HARDWARE IN THE LOOP AS A TOOL FOR THE DEVELOPMENT OF WASH MACHINE SUSPENSION

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Abstract. *During a traditional product or component development, the time and resources allocated for all project execution is generally scarce. In addition, the complexity and the non adherent results of some of the available modeling tools, render them inefficient in face of non-linearities and uncertainties. Focusing on accuracy and efficiency during a component development cycle, aiming at the right decisions at the right time, a technique known as hardware in the loop (HIL) has been widely applied. In general, this technique makes use the real physical subsystems (hardware) and the model (software) that represents the other parts of the electro-mechanical assembly. The present work presents an example of component development of a washing machine suspension using HIL method. This study aims at accessing the feasibility of using a closed-loop control system based on force and acceleration signals and an electrodynamic shaker as actuator, in a HIL approach where the hardware is a structural subsystem. The other study on going and presented here is the process of obtaining the state space matrices that are able to run in a Matlab/Simulink environment and how to derive the matrices from a multibody dynamic model built in ADAMS, both under a real-time framework. The process to translate the multibody model in a state space matrix, necessary for the real-time HIL simulation, will also be addressed.*

Keywords: *hardware in the loop, suspension, washing machine, dynamic substructuring.*

1. INTRODUCTION

The work of common washing machines include, in general, the following tree steps: washing, rising and spin drying. During the later, the basket of the washing machine spins up rotating and generating dynamic forces due the unbalance mass resulting from lopsided clothes inside the basket. Because of that, there is a common issue related with noise and vibration that have to be solved before those products achieve their customers. Thus, a careful project of a washing machine have to consider all parameters responsible to guarantee the adequate functionality of the product at the stage of spinning drying process to avoid costumers dissatisfactions and safety issues. The parameters that supports a better performance at the spinning cycle reducing its level of vibration have been studied since the early models of washing machines; LeBlanc (1914) proposes on his patent a balance ring filled with water in order to reduce the level of vibration when the rotating bodies achieves its maximum speed. A detailed review of the dynamic behavior of the top loads washing machines was conducted by Conrad and Soedel (1994).

According Chen and JuZhang (2010) the washing machine´s dynamic literature is separated into four areas; they are suspension, walk characteristics, dynamic balancing and clothes loading. One purpose of a simple modeling to identify the "walking" phenomenon on washing machines was done by Conrad and Soedel (1994). Difficulties to modeling some of the parameters as damping, joints and stiffness were studied by Koizumi *et. al* (2003); this work focused on obtaining experimentally the behavior of the suspensions and joints before refining and validating the model.

Recently, Yörükoglu and Altug (2009) developed a computational model of a horizontal axis washing machine using a computational model implemented on a commercial multibody system (MBS) environment; in this case, the authors also studied the nonlinear components behavior, as balance ring and suspension, using an experimental approach before adjusting and validating the model.

The use of HIL techniques in the development of washing machines dynamic studies seems new, but have been seen in recent publications. Mendes (2012) apply the HIL technique to assess the dynamic behavior of two non-linear mechanical system and to verify the performance of the technique in these cases; firstly the author evaluated a pre tensioned gear subjected to dynamic contacts and impacts which are difficult to be modeled. His second study focused on elastomeric torsional vibration damper, used in internal combustion engines, which has non-linear material properties that depend on the rubber temperature. Conrad (1994) proposed the application of HIL as a support tool in

the development process of an artificial robotic hand. His efforts were concentrated on the development of a computational and experimental environment which would work simultaneously. Montazeri-Gh *et al*. (2012) presented an actuator-based HIL simulation for testing of a jet engine fuel control unit (FCU). In this approach the FCU operates dynamically as the hardware in connection with an integrated flight and propulsion numerical simulation.

Therefore, the present work uses HIL in a real time simulation and experiments in order to link a trusty model of just a part of the washing machine and a real mechanical component (suspension). The motivation behind this study is the fact that suspension elements of washing machines usually present nonlinear behavior and uncertainties, which leads to inaccurate models. Using this technique, the main objective of the physical test is supply the force signal information to the subsystem model, which than requires the hardware to move. With that, it would be possible to develop new concepts based on existing parts and validate the model in real time.

2. THEORY

This present study intends to investigate the feasibility of the use of a standard test bench involving the HIL methods in order to identify the dynamic behavior of the suspension component of washing machines. In general, HIL simulation enables the operation and testing of real components; it has being done using the actual component of a system along with virtual computer-based simulation models of the rest of the system in real time. Montazeri-Gh *et al*. (2012) mentioned that in a typical HIL test, the hardware component consists of a box of electronic components which can communicate with the software models via electric signals exchanged using a data acquisition card. Further, Montazeri-Gh *et al*. (2012) also mentioned that recent works have been attracted to test mechanical components calling this kind of simulation as actuator-based HIL or dynamic substructuring; the author also mentioned that the actuator-based HIL has significant power flows between the real hardware and simulation that makes it more challenging. As a response to the actuator-based HIL challenge, Gawthrop *et al*. (2008) show the role of the *transfer system* that is responsible to link the software and the hardware subsystem in a actuator-based HIL environment. The transfer system typically comprises sensors and actuators and the dynamic effects of these components need to be eliminated to give accurate results. Gawthrop *et al*. (2008) show that an emulator-based control could solve both problems, of stability and fidelity, caused by the unwanted dynamic behavior of the transfer system (sensors and actuators).

2.1 State of the use

Through the search of recent publications (Nygårds and Berbyuk, 2012; Chen and JuZhang, 2010.; Conrad and Soedel, 1994; Papadopoulos and Papadimitriou, 2011) which also bring experience from engineers who developed washing machines, it is possible to conclude that there is a common approach on the development of washing machine components in terms of noise and vibration, which is related with two steps: modeling and experiments. The modeling focus on linear parameters and experiments help to identify and quantify nonlinearities and attempts to refine the model with its results. The following sections will describe with some details these two steps focusing on the suspension component.

2.1.1 Modeling of washing machine

A wash machine is a mechanical system comprised of multiple bodies developing large relative displacements and interacting with each other by means of joints and forces. The modeling of such multi-body systems is not a trivial task and solving the resulting nonlinear differential equations by hand is usually not feasible. According to Costa (1984) the first computer codes intended to automate the task of modeling and solving multi-body systems appeared in the 1960's in the aerospace research area, but by the 1970's specific codes developed for the automotive and machinery industries have already arisen (Sharp, 1994).

Nowadays, one of the most widespread general purpose multi-body simulation codes is ADAMS, which stands for "Automatic Analysis of Mechanical Systems". ADAMS uses a Lagrange formulation to describe the motion equation for each body separately. Afterwards the constraints equations are included. These motion equations are then transformed into a set of first order differential equations. Thus each body could be represented by twelve equations, but three additional equations are added as the angular momenta and are also considered as state variables. The resulting number of equations is, therefore, fifteen times the number of bodies plus the constraint equations. This system of non linear differential and algebraic equations is assembled in a matrix format suitable to the application of numeric integration techniques. The ADAMS main integration predictor-corrector algorithm is based on the Gear's method, though some alternative algorithms are also available (ADAMS/Solver Primer, 2004).

Although ADAMS can make it possible and relatively easy to generate and solve the equations of motion of multi-body systems, there are a number of details that still make the work of building a washing machine multi-body model a quite complex job. For example, ADAMS depends on the user to specify the expressions for accurately describing the suspension and balance ring forces. Suspension damping is often a non linear function of displacement and frequency, and can also vary with temperature and time (wearing).

Balance ring behavior is driven by the interaction of fluid dynamics and rotordynamics phenomena, so some thought has to be put on how to build a computationally feasible and still accurate force function. Finally, after defining suitable models for suspension and balance ring forces it is generally necessary to identify and validate the parameters for their force functions through a number of experiments with physical prototypes. We have used suspension and balance ring as examples because they have the most strong impact on the model behavior, but a number of other forces like joint frictions and motor torques need to be modeled as well.

2.1.2 Experimental analysis of the suspension

The washing machines suspension comprises a damper and spring integrated into one component. There are several kinds of suspension that in general could be divided into the product application (top load or front load washing machines) and their mechanism of damping that is divided into viscous or friction. The mechanism of damping has a high dependency on the suspension material and its style, where it could be the friction dampers are manufacture by foam or sponges with less quantity of grease (very common on front load) and viscous damper that makes use a kind of piston with a cup, a seal and higher quantities of grease. All those kind of suspensions have many challenges and particularities about how to obtain adherent results with mathematical models due nonlinear behavior. Because of that, most part of the studies, Nygårds and Berbyuk (2012) for example, have treated this challenge by using experiments to identify the suspension parameters at some given conditions. As examples of the state of the use, this section will describe the equations and parameter identification of a suspension type.

Firstly, x is assumed as the degree of freedom of interest for the suspension. The most common model used as starting point considers the damper as a friction with just coulomb friction, as e given in (1).

$$F(t) = F_0 . sign(\dot{x}(t)) \tag{1}$$

where F_0 is the friction force and $\dot{x}$ is the relative velocity of the damper in its effective direction. As the theory of damping includes the dependency of the velocity of the excitation, a viscous damping also could be added.

$$F(t) = F_0 . sign(\dot{x}(t)) + C \dot{x}(t) \tag{2}$$

where C is the coefficient of viscous damping. In order to try to refine the behavior of the friction force portion; Berger (2002) studied the idea of smoothening the sharp transition of the velocity direction with an *arctan* function changing the Eq. (2) into:

$$F(t) = F_0 . \arctan(\dot{x}(t)) + C \dot{x}(t) \tag{3}$$

Adding the stiffness effect in the suspension model, finally we have the equation to describe the damping force of a washing machine suspension given the operation condition $x(t)$.

$$F(t) = F_0 . \arctan(\dot{x}(t)) + C \dot{x}(t) + K x(t) \tag{4}$$

Where K is the stiffness portion, which is mainly given by the spring in the suspension design. If the pre-load on the suspension, due to the washing machine weight, would be considered, a new portion F_w should be added to Eq. (4) which represents the weight static force, rendering:

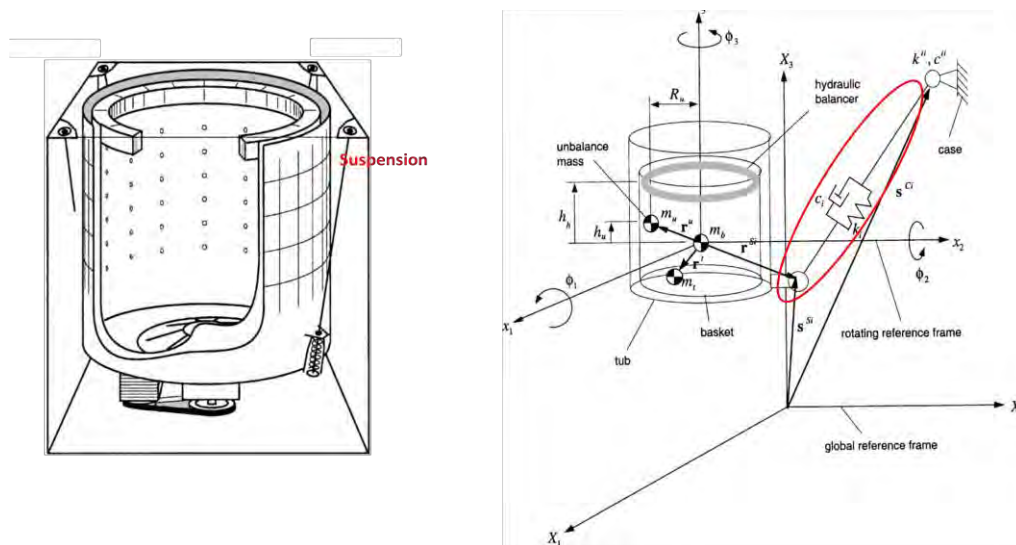$$F(t) = F_w + F_0 . \arctan(\dot{x}(t)) + C \dot{x}(t) + K x(t) \tag{5}$$

Figure 1: Top load suspension style and its modeling (based on Bae *et al.*, 2002).

The constants F_w, F_0, C and K are obtained xperimentaly. In order to obtained these parameters experimentally, the system undergoes a stationary sinoisodal input represented by $x(t)$ and its derivatives. In order to obtained the damper properties it is necessary to make use of a test bench. Nygårds and Berbyuk (2012) use a comercial rig (Fig. 2) to record the signals corresponding to $F(t)$ and $x(t)$ using a force transducer and a position sensor, respectively.
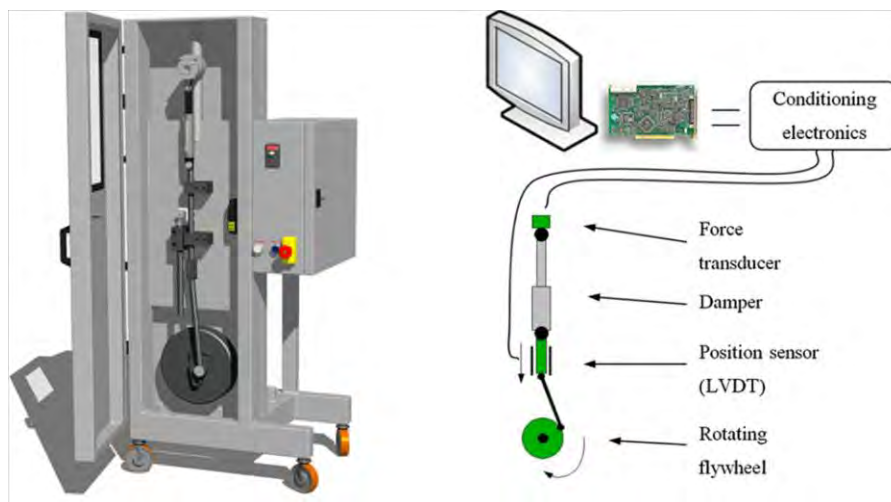

Figure 2: Bench test to indentify suspension parameters (Nygårds and Berbyuk, 2012)

As a results of the damper characterization, the curves of displacement and force and its fits with the mathematical models presented on (5) gives the constant parameters previously mentioned. In order to optimize the fit of the curves Nygårds and Berbyuk (2012) propose three different algorithms based on a Matlab toolbox which approaches the problem as an optimization function. As a result of the optimization method, the authors could compare the three different syptimization techniques through the accumulative error of those. Figure 3 shows typical curves (measured and simulated) for force VS time and force VS displacement for such kind of suspension.
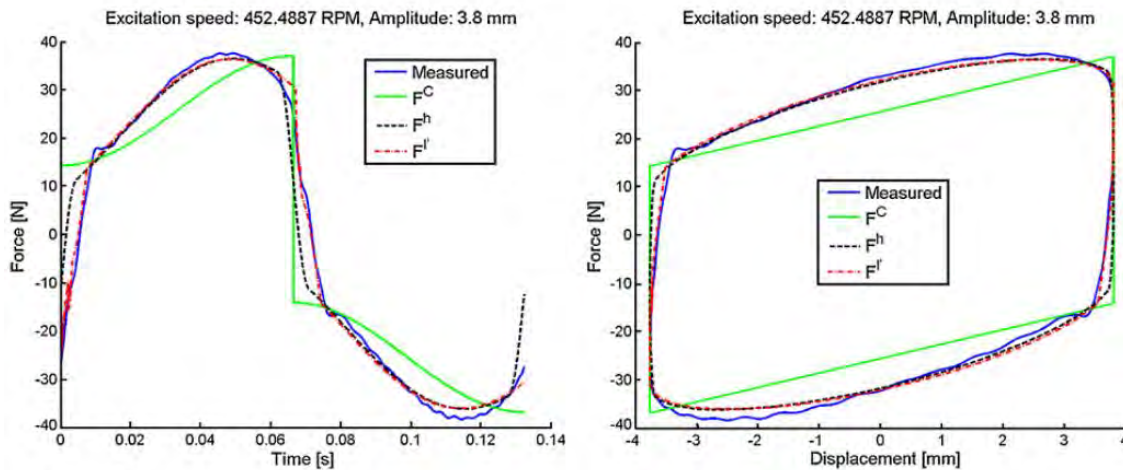
Figure 3: Comparison between measured data and mathematical model (Nygårds and Berbyuk, 2012).

According the figures its is clear that the methods F^h and $F^{l'}$ are more accurate and fits better with the raw data than F^C, in order to refine and choose of the best method an error accumulative value also could be compared.

3. PRELIMINARY RESULTS

The first objective of the present work is to validate the HIL technique to identify the behavior of a known type of washing machine suspension. At this point, the proposed HIL scheme follows the dynamic substructuring principle, where the hardware is the suspension and the software is a numerical model of the washing machine without suspension. The suspension studied has a known nonlinearity mechanism of damping because of its concept that makes use of a friction, viscous and pump damping. Because of that, many attempts in modeling its behavior have been unsuccessful. This kind of component has a cup where fits up a seal that slides inside the cup in order to dissipate the energy through the friction between them and via the pumping of the air from the cup (piston effect). As the first step of the work is to validate the suspension results as a hardware for the HIL scheme, this stage will consider the washing machine model as simple as possible to avoid misunderstandings regarding the own suspension. This methodology try to follow the KISS principle (*keep it simple and sequential*); this methodology states that most system work best if they are kept simple rather than made complex; therefore simplicity should be a key goal in design and unnecessary complexity should be avoided (Leonard and Johnson, 1995).

The work will be divided into three stages focusing on the understandings regarding the effectiveness of the HIL simulation. Because of that, a simple model (software) must be built and validated in an experimental bench trying to avoid or separate the responses that does not belong to the suspension (hardware). For this first assessment, the simple model to be considered is a mass spring model with one degree of freedom. In the concept of the hardware in the loop of the suspension, this model is associated with the washing machine without damping mechanism (pure free-free mass) that could be presented as the model on figure 4 (a).
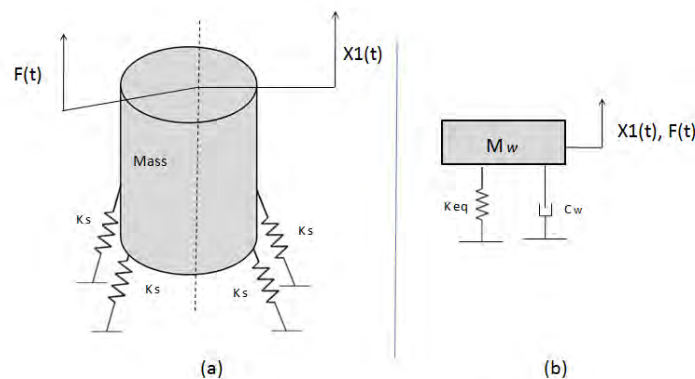

Figure 4: Simple model for the software (washing machine) to validate the HIL methodology

Bringing this system to an experimental bench test the model suppose to be change from Fig. 4 (a) to (b). Then it will be possible to validate this bench test through comparison between responses from model and the bench. In order to

obtaine the differential equations of this system, a transfer function using the Laplace transform is one option. This system of equations using transfer function in the Laplace domain was chosen because of the functionality with the Simulink software that would be necessary to conclude the HIL process. Through the Newtonian approach the movement equation of the system (b) is:

$$m_w \ddot{x}_2(t) + C_w \dot{x}_2(t) + K_{eq} x_2(t) = F(t)$$

(6)

Taking the Laplace transform and ignoring the initial conditions:

$$\left[m_w s^2 + C_w s + K_{eq} \right] x_2(s) = F(s)$$

(7)

In order to solve this system using Simulink, one possible way is to put it in a diagram block considering the idea about transfer function. In this case the ratio of the Laplace transform of the output $x_2(s)$ by the Laplace transform of the input $F(s)$ is the transfer function $G(s)$. Thus, the transfer function of the Eq. (7) is described in (8) and represents the block called *Washing machine* in Fig. 5.

$$G(s) = \frac{x_2(s)}{F(s)} = \frac{\dfrac{1}{m_w}}{s^2 + \dfrac{C_{eq}}{m_w} s + \dfrac{K_{eq}}{m_w}}$$

(8)

Considering the application of the system in a test bench, the source of the forces have to be an actuator that on this study is suppose to be a shaker. In order to model this interface it is necessary to know the interaction equation between the displacement of the washing machine model and the forces to be applied in the hardware (suspension). This approach is treated in Oliveira (2003) where an electro-mechanical system is proposed to solve the outputs considering the shaker actuator and a displacement as the input. This equation corresponds to a SISO (single input and single output) system and is given by the follow differential equation:

$$m_a \ddot{x}_1(t) + C_1 \dot{x}_1(t) + K_1 x_1(t) = Kf\, i(t)$$

(9)

Where Kf is the constant of the current force of the shaker and m_a, C_1 and K_1 are the mechanical properties of the shaker.

Again, taking the Laplace transform:

$$\frac{m_a s^2 x_1(s) + C_1 s x_1(s) + K_1 x_1(s)}{Kf} = i(s)$$

(10)

And again, using the transfer function approach, the block diagram that represents it is called *Model electro-mechanic* and it is showed in Fig. 5:

$$G(s) = \frac{x_1(s)}{i(s)} = \frac{K_f}{m_a s^2 + C_1 s + K_1}$$

(11)

Using the following values to run first assessment of a washing machine model (showed on Fig. 4) and the shaker, it is possible to evaluate the bode diagrams of both system separately. Through the frequency response function and showed in Fig. 6, it is possible to get information as the natural frequency, level of damping and degree of freedom of each system. Hereafter, these systems will be considered as the software of the proposed HIL simulation, so it is strongly recommended to know these properties in a early stage.

In order to assure that the proposed HIL is adequate in terms of parameters values and bench building feasibility, it is necessary to consider the hardware as a software, *i.e.*, a model; as this hardware is a suspension model it also could be mathematically represented as a transfer function. A previous study taking a hardware as a computational model would help the validation and stability assessment of the control that is necessary to run the physical experiment with the hardware.

Table 1: Washing machine and shaker parameters

Washing machine model

M_w =	22 [kg]	C_{eq} =	0 [N.m/s]	K_{eq} =	6000 [N/m]

Shaker

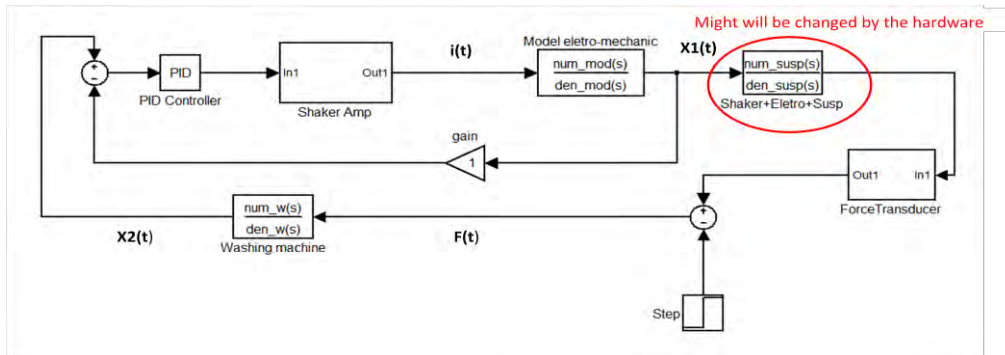|							
m_a =	0.45 [kg]	C_1 =	110 [N.m/s]	K_1 =	35000 [N/m]	K_f =	10000[N/A]

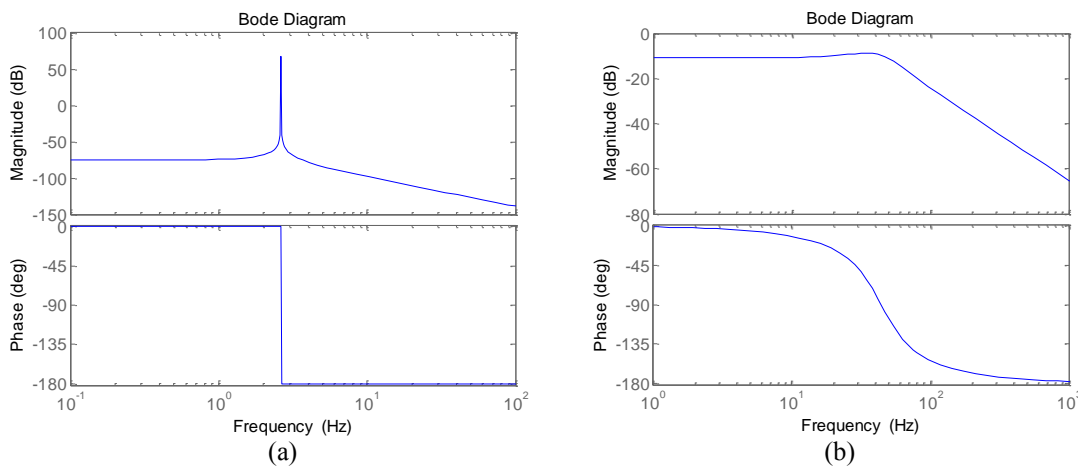Figure 5: Simulink diagram to solve the equations

Figure 6: Bode diagram of the blocks (a) *Washing machine* and (b) *Model electro-mechanic*

Placing the suspension on the computional model is equivalent to add the suspension together with the springs K_S in Fig. 4. Adding the suspension on this system requires taking into consideration that it will be replaced later by a hardware, so it is necessary to model an adjustable system. As a HIL simulation makes use of a system that have to be linked with an experimental environment, all system have to be modeled on Simulink platform that is capable to link computational and experiments using a real time board.

By switching the suspension block called *"Shaker+Electro+Susp"* on Simulink diagram, it is possible to verify the fidelity of the model by analyzing its step response. Since there is no kind of dissipation mechanism (see also on Fig. 5a) when the suspension block is switched off, the attenuation on $X_2(t)$ is not present. Further verification, as the analyses of the frequency response functions, also help validating the work done until here.

Comparing the signals of the displacement X_1 and X_2 (with respect to Fig. 5) and X_1 (Fig. 4) and knowing of the particularities of these signals, it is intuitive to conclude that those signals should be the same. Therefore, in order to validate the process, it is required that those signals are compared. That way it would also be possible to have a first assessment of the closed loop system stability.

If simulations are carried out using a similar block diagram as in Fig. 5, but without using the PID controller (considering an ideal force source), signals X_1 and X_2 will not match, as shown in Fig. 8(a). This divergence is explained by the interference of the shaker dynamics. Thus, in order to guarantee the signals similarity, hence the procedure validity, the PID control is used. By adjusting the control gains through a manual fine tuning, it was possible to reach an acceptable level of similarity between those signals, as showed in Fig. 8(b). Therefore, the control system

guaranties the similarity between X_1 and X_2 which will allow the final HIL scheme to assure that the input on the hardware is adequate.
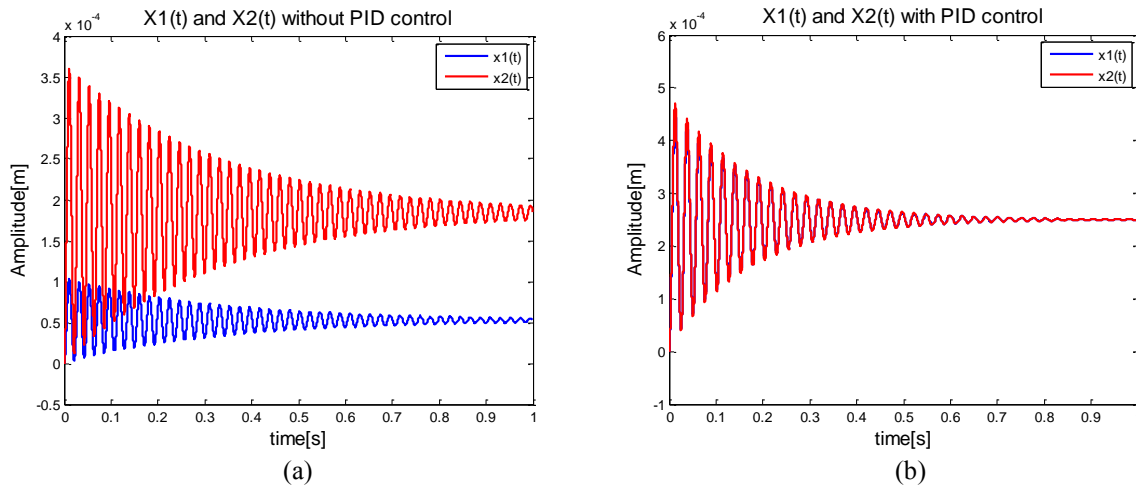

Figure 8: Displacements X1 and X2 considering the use of PID control.

Considering the next steps of this work the main differences of the current state and the final HIL validation is on the exchange of the block *Shaker+Electro+Susp* from a preliminary model to a real test bench with actuators and sensors. In this case (see Fig.9), the actuators (together with the PID controller) will work as a displacement input to the real suspension and the sensor (load cell) will measure the force data and supply it to the computational model of the washing machine. Another important difference from this results to the actual test bench is that the washing machine model, that up till now, has been considered as a single DoF system will be replaced by a multi-DoF system resulting from a MBS model reduction. The multi-body model in Adams corresponds to a set of highly complex non-linear differential equations, so that knowing its literal (symbolic) form would provide very little insight on the system behavior. Besides that, the model mathematical representation in Adams is not accessible to the user, since it is in a matrix numerical format suitable just for numerical integration through the code internal algorithms. However, Adams provides a feature that allows exporting a linear representation of the model in state space matrix format. So, it is possible to import to Simulink and, hopefully, run it in real-time on the prototyping DSP board.
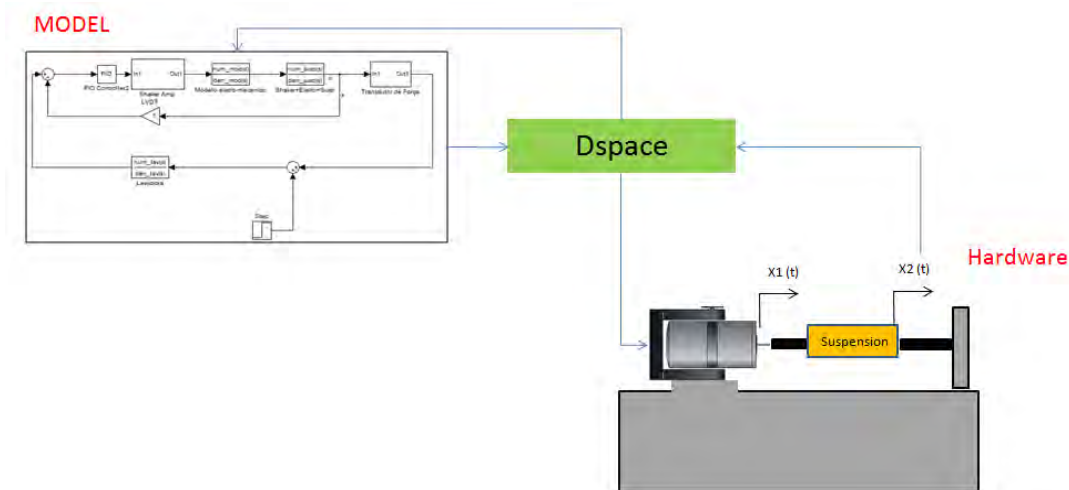

Figure 9: Hardware in the Loop for suspension washing machine

4. CONCLUSION AND FUTURE WORK

The development of washing machine suspension or other similar components has many manners of using different tools and approaches. All techniques show benefits and limitation and they could be acceptable depending on the project targets. The level of project details and objectives also drive the development. The present work proposes a

technique that could help the development of washing machine suspensions, trying to cover different concepts and application through a robust hybrid modeling technique. Comparing the literature review and following the development under the washing machine producers, the opportunity to improve this kind of development was identified with HIL techniques. It was observed that the modeling difficulties of some suspension types specially because of their hard proximity with mathematical theories, can be aided by the use of dynamic substructuring techniques such as the proposed HIL approach.

The current status of this work comprehends the sensors and actuator selection as well as some specific subsystem design and manufacturing. The first system to be used is a simple 1 DoF system which will be connected to the actual washing machine suspension. That way, the proposed scheme can be validades without using a more complicated model. In the next step the real MBS washing machine model would be used and confronted with a full washing machine experiment.

5. ACKNOWLEDGEMENTS

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