NON-LINEAR SIGNAL ANALYSIS APPLIED TO SURFACE WEAR CONDITION MONITORING IN
RECIPROCATING SLIDING TESTING MACHINES

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ABSTRACT

Experiments conducted on elastic bodies under friction forces shown that the dynamical system is self-excited by the non-linear behavior of frictional forces. The main objective of this paper is to study the vibrations signals measured on a reciprocating wear testing machine using non-linear signal analysis formulation. A two input and one output MISO model is proposed to represent the non-linear system dynamics. The global output is the sum of two outputs produced by one linear path associated in parallel with a non-linear path. This last path has a non-linear model that represents the friction force and another linear transfer function connected in series. Since the linear path is identified by traditional signal analysis, the non-linear function can be evaluated by the global input/output relationships, and can be correlated to wear conditions of the contact surfaces. Validation tests are conducted in a tribological system composed by a sphere in contact with a prismatic body which has an imposed harmonic motion.

1. INTRODUCTION

Physical parameters of the nonlinear system cannot be identified by traditional linear analysis since this technique implies that the probability density function of the inputs and outputs should have the same nature, condition not verified in nonlinear systems [1]. Therefore, a linear system subjected to a non-linear force will produce a non-linear response. Tribological tests machines are a good example of this kind of system since the machine, considered as linear in its behavior, is subjected to non-linear friction force acting between the specimens [4].

Tribological researchers use mainly the friction forces as a parameter to evaluate wear in materials, to evaluate lubricant performance and as one of most important parameter to characterize tribological systems. However, the force measured by a load cell in tribological machines is the response of the machine to the friction force and should be processed to extract its correct value. This can be achieved by using non-linear MISO analysis [4].

2. NON-LINEAR MISO ANALYSIS

A reverse multiple input and one output model, MISO model, can be used to represent any kind of non-linear systems including systems with feedback [2]. A non-linear model is proposed to represent a linear system subjected to friction force as excitation force. This model has as output a force, representing the response of the tribomachine to the friction between body and counter body, which is the sum of two paths. A linear path represents the response of the systems to the past events and a non-linear path represent the friction force between body and counter body [4].

To build the proposed model a modification in the tribometer equation of motion should be done. This modifications consist in isolate at right side of equation the response of linear system to the friction force, in this case the force measured by load cell of the tribometer. The block diagram in Figure 1 represents the tribometer, where the input is the relative displacement between body and counter body, and the output is the total load measured by a load cell. The function \( g(x) \) is a non-linear function that represents the friction force, the variable \( y_{h}(t) \) is the linear part of the load and \( y_{v}(t) \) is the friction force between body and counter body.

![Figure 1. Non-linear MISO model used to represent a tribometer.](image-url)
The function $g(x)$ includes the stick-slip and the hysteresis effects of the friction force [3] as shown in Figure 2 and Equation 1.

![Figure 2. Non-linear friction force](image)

If the body is at rest and will start the movement

$$F_{\text{Coulomb}} = \text{sgn}(v_{rel}) \cdot u_{rel} \cdot K_{\text{Coulomb}}$$

if the body is slipping in the static surface

$$F_{\text{Coulomb}} = \text{sgn}(v_{rel}) \cdot F_{\text{Coulomb}}$$

$u_{rel} = u_{rel}$

if the body is adhered to surface after its slip in the static surface

$$F_{\text{Coulomb}} = \text{sgn}(v_{rel}) \cdot (u_{rel} - u_{rel}) \cdot K_{\text{Coulomb}}$$

### 3. EXPERIMENTAL RESULTS

The experiments have been done with a spherical counter body making contact with a prismatic body. The counter body was made of AISI 52100 steel hardened to 848 HV and the body was made of aluminum covered with a thin layer of Teflon. The normal load, achieved by dead weight, was 8.82 N. The body has an imposed harmonic displacement with 6mm of stroke at 2 Hz of frequency. The counter body velocity was measured by a laser Doppler vibrometer and the body velocity was measured by an accelerometer and these variables were used to calculate the input $x(t)$ shown at the model of Figure 1 and the relative velocity shown at the model of Figure 2.

Three experiments groups were conducted, each one with distinct time duration. The first, with 18 minutes, estimates the friction force signature with no visible damage at the Teflon layer. Second group has 2 hours of duration, so some cracks and debris appear at the Teflon layer surface. At the third group the Teflon layer was completely removed and the aluminum surface was damaged.

![Figure 3. SEM photography of the body surface. A) Second group of experiments; B) Third group of experiments.](image)

Figure 3 shows two scanning electronic microscopic pictures of the body surface. Figure 3A shows some cracks and some regions with powder aspect. Figure 3B shows the wear of aluminum surface with some regions of reminiscent Teflon layer. At the Figure 4 is shown the estimated RMS value of the friction force and its correspondence with tribological mechanisms. It should be noted that the RMS value of the friction force increase with the wear at the body surface.

![Figure 4. Estimated RMS value of friction force during experiments.](image)

### 4. CONCLUSIONS

A new methodology to estimate the friction force in tribological tests was presented. This methodology permits the correct estimation of friction force without influence of dynamical behavior of machine. The estimated friction force is sensible to the modifications at contact conditions and to the severity of wear in body and counter body surfaces.

### 5. ACKNOWLEDGMENTS

The authors’ acknowledgement the financial support provided by CNPq.

### 6. REFERENCES


