HYBRID SYSTEM NONLINEARITIES USED IN MODELING MECHATRONIC APPLICATIONS

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Abstract: *The present paper is a short review of some of the concepts, procedures and achieved results, oriented toward the modeling of complex, large installations, known under the name of HYPAS. Physical phenomena involved in hydraulic, pneumatic, mechanic and electric systems are depicted by mathematical models (MM) with static and dynamic nonlinearities (NL). This means that, when building large installations, the MM provide multiple NL. They should be completely known in order for the controller to be designed appropriately enough to provide desired behavior, while complying with economical conditions. To facilitate the automatic mathematical model generation, a library with multilayer models was created and are made available. This approach was necessary because the MATLAB® library provides only few general NL. In cases where applicable, neuro-fuzzy techniques were employed for modeling of NL. The paper presents some of the most important results, accompanied by their MATLAB Simulink® representation.*

Key words: *hybrid systems, nonlinear systems, modeling, simulation, libraries, HYPAS.*

1. INTRODUCTION

Most mathematical models of pneumatic, hydraulic and electric systems are nonlinear. Nonlinear differential equations describe their behavior and this also applies to hybrid systems, *e.g.* servo systems. Principle of superposition does not apply for these systems [3, 18, 19]. Among the nonlinear systems, the hydraulic ones are, maybe, the most nonlinear. Various mechanical, hydraulic and electrical phenomena are contributing to this situation. Nonlinearities can be statistical, dynamical, structural or time dependent. They are responsible for critical situations occurring during operation. Also they are hindering theoretical investigations and the numerical simulations. To simulate a hydraulic drive system, the critical problem is to possess an accurate mathematical model. Thus, the modeling of nonlinearities is a *sine qua non* task in order to accurately describe dynamic processes [1, 2, 17].

Some of these NL along with the respective mathematical equations for analytical models are given in Table 1. We can see from this table that many systems have hysteretic behavior. Other frequent differential equation models have solutions given as nonlinear piecewise monotonic functions.

In controlled systems, hysteresis can have a series of undesirable effects, including loss of robust stability, limit cycles and steady-state error, to name but a few [4–8]. The major hurdles control engineers must overcome when faced with hysteretic nonlinearities are obtaining an accurate model of the hysteretic behavior and finding corresponding means of analysis and design capable of dealing with nonlinear and non-single-valued behavior.

MATLAB/Simulink [20] is a standard tool for simulation. Simulink uses numerical solvers in order to simulate systems given by differential equations. The actual toolbox, entitled "Discontinuities" include many of the most common discontinuities used in practice. However, some of the discontinuities that are particularly interesting in hydraulics and electrics are nonlinear and they are not included in this toolbox. Moreover, some of them are very complicated to implement. In case we need some of these nonlinearities to be in the same diagram or we frequently use a particular set of them, a toolbox contains all possibilities is very useful.

More complex phenomena, such as friction characteristics, must be carefully analyzed case by case. The modeling environment must deal with these problems in special ways, since they strongly influence the numerical behavior of the underlying differential equation solver [9, 10, 16]. Simulink does that for discontinuities from its library. Using these discontinuities and the other modules from existent toolboxes we can develop a new toolbox that includes the proposed set of nonlinearities.

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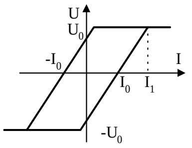
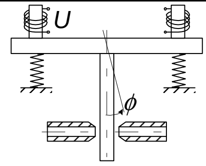
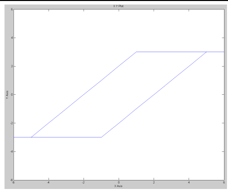
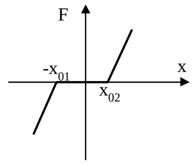
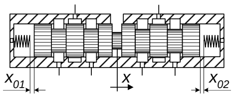
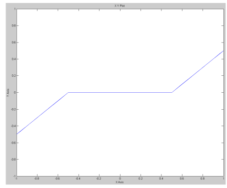
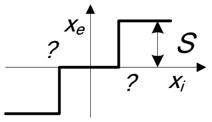
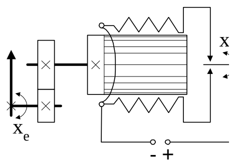
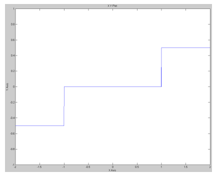
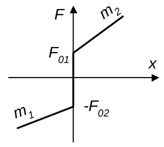
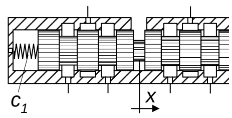
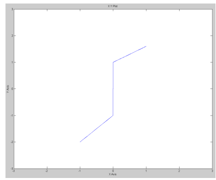
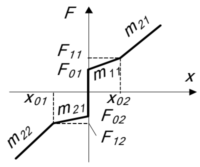
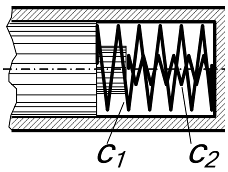
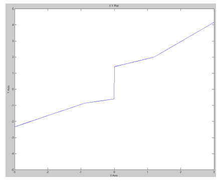
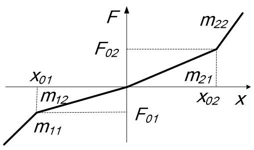
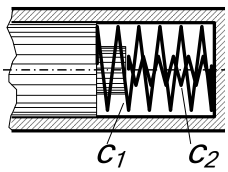
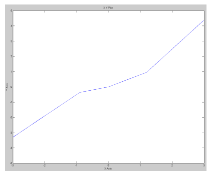
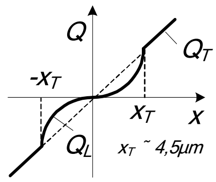
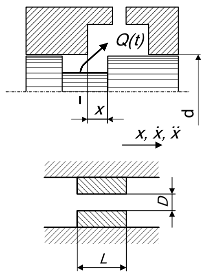
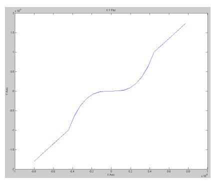
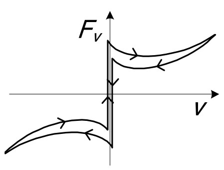
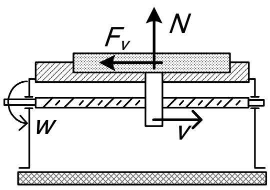
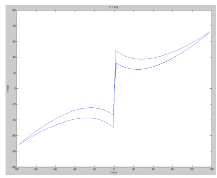
Table 1

Some of the studied NL, described with graph, mechanical example, mathematical function and Matlab® figure

Graphical representation	Mechanical representation	Mathematical expression	Matlab® figure
 a. HYSTERESIS		$U = I - I_0,\quad \frac{dI}{dt} > 0$ $U = I + I_0,\quad \frac{dI}{dt} < 0$ $\frac{dU}{dI} = 0,\quad \lvert U - I\rvert < I_0$	
 b.INSENSIBILITY ZONE 1st order		$F = \begin{cases} 0 & x \in [-x_{01}, x_{02}] \\ mx - F_0 & x > x_{02} \\ mx + F_0 & x < -x_{01} \end{cases}$	
 c. INSENSIBILITY ZONE 2nd order		$x_e = \begin{cases} 0, & \lvert x_i\rvert < \eta \\ s, & x_i \geq \eta \\ -s, & x_i \leq -\eta \end{cases}$	
 d. DOUBE SLOPE		$F = \begin{cases} 0, & x = 0 \\ F_{01} + m_2 x, & x > 0 \\ -F_{02} - m_1 x, & x < \end{cases}$	
 e. TRIMODULAR		$F = \begin{cases} c_1 x, & x < x_{02} \\ c_1 x_{02} + (c_1 + c_2)x, & x > x_{02} \end{cases}$	
 f. PIECEWISE 4		$F = \begin{cases} m_{11}x + m_{12}x_{01} - m_{11}x_0 & x < x_{01} \\ m_{12}x & x_{01} \leq x \leq 0 \\ m_{21}x & 0 < x \leq x_{02} \\ m_{22}x + m_{21}x_0 - m_{22}x_{02} & x > x_{02} \end{cases}$	
 g. LAMINAR and TURBULENT FLOW		$Q_L = \frac{4\delta^2}{\mu}\pi d x^3 \Delta p \quad \delta = 0.136$ $\nu = 30 \cdot 10^{-6}\,[m^2 \cdot s^{-1}]\ \rho = 820\,[kg/m^3]$ $x_T = \frac{\nu R_{ecr}}{2\alpha_{Dcr}\sqrt{(2/\rho)\Delta p}} = 4.446\,[\mu m]$ $Q_T = \alpha_D \pi d \sqrt{2/\rho}\,\sqrt{\Delta p}$ $\alpha_{Dcr} = \pi/(\pi + 2) = 0.611$	
 h. VISCOUS FRICTION with HYSTERESIS		$F_N \cong d\dot{x};\ d = \arctan\alpha$ $F_{col} = c_{fc}\frac{\dot{x}}{x}\quad F_N = \begin{cases} a_5\dot{x}^5 + a_4\dot{x}^4 + \ldots \\ + a_1\dot{x} + a_0, \dot{x} > 0 \\ b_5\dot{x}^5 + b_4\dot{x}^4 + \ldots \\ + b_1\dot{x} + b_0, \dot{x} > 0 \end{cases}$	

More complex phenomena, such as friction characteristics, must be carefully analyzed case by case. The modeling environment must deal with these problems in special ways, since they strongly influence the numerical behavior of the underlying differential equation solver [9, 10, 16]. Simulink does that for discontinuities from its library. Using these discontinuities and the other modules from existent toolboxes we can develop a new toolbox that includes the proposed set of nonlinearities.

2. MODELING STATIC AND DYNAMIC NONLINEARITIES

We study two types of nonlinearities: static nonlinearities and dynamic nonlinearities. A static model doesn't take into account the time, it is a simple mapping of the input to an output. Static models are usually represented by analytic formulas that map the input to an output, using often the word if in order to select different singularity or angular points. The dynamic model depends both on the input and the time. Dynamic models are usually implemented by difference equation or differential equations [11 – 14].

Modeling by differential equation has some disadvantages. In many cases, this modeling cannot capture the exact sense of the physical phenomena. In other cases, the nonlinearities of step (staircase) type are difficult to be catch in a differential equations modeling.

MATLAB/Simulink has a library of static nonlinearities. However, many of nonlinearities in mechatronic systems are not included or are difficult to be modeled using simple blocs from this library. In the next sections we propose a custom library implemented in Simulink in order to overcome this problem.

3. THE LIBRARY OF NONLINEARITIES

Note that all the new nonlinearities except the hysteretic ones should implement a behavior very similar with the discontinuities already present in the Simulink toolbox. Next, we present all the blocks implemented in the library *NonLinMechatronics* (Fig. 1).

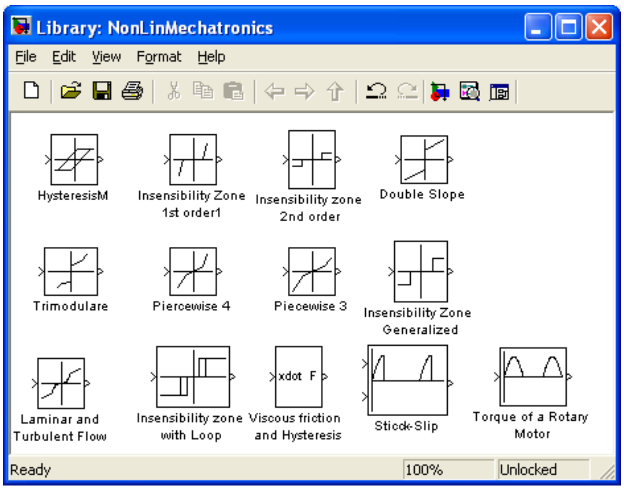


Fig. 1. The library of nonlinearities [C].

All the blocks have an icon drawn according to the function represented and the input parameters. The blocks are implemented as subsystems with mask. The mask is made according to specification from MATLAB®/Simulink®.

All the blocks are built using elementary Simulink® modules from the standard library. In order to optimize nonlinearities, each one is treated separately, using particular optimization and adequate methods.

An example is the NL Viscous Friction Hysteresis. The block requires reading the coefficients for both curves, as described in Table 1. They must be present in the MATLAB workspace, having predefined names.

The coefficients can be obtained using polyfit function from MATLAB or in a Simulink scheme using the least square polynomial fit block Polyfit from the Math Functions / Polynomial Functions toolbox.

All the other twelve blocks are implemented and tested before prior to inclusion in the library. In order to work with this library, it must be loaded as a Simulink library in the MATLAB environment.

4. A GENERAL METHOD TO CONSTRUCT PIECE WISE NONLINEARITIES USING NEURO-FUZZY APPROACHES

In general, neural networks cannot match nonlinear systems exactly. The identification procedure applied to any nonlinear (or linear) system approximate better or worse the plant that exhibits the nonlinear behavior.

In order to use ANFIS (Adaptive Neural Fuzzy Inference System) for nonlinear system identification, the first thing we need to do is to select the input variables. Let us denote by y the output and u the input. In the case of a dynamic system (recurrent ANFIS), we can select the best input candidate from either of following two sets, $Y = \{y(k-1), y(k-2),\ldots, y(k-n)\}$ and $U = \{u(k-1), u(k-2), \ldots u(k-m)\}$.

Few examples are presented below. An interesting nonlinearity is Laminar and Turbulent Flow (LT). The output structure file is *fismatLTF.fis*, ANFIS has two inputs and one output: $u(k-1)$, $u(k)$ and $y(k)$. The membership functions are Gaussian, 5 membership functions for the input variable, the number of iterations in the training stage is 400. The training data set has 200 samples and the test data set has 200 samples. The R_a = 0.02469 in the test stage, *an excellent approximation* of the output target (Fig. 2).

It is known that ANFIS can identify an nonlinear plant that have a hysteresis functionality if we provide at input of ANFIS structure, in the case of friction, e.g. the displacement $x(t)$ and the velocity $v(t) = \dot{x}(t)$. In discrete form, we can have for inputs, e.g. $x(k)$, $x(k-1)$, and $v(k)$ and for output $y(k)$ (Figs. 3 and 4).

Some of the nonlinearities refer as time-dependent function (Torque of a Rotary Motor (TRM) and Stick-Slip (SS) (Figs. 5, 6 and 7). This implementations require a different approach in modeling and implementation. The model act as input output mapping function dependent of time.

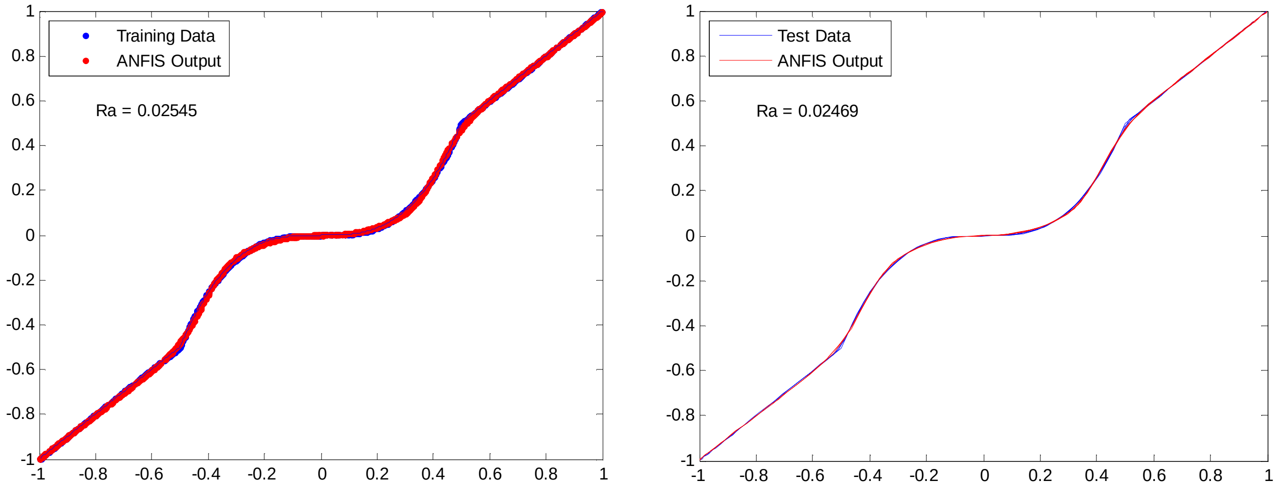


Fig. 2. Experimental results for learning phase (left) and test stage (right), LTF.

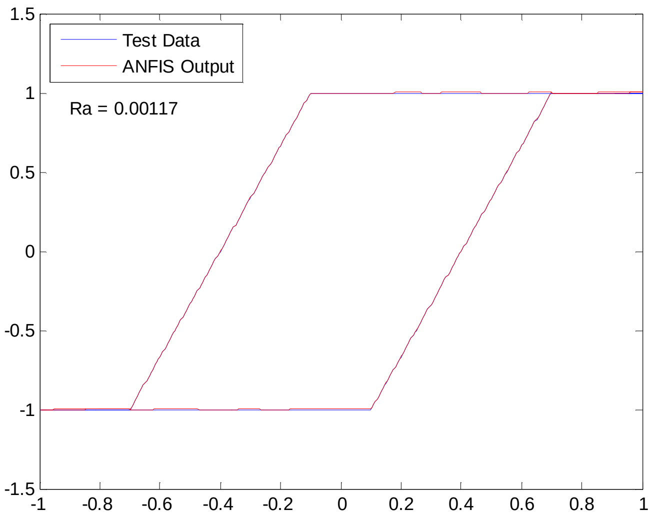


Fig. 3. Experimental results for test stage for Hz nonlinearity.

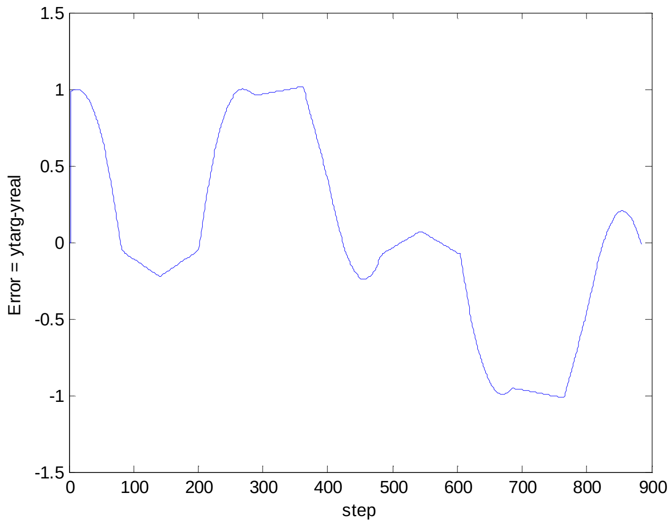


Fig. 4. Residual Error $R_e(k) = \ y - \hat{y}$ in the test stage for Hz nonlinearity, free evolution.

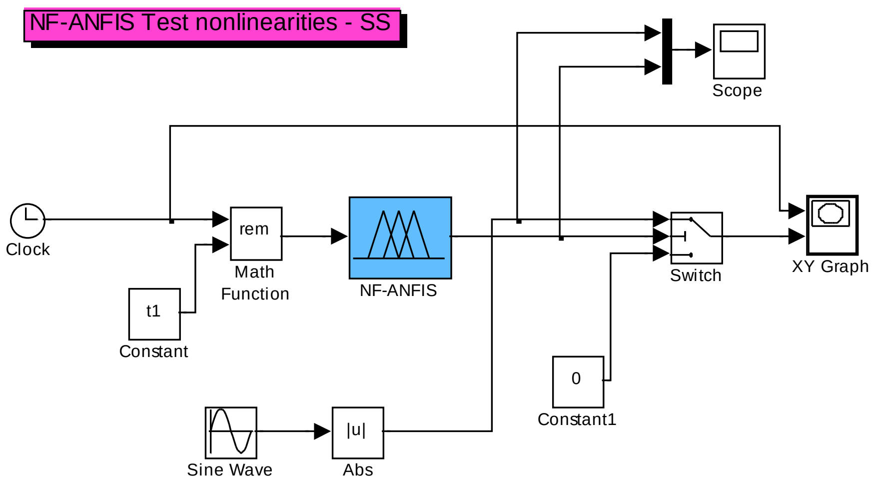


Fig. 5. Experimental test schema implemented in SIMULINK (SS).

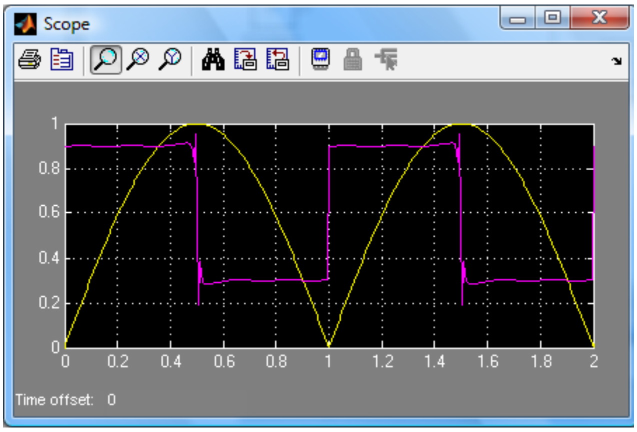


Fig. 6. Experimental results from SIMULINK schema, the input and the ANFIS output.

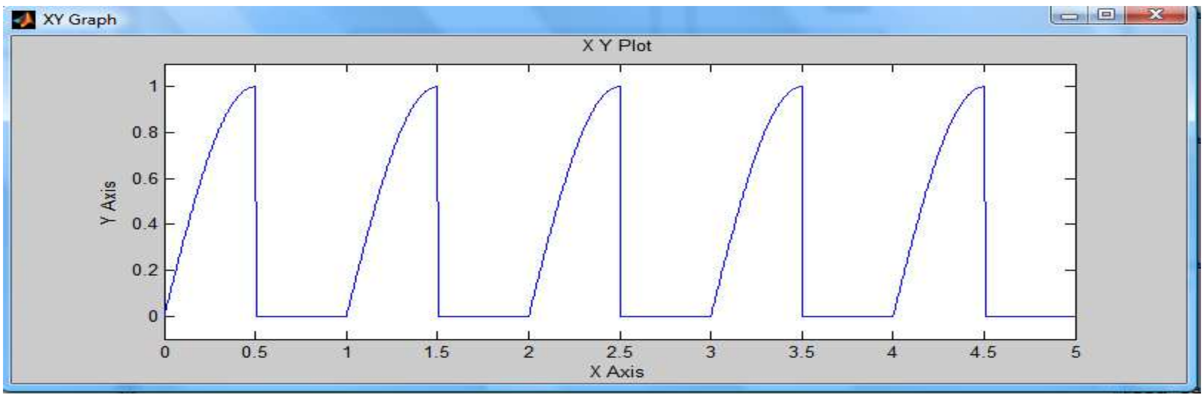


Fig. 7. Experimental results from SIMULINK schema, the output of test.

5. CONCLUSIONS

We proposed a new library implemented for Simulink applications for mathematical modeling of pneumatic, hydraulic and electric systems. There are 13 systems in this library that provide a general test diagram for each nonlinearity.

A general method for constructing piecewise nonlinearities is also proposed. The advantages and disadvantages of the proposed method are discussed.

Finally, a novel approach to modeling piecewise nonlinearities using neuro-fuzzy systems is proposed.

In the future, we plan to append other nonlinearities to this library. Also, we plan to develop a recurrent neuro-fuzzy structure, implemented in Simulink that can be used for complex nonlinearities, e.g. hysteresis form.

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