The 2010 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 18-22, 2010, Taipei, Taiwan

Flexible Model Identification of the Parallel Robot Par2

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Abstract— **The open-loop flexible modes identification of a high-speed and high-accuracy pick-and-place parallel robot is carried out based on two approaches: an ARMAX model and a subspace identification technique. Models of piezoelectric dynamics and disturbances can be obtained for many distinct operation conditions, allowing, in a future work, the conception of robust control laws.**

I. INTRODUCTION

Industrial handling and assembly applications require reduction of cycle time and increase of the process quality [8]. Due to their speed, precision and stiffness, parallel robots are a good alternative for fast and accurate pick-and-place operations, performing notably well in sectors like food, pharmaceutical and electronical assembly [10].

A parallel robot is a closed-loop kinematic chain mechanism whose end-effector is linked to the base by several independent kinematic chains [2]. Its motor actuators can be fixed to its base, a characteristic that tends to diminish the robot moving masses, enhancing the structure dynamical performances [5].

The Par2 prototype given in Fig. 1 is an innovative two degrees-of-freedom parallel robot destinated to cycle time reduction in high-speed, high-precision pick-and-place industrial operations. It was conceived as a joint effort of the Montpellier Laboratory of Informatics, Robotics, and Microelectronics (LIRMM) and the spanish foundation Fatronik. Due to its high stiffness and low weight, Par2 was able to accomplish already accelerations above 40G (without load at the end-effector)[6][7].

At the operation cycle stop points, as a consequence of the high acceleration levels of the end-effector trajectory, the flexible modes of the arms are excited, leading to undesirable vibrations. These vibrations, sensed by means of three orthogonally oriented accelerometers placed on the end-effector, contribute to an increase in the operation cycle time, once they augment the time the end-effector disposes to reach a certain precision during the positioning task.

As a solution for the vibration attenuation, piezoelectric patches wrapped around the robot arms are intended to be used for implementing active control [8]. For control purposes, a good model of the dynamical behavior from the piezoelectric input voltages to the accelerometers is important. This model will be called here a flexible model of the robot, in opposition to the robot rigid model, which concerns the dynamical behavior from the motor drives to the motor encoders. In [6] a nonlinear dual mode adaptive controller was used for the rigid model and in [7] the use of piezoelectric patches as an alternative for vibrations suppression in Par2 was suggested.

This work is supported by ANR - Agence Nationale de la Recherche (France) in the context of the *Objectif 100G* project

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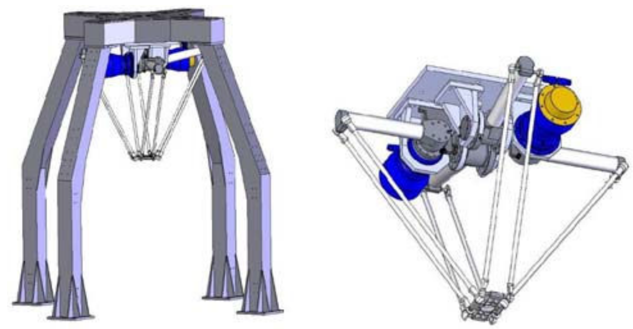

Fig. 1. Parallel Robot - Par2

This paper presents the results accomplished up to now in respect to the flexible model obtention, paving the way for the following step, namely the elaboration of the vibration attenuating control law. A well consolidated way of obtaining a dynamical model is by means of the theory of system identification [1]. Two different approaches are compared: an ARMAX model and a method based on subspace identification. Besides identifying the piezoelectric dynamical model, also identifications of the remaining vibrations (system disturbances at the stop points) due to different trajectories were performed. Considering the potential enrichment these models can afford to the flexible model, further improvements for the control law can be expected. All identifications were carried on for many distinct operation conditions where the robot shall be controlled, urging the use of robust control techniques [4].

II. FUNDAMENTALS OF IDENTIFICATION

System identification deals with the problem of building mathematical models of dynamical systems based on observed data from the system [1].

Depending on the adopted criteria, there are many possibilities for models classification. A criterion that is meaningful in the context of this work is to differentiate between parametric and non-parametric models.

Non-parametric models, like an impulse response or a frequency response diagram, are so called because of the lack of a parametrically structured mapping determining an

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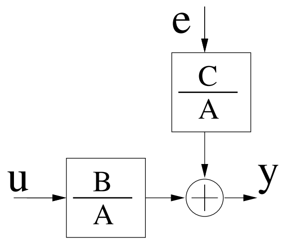

Fig. 2. ARMAX model

univocal relation between input and output signals. They are just a sequence of values, from which the dynamic characteristics of the system can be appreciated.

On the other hand, parametric models are based on an algebraic closed form, establishing a parametrically constructed relation between inputs and outputs. Parametric models obtention imposes some *a priori* knowledge about the structure that is being pursued. As examples of parametric models we could mention the ARMAX (Auto-Regressive, Moving Average with eXogenous inputs) class of models and the models obtained from subspace identification techniques, both explained a bit further in the following.

Once a model is obtained, it is indispensable to validate it somehow, before its use in the elaboration of a control law. Between different model validation strategies, like cross-validation, whiteness test [1], a very common practice in the field of structural vibration control is to validate the model comparing the adequacy of a non-parametric model with the to-be-validated parametric one, the comparison being made in some desired frequency range [3].

A. ARMAX Model Identification

ARMAX models are very common in engineering practice [11], and can be described by Eq. (1), where the actual output $y(t)$ depends on the past outputs $y(t-k)$ (Auto-Regressive terms), past control inputs $u(t-k)$ (eXogenous inputs terms) and past and actual white noise inputs $e(t)$, $e(t-k)$ (Moving Average terms).

$$\begin{aligned} y(t) = &-a_1 y(t-1) - \ldots - a_{na} y(t-n_a) + \\ &b_1 u(t-1) + \ldots + b_{nb} u(t-n_b) + \\ &e(t) + c_1 e(t-1) + \ldots + c_{nc} e(t-n_c) \end{aligned} \tag{1}$$

This equation can be represented by the block diagram in Fig. 2, where the polynomials A, B and C are given according to Eqs. (2) and (3).

$$\begin{cases} A(q) = 1 + a_1 q^{-1} + \ldots + a_{na} q^{-n_a} \\ B(q) = b_1 q^{-1} + \ldots + b_{nb} q^{-n_b} \\ C(q) = 1 + c_1 q^{-1} + \ldots + c_{nc} q^{-n_c} \end{cases} \tag{2}$$

$$A(q)y(t) = B(q)u(t) + C(q)e(t) \tag{3}$$

We can observe that the polynomial A is used to estimate concomitantly both control input and noise dynamics, the distinction of each being made by means of polynomials B and C.

B. Subspace Identification

Subspace identification methods use as basic information only the experimental input-output data vector. Optional entries are the expected system order and some ponderation matrices that influence the identified stochastic signals characteristics and the state-space base representation of the system.

Consider the system in the state-space representation given by eq. (4), where $x(t)$, $u(t)$ and $y(t)$ are respectively the state, input and output vectors and $w(t)$ and $v(t)$ are the process and measurement noises.

$$\begin{cases} x(t+1) = A_{ss}x(t) + B_{ss}u(t) + w(t) \\ y(t) = C_{ss}x(t) + D_{ss}u(t) + v(t) \end{cases} \tag{4}$$

The simplified sequencial steps of a subspace identification method can be summarized as follows.

Basically, a state vector sequence can be estimated by means of an orthogonal projection of the row space of a certain block Hankel matrix of data into the row space of other data block Hankel matrices. This projection is proved to be related to the extended observability matrix of the system. By means of a singular value decomposition (SVD) of this projection matrix, the order of the system can be estimated, taking in consideration the most representative Hankel singular values. Once the observability matrix in some base representation and the order of the system are known, it is a direct step to obtain the system matrices A_{ss}, B_{ss}, C_{ss} and D_{ss} using a least-squares method. These, together with the information of the state vector sequence allows one to estimate the properties of the process and measurement noises [9][1].

In some less technical terms, once the input-output data vectors are known, it is possible to have a very good estimation of the model, even without the specification of desired structures, which is a requirement in the ARMAX case, where the choice of orders for the polynomials A, B and C is a necessity.

III. Identified Models

The pick-and-place trajectories, constrained to the xz plane, evolve between stop positions Pos1 (x=0.35, z=-0.925) and Pos2 (x=-0.35, z=-0.925), designated in Fig. 3. These displacements are promoted by the active arms (arms directly connected to the motors, Fig. 1) while the passive ones were conceived to prevent perpendicular motions.

As already mentioned, two different kinds of dynamics were identified: piezoelectric dynamics G_u and disturbance dynamics G_w (residual vibrations immediately after arriving at the stop points). With the knowledge of G_u and G_w, the objective is to build up a complete identified model, as can be seen in Fig. 4, which will be later used for control purposes.

The models were obtained for different operation conditions comprising variations of transported loads (either

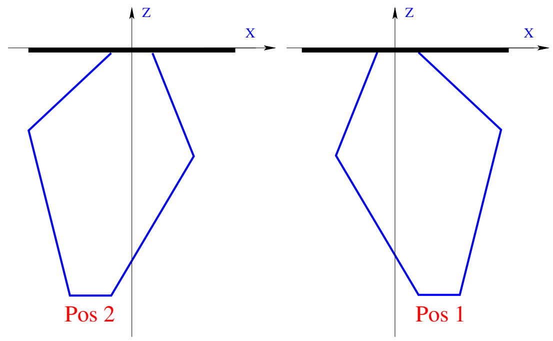

Fig. 3. Stop positions

without load or with 1 kg load at the end-effector), end trajectory positions (stop positions Pos1 and Pos2), trajectory accelerations (only for disturbance models, accelerations of 10G, 20G and 30G) and selection of piezo-actuated arms (only for piezoelectric models). The end-effector is illustrated in Fig. 5, where the piezo-actuated arms are labelled with letters *A* and *P*, given accordingly to the active or passive characteristic of the arm.

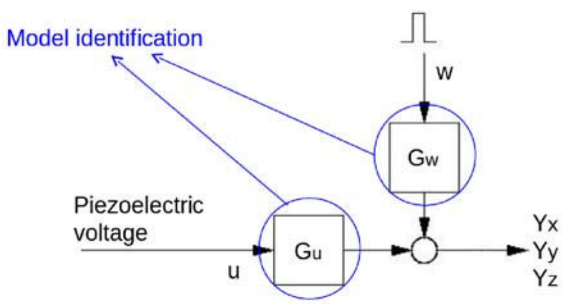

Fig. 4. Complete identified model

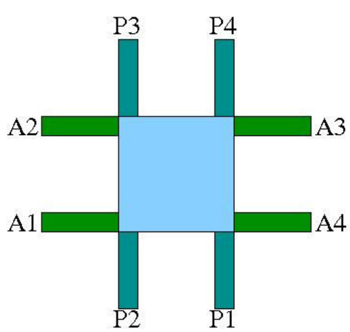

Fig. 5. Piezoelectric Actuated Arms

As the objective here is to present the methodology utilized for identification, one example of a disturbance model, as well as one from a piezoelectric model, will be given in the sequel. The sampling rate was 2kHz in all the experiments.

A. Disturbance Model

Identification of the residual vibrations after arrival at the stop points were made for the aforementioned operation conditions. Here, in Fig. 6, we present as an example the results obtained for a complete cycle identification of a 30G trajectory without load at the stop point Pos2 (starting and ending in Pos2, passing by Pos1). The accelerations are measured by three orthogonally oriented accelerometers (X, Y and Z).

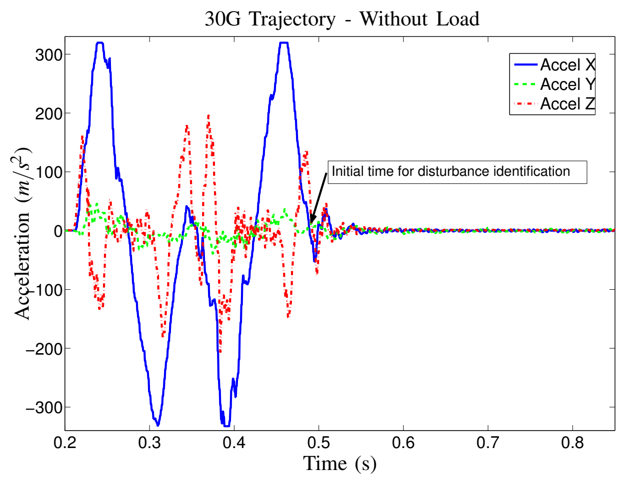

Fig. 6. Robot Accelerations - 30G - Without Load

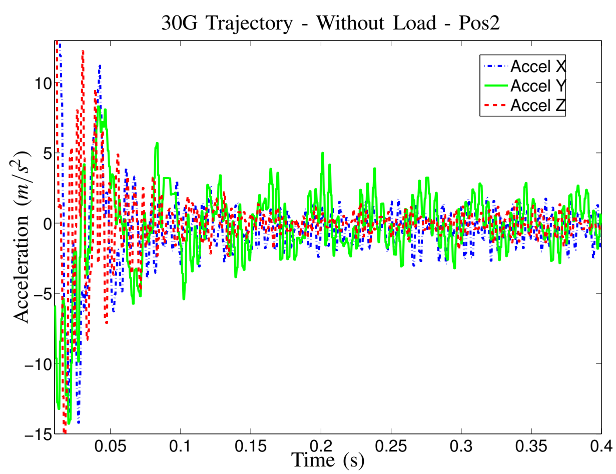

Fig. 7. Robot Accelerations - 30G - Without Load - Pos 2

In approximately 0.5 seconds the end-effector reaches Pos2 again. From that moment on, the disturbance identification procedure takes place. Vibrations are more expressive in the Y direction (perpendicular to the plan of displacement), which can be verified in Fig. 7.

Fig. 8 shows the frequency spectrum for the three accelerometers, where once again we can see the predominance of the response at accelerometer Y, with a well characterized resonance frequency at about 26.7Hz.

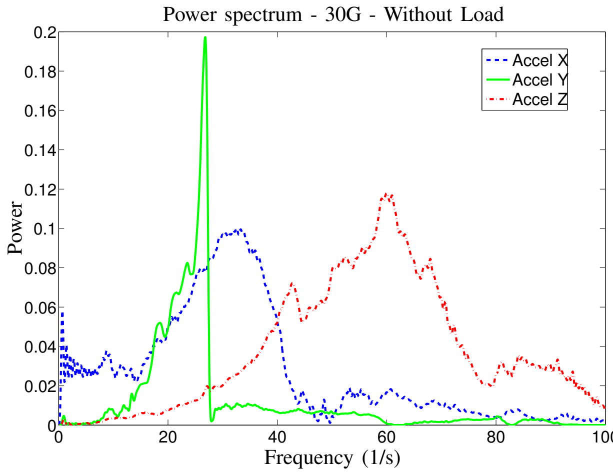

Fig. 8. Power Spectrum - Accelerometers X, Y and Z

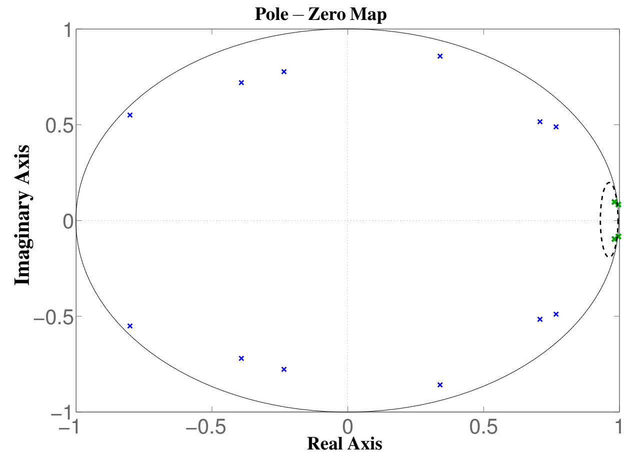

Fig. 10. Pole-Zero Open Loop AR Model Reduction

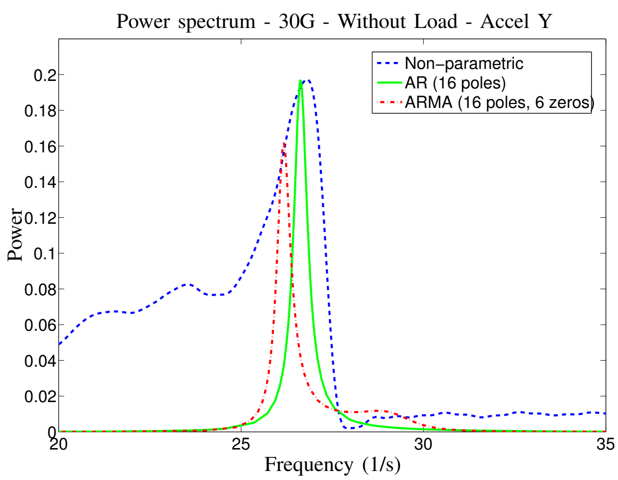

Fig. 9. Power Spectrum - Accelerometer Y

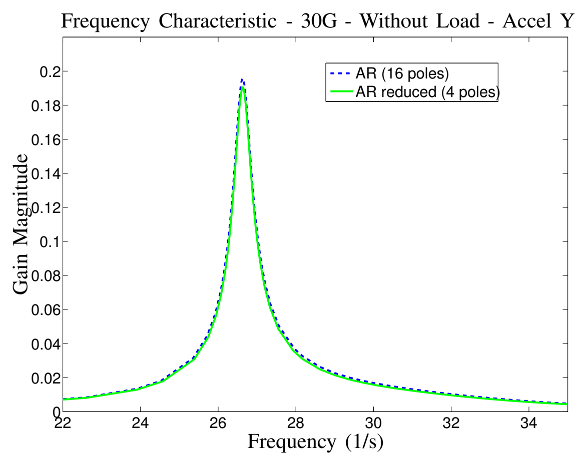

Fig. 11. Complete and Reduced Order AR Model

The instant the end-effector abruptly arrives at the stop point, some modes of the robot arm are excited, generating what we call the disturbance of our system. In order to identify these vibrations, the following metaphor is used. Suppose the end-effector is at rest at the stop point and we hit the effector with a hammer, transmitting a signal that is very rich in frequencies and short in time, similar to an impulse. Which from these frequencies would excite the robot arms? This question is answered by the identification of the impulse response of the system. Once we know the dynamical behaviour of the disturbance represented as a time-series, we can determine the filter that generates this oscillatory pattern from an impulse.

This proposal was accomplished using two different simplifications of the ARMAX model: an Auto-Regressive AR model and an Auto-Regressive Moving Average ARMA model, both convenient for time-series identification [1].

The results obtained using these two models are compared, in Fig. 9, with the non-parametric model, in this case, a periodogram of the disturbance time-series. Both parametric models are represented as 16^{th} order systems. We can see that in this experiment the extra zeros from the best 16^{th} order ARMA model did not contribute to the improvement of the model quality. In the matter of fact the AR model was more successful in finding the main resonance frequency of the disturbance at about 26.6Hz.

A reduction of the AR model is undertaken by eliminating the high-frequency modes, diminishing to four the order of the system. Fig. 10 shows the pole-zero plot from the complete and reduced AR models. The reduced system modes are encompassed in the dashed ellipse. In Fig. 11 we can see that the reduced model preserves the quality of the identification around the main frequency at 26.6Hz. The reduced AR model equation is given by (5).

$$G_W = \frac{0.0005}{(z^2 - 1.992z + 0.9986)(z^2 - 1.963z + 0.9729)} \tag{5}$$

B. Piezoelectric Model

Considering the high oscillations sensed after arriving at the stop points, the Y direction accelerometer was chosen to illustrate an example of piezoelectric dynamics identification. The selected operation conditions were: stop point Pos2, end-effector without charge and piezo-actuator A1 (Fig. 5). The procedure can be similarly recreated for all mentioned operation conditions, and it was experimentally verified that the piezo-actuator A1 excites very properly the flexible mode close to the first mode of the disturbance vibration in the Y direction.

The input control signal varies from -10V to 10V, being amplified to operate linearly from 0V to 400V on the piezo-actuators. Different kinds of input signals were experimented, the best results comming from a chirp signal with frequency ranging from 0 to 100Hz during 20 seconds. The Y acceleration outputs were registered at the sampling rate of 2kHz.

The input voltage and output acceleration values used for the identification can be seen in Fig. 12, after being filtered through a five order butterworth filter with 100 Hz cut-off frequency.

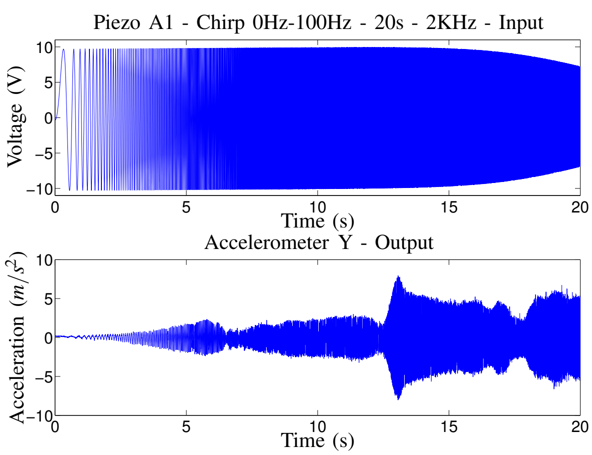

Fig. 12. Input (Piezo A1) - Output (Accel Y)

Fig. 13 shows a comparative between two ARMAX models, a N4SID model (Numerical algorithm for Subspace state space system IDentification) and the non-parametric validation data. We can notice that a model of order 32 was required for a good identification using ARMAX, while using N4SID with order 20 very good results were obtained.

Besides the smaller order employed for finding a good model, another advantage of N4SID consists in having less set-up parameters, as mentioned in section II-B. The ARMAX model structure demands as entry parameters the quadruplet (na,nb,nc,nk), where the elements correspond to the number of poles, number of zeros associated to the control input, number of zeros associated to the noise and number of delay instants to be considered. The parameters attributed for the ARMAX identification were (32,32,26,0).

Figs. 14 and 15 show that even small variations in these parameters can totally compromise the quality of the models.

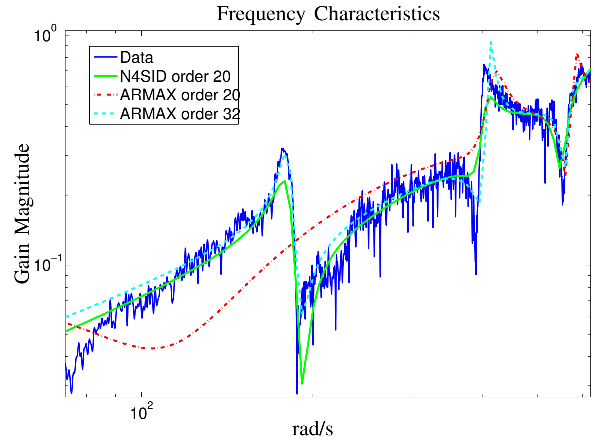

Fig. 13. Piezo A1 - Accel Y - Without Load - Models

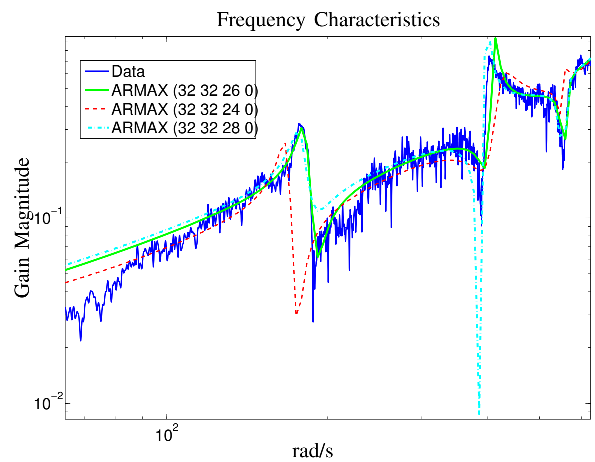

Fig. 14. Piezo A1 - Accel Y - Without Load - Models ARMAX (I)

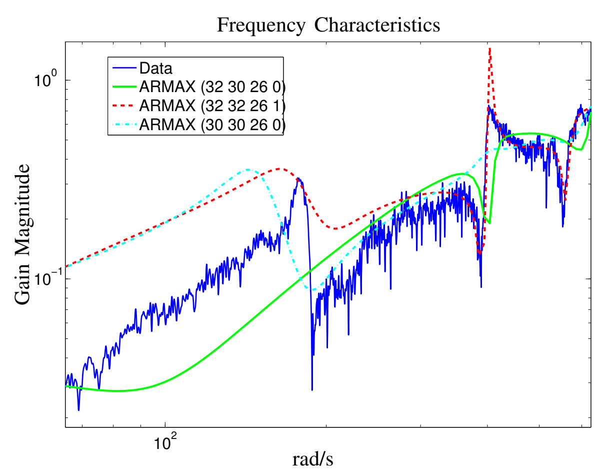

Fig. 15. Piezo A1 - Accel Y - Without Load - Models ARMAX (II)

In a similar way, variations were made around the unique entry parameter for the N4SID subspace identification technique. We can observe from Fig. 16 that good models were obtained. For the 18^{th} order model the correspondence to the non-parametric data was a little bit inferior, and for the 22^{th} order only very small improvements were found.

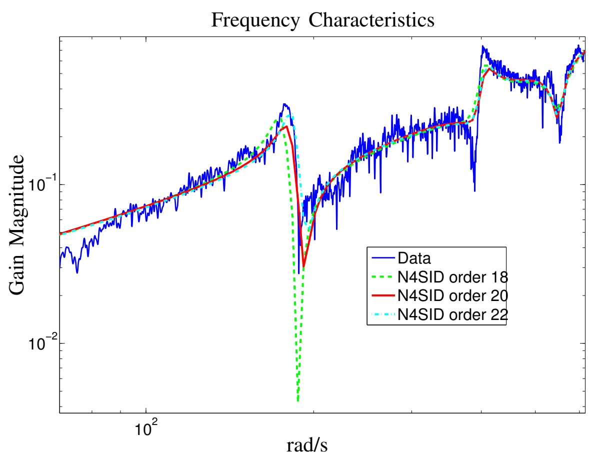

Fig. 16. Piezo A1 - Accel Y - Without Load - Models N4SID

In the same way the disturbance identified model was reduced, a reduction for the 20^{th} order N4SID model was performed. Eliminating the high frequency poles and zeros, we obtained a reduced 8^{th} order N4SID model, which was then filtered with a second order butterworth filter, with cut-off frequency at 100Hz, in order to minimize the dynamics ocurring out of the desired bandwidth of 100Hz, according to Fig. 17. This model, identified in terms of state-space matrices, is represented in (6) as a transfer function.

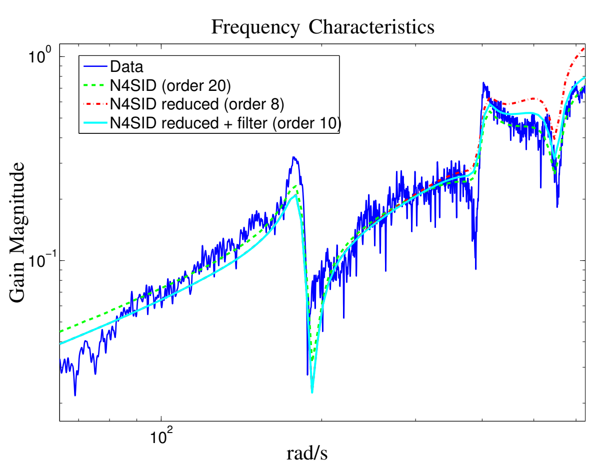

Fig. 17. Piezo A1 - Accel Y - Without Load - Reduced N4SID Model

$$G_U = \frac{\dfrac{-0.055(z-1.003)(z-1.15)(z^2-1.993z+1.002)}{(z+1)^2(z^2-1.947z+0.985)(z^2-1.914z+0.989)}}{\dfrac{(z^2-1.985z+0.993)(z^2-1.561z+0.641)}{(z^2-1.947z+0.988)(z^2-1.901z+0.976)(z^2-1.586z+0.97)}} \tag{6}$$

IV. CONCLUSION AND FUTURE WORKS

In this article, the identification of disturbance and piezoelectric dynamics for the parallel robot Par2 were carried on, based on two different strategies, namely ARMAX models and the N4SID subspace identification technique. The disturbance, considered as the vibration after the arrival of the end-effector at the stop points, is more intense in the Y direction, motivating therefore the selection of this direction as the one to be considered for the identified examples. The results obtained can be applied in a similar way to different operation conditions as charge, stop positions, different trajectories and selected piezo-actuators.

For the disturbance identification an AR model performed better than an ARMA model of the same order. The AR model was reduced to give a final disturbance model of order 4. In the case of the piezoelectric dynamics, the N4SID technique was able to identify a model of order 20 with a quality close to the 32^{th} order model obtained using the ARMAX stucture. Besides this advantage, the N4SID model has less set-up parameters than the ARMAX one. A redution of the N4SID model was performed, the resulting model filtered and a final order of 10 was obtained.

Now we have a model for the system and in the following we are going to test different control strategies on Par2. The idea is to control the piezoelectrical input voltages using the identified models to suppress the vibrations sensed by the accelerometers. The controllers to be designed, initially $\mathscr{H}_2$ and $\mathscr{H}_\infty$ controllers [4], shall be robust against variations in the operation conditions. Extensions to multivariable models, coupling different piezo-actuators and the three accelerometers will also be tackled.

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