous friction terms because the velocity is constant over a time period and of the Coulomb term due to the change of sign of the velocity. Vector \ddot{q} was derived from the speed vector \dot{q} and all data were filtered as described in section 3.2.

The parameters obtained with the least-squares technique are given in Table 3 and compared to their nominal values. In order to obtain the best results, different tests and identification were realized, each one giving a new set of parameter. The average value of all tests has been presented in the table which shows that the differences between the nominal values and estimated values are minimal. Notice that M_Y is probably due to a non-homogeneity of the handle.

Figure 6 shows the trapezoidal waveform of the speed ω used as the identification trajectory, the measured and estimated torque Γ and the torque estimation error obtained after identification. The obtained torque error is less than 10% relative to the measured torque. In addition to the previous

comparison made between calculated and estimated values, this figure validates our procedure concerning the mechanical parameter identification.

Table 3 Estimated and calculated mechanical

parameter values.				
Mechanical parameters	Nominal values	Estimated values	$\%\sigma_{\hat{X}_{r}}$	
J (kg.m ²)	$1,45.10^{-3}$	$1,46.10^{-3}$	0,4	
$M_X(kg.m)$	$2,5.10^{-3}$	$2,3.10^{-3}$	4,7	
$M_{Y}(kg.m)$	0	$0,9.10^{-3}$	6,5	
f _v (Nm.s.rad ⁻¹)	$2,3.10^{-3}$	$2,2.10^{-3}$	2,5	
f _c (Nm)	6.10^{-2}	6.10^{-2}	0.8	
	Cond(W)=20			

4.4 Estimation of haptic system limits

The identification of the electrical parameters improves the control strategy of the PMSM in terms of response time and dynamics. It allows afterward the implementation of a 'virtual wall' as described by Abbot and Okamura (2004) in order to test the haptic device. This wall is passive as long as the following relation is satisfied:

$$K \le \min\left(2\frac{f_{\nu}}{T}, 2\frac{f_{c}}{\Delta}\right) \tag{22}$$

K is the stiffness of the virtual wall. It corresponds to the static torques that can be elicited by penetrating a given angular distance into the virtual surface. f_v and f_c are respectively the viscous and Coulomb friction coefficients identified previously, T is the sampling period of the haptic loop regulation, and Δ is the encoder resolution.



Fig. 5. Current trajectory used for LS estimation, measured and estimated voltage and voltage estimation error.



Fig. 6. Speed trajectory used for LS estimation, measured and estimated torque and torque estimation error.

Theoretical results show that in this case, stiffness is limited by the term f_v/T . Figure 7 presents the torque elicited by penetrating a given angle in the 'virtual wall'. The slope of the curve corresponds to the stiffness experimentally obtained. It is 10% smaller than the maximum shown in Eq. (22). Thus, the identification of the mechanical parameters allows the validation of the developed control strategy in terms of 'wall passivity'.

The presented protocol is very useful in order to identify an unknown interface and establish the correct control strategy without previous knowledge of the electrical and mechanical parameter values.

5. CONCLUSION

This paper presented the identification of the electrical parameters of a permanent magnet synchronous machine, along with the identification of the dynamic parameters of the haptic device, using inverse dynamic model and the least-squares technique. The estimated parameters are close to the nominal ones and the comparison of the measurement and estimated voltage and torque vectors show a less than 10% error. The results obtained show the feasibility of the described protocol.

REFERENCES

Abbot, J.J, A.M. Okamura (2004). A sufficient condition for passive virtual walls with quantization effects. In: *Proc. Of IMECE2004*, USA, pp. 1065-1073.



Fig. 7. Stiffness of the virtual wall: Torque vs. penetration angle.

- Colgate, J.E., P.E. Grafing, M.C. Stanley, G. Schenkel, (1993). Implementation of stiff virtual walls in force-reflecting interfaces. In: *Proc. IEEE-VRAIS*, pp. 202-208.
- Gautier, M., and W. Khalil (1988). On the identification of the inertial parameters of robots. In: 27th CDC, pp. 2264-2269.
- Gautier, M., (1990). In: Contribution à la modélisation et à l'identification des robots, thèse Université de Nantes.
- Gautier, M., P.P. Restrepo and W. Khalil (1995), Identification of an industrial robot using filtered dynamic model. In: *Proceedings, 3rd ECC*, Rome, pp. 2380-2385.
- Gautier, M., (1997). Dynamic identification of robots with power model. In: *ICRA'97, Albuquerque*.
- Khalil, W., and E. Dombre (2002). In: *Modeling, identification and control of robots*, chapter 12. Hermes Penton, London-Paris.
- Khatounian, F., S. Moreau, J.P. Louis and E. Monmasson, (2005). Modeling and Simulation of a Hybrid Dynamic System Used in Haptic Interfaces. In: 8th Electrimacs Conference, Hammamet, Tunisia, Proc., CD-ROM, ISBN 2-921145-51-0.
- Leonhard, W. (1985). In: *Control of electrical drives*, Springer Verlag.
- Millman, P.A., M. Stanley, J.E. Colgate (1993). Design of a high performance haptic interface to virtual environments. In: *IEEE Annual Virtual Reality Symposium*, pp. 216-222.
- Pham, M. T., (2002). In: Contribution à la modélisation, l'identification et à la commande de systèmes mécaniques à flexibilités localisées, thèse Université de Nantes.
- Spetch, R., R. Isermann, (1988). On-line identification of inertia, friction and gravitational forces applied on industrial robots. In: *Proc. IFAC, Symp. on robots control, SYROCO'88*, pp. 88.1-88.6.
- Vas, P. (1990). In: *Vector control of AC machines*. Ed. Clarend Press Oxford.