Further Investigation on LuGre Friction Force Model under Normal Load Variations

Filipe Marques[1], Łukasz Woliński[2], Marek Wojtyra[2], Paulo Flores[1], Hamid M. Lankarani[3]

[1]CMEMS-UMinho
Department of Mechanical Engineering,
University of Minho
Campus de Azurém, 4804-533 Guimarães, Portugal
[fmarques, pflores]@dem.uminho.pt

[2]Warsaw University of Technology
Institute of Aeronautics and
Applied Mechanics
ul. Nowowiejska 24, 00-665 Warsaw, Poland
[lwolinski, mwojtyra]@meil.pw.edu.pl

[3]Department of Mechanical Engineering
Wichita State University
Wichita, KS 67260-133, USA
hamid.lankarani@wichita.edu

EXTENDED ABSTRACT

1 Introduction

A large number of friction force models have been proposed in the literature to include the different friction attributes and to represent the frictional behavior with more detail [1, 2]. Generally, the friction models are divided into two groups, the "static" and "dynamic" models. The former group describes the steady-state behavior of friction force by enforcing a constant relationship between the relative tangential velocity and the corresponding friction force. The dynamic models are usually more complex since they consider an extra state variable, which describes the friction state, governed by a differential equation. Among the dynamic friction model, the LuGre model [3] has been gaining popularity and acceptance by the scientific community, since it presents a reasonable trade-off between easiness of implementation, range of modeled frictional phenomena, computational efficiency, and ability for parameters identification. These characteristics make LuGre model suitable for many applications in modeling of multibody mechanical systems. Despite its wide utilization, the LuGre model presents limitations under normal load variations, which resulted in its authors to present an amended version [4] to overcome some of those shortcomings. However, even the amended version has revealed some physical inconsistencies due to the occurrence of a drift during the sticking phase [5, 6]. In this work, a modification to the LuGre friction model is proposed to deal with normal load oscillations without the shortcomings of both the original and amended versions of the model.

2 LuGre Friction Force Models

The original LuGre model was proposed in 1995 [3] as an advancement of the Dahl friction model [7]. This model considers an analogy between the friction phenomena and a bristle deflection. An extra state variable used by the LuGre model, z, represents the average of bristle deflection and is governed by the following differential equation

$$\dot{z} = v - z\frac{\sigma_0 |v|}{G(v,N)}, \tag{1}$$

in which v denotes the relative tangential velocity, σ_0 represents the bristle stiffness coefficient, N denotes the normal load magnitude, and G is a function that describes the friction force as velocity-dependent, represents the Stribeck effect, and incorporates static and kinetic friction force levels. In the original LuGre model, the friction force can be evaluated as

$$F = \sigma_0 z + \sigma_1 \dot{z} + \sigma_2 v, \tag{2}$$

where σ_1 is the bristle damping coefficient which represents the micro-damping, σ_2 denotes the viscous friction coefficient that corresponds to the macro-damping. This original version of the LuGre friction force model has been developed for constant normal force situations. Therefore, it cannot appropriately deal with cases in which the normal load varies, since load changes do not directly affect the result of Eq. (2).

Later, Canudas-de-Wit and Tsiotras [4] extended the original LuGre friction force model to overcome some of its limitations. In this amended version, the differential equation that governs the state variable is given as

$$\dot{z} = v - z\frac{\sigma_0^{\mathrm{A}} |v|}{G^{\mathrm{A}}(v)}, \tag{3}$$

where σ_0^{A} is a constant coefficient that represents the stiffness of bristle deflection per unit of normal load. In this amended model, the Stribeck function G^{A} is defined as a function of the static and kinetic friction coefficients, instead of the static and kinetic friction forces as in the original model. In the amended LuGre model, the friction force is calculated directly as a function of normal load, i.e.

$$F = \left(\sigma_0^{\mathrm{A}} z + \sigma_1^{\mathrm{A}} \dot{z} + \sigma_2^{\mathrm{A}} v\right) N \tag{4}$$

where σ_1^{A} and σ_2^{A} are constant parameters that represent the bristle damping coefficient and viscous friction coefficient, respectively, per unit of normal load.

Both the original and the amended model exhibit limitations when the normal force varies during the contact interaction, as demonstrated in Section 3. The proposed modification to the LuGre friction model is intended to mitigate these limitations and is similar to the amended model; however, the coefficients are defined differently, i.e.

$$\sigma_0^{\mathrm{P}} = \sigma_0^{\mathrm{A}} N, \qquad \sigma_1^{\mathrm{P}} = \sigma_1^{\mathrm{A}} N, \qquad \sigma_2^{\mathrm{P}} = \sigma_2^{\mathrm{A}} N, \tag{5}$$

and the friction force is given as

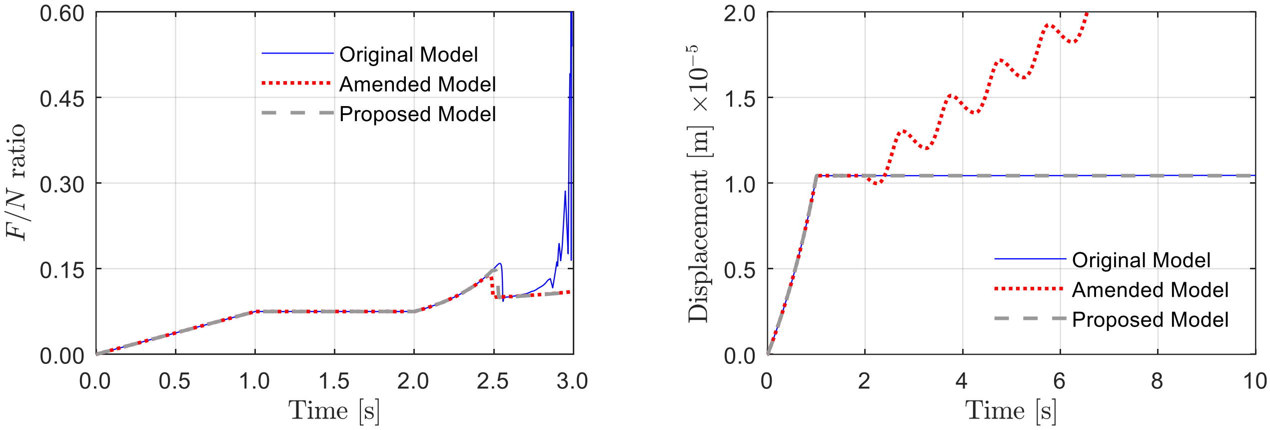
$$F = \sigma_0^{\mathrm{P}} z + \sigma_1^{\mathrm{P}} \dot{z} + \sigma_2^{\mathrm{P}} v. \tag{6}$$

The most relevant feature of this modification is that it enforces a constant stiffness coefficient when the contact is in the sticking regime. In this way, it avoids the drift due to a variable stiffness, when the normal load varies.

3 Results and Discussion

In order to demonstrate the effectiveness of the proposed modification of the LuGre friction model, a simple block of mass moving on a horizontal surface is considered as an application with two examples. In these examples, the normal and pulling forces are prescribed to highlight the issues associated with each model.

Figure 1 shows the results of two examples considered. In the first case, a constant normal load is applied until 2 seconds of simulation and then it continuously decreases until the end of the simulation. As demonstrated in Figure 1a, the original LuGre model produces a ratio between the friction and normal forces that exceeds, in a significant manner, the static and kinetic friction coefficients. In the second case, a constant pulling force is applied well below the break-away force, and the normal force is subjected to continuous oscillations of about 10% of its average magnitude. The results of Figure 1b show that the amended model presents an unrealistic drift between the contacting surfaces, whereas the newly proposed model is free of this flaw.



(a) (b)

Figure 1: Results of (a) friction to normal force ratios in a case of normal force decreasing, and (b) displacement of the mass block in a case of normal load oscillation in the sticking regime

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