

BULETINUL INSTITUTULUI POLITEHNIC DIN IAȘI

Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iași
Volumul 70 (74), Numărul 4, 2024

Secția
CONSTRUCȚII DE MAȘINI
DOI:10.2478/bipcm-2024-0018



A SIMPLIFIED FRICTION FORCE MODEL OF TRANSIENT SLIDING CONTACT BETWEEN HARD AND SOFT SURFACES

II. EXPERIMENTAL VALIDATION WITH PROPOSED MODEL

BY

CEZARA MĂRIUCA GAVRIL*, VLAD CÂRLESCU and BOGDAN CHIRIAC

“Gheorghe Asachi” Technical University of Iași,
Department of Mechanical Engineering, Mechatronics and Robotics

Received: January 30, 2025

Accepted for publication: February 8, 2025

Abstract. The authors realized reciprocating-sliding friction tests by using different type of contacting surfaces such as steel ball on steel plate, steel cylinder and glass on finger skin in dry and lubricated conditions. The experimental tests put in evidence the transient regime of the tangential force and relative velocity. In case of steel-on-steel contact the transition of tangential force shows almost the same trend as the relative velocity. For the sliding friction between steel-on-skin and glass-on-skin it was observed that the tangential force showed a time delay when pass from positive to negative values compared to velocity. The time period in which tangential force pass through zero is depending on the viscoelastic properties of the finger skin. Experimental results were validated with a simplified model based on Heaviside step function and showed a good correlation, especially for the lubricated sliding contact. The proposed methodology gives satisfactory results only if the tangential friction force is varying symmetrically in the transient sliding friction process.

*Corresponding author; *e-mail*: cezara-mariuca.gavril@academic.tuiasi.ro

© 2024 Cezara Măriuca Gavril et al.

This is an open access article licensed under the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0).

Key words: friction force, reciprocating-sliding friction tests, soft and hard contacts, Heaviside step function.

1. Introduction

In reciprocating sliding friction process, the velocity and the tangential force are changing their sign with respect to the change in sliding direction. The sliding velocity have a sudden transition with a very small delay time when pass to zero due to the system's inertia, compared to tangential force that may have a greater delay when pass to zero which is influenced by the type of contacting material. According to the classical Coulomb's friction model, the friction force shows a discontinuity where the relative velocity is 0. This discontinuity is an important issue for dynamic modeling and simulations because it introduces numerical instability in the system's response (Marques *et al.*, 2016, 2021; Kang *et al.*, 2015; Brown and McPhee, 2016).

2. Experimental

2.1. Equipment description

The experimental friction tests were performed by using a CETR UMT-2 Tribometer which can be used for determining the mechanical and tribological properties at micro-scale of ferrous and non-ferrous metals, plastics, ceramics, paper, composites, thin and thick coatings, as well as of solid lubricants, lubricating fluids, oils, and greases.

The UMT-2 Tribometer is equipped with 3 interchangeable force sensors (with magnitude from 0,1 mN to 20 N) that can be attached to a vertical linear motion system ("carriage") with a travel length of 150 mm on Z axis. A lateral positioning system ("slider") with maximum travel of 75 mm on X axis is embedded in the carriage. The upper specimen can be attached to the force sensor by using various sample adapters. The lower specimen is held by a linear table with a maximum travel of 75 mm and speed up to 10 mm/s that can perform horizontal reciprocating motions on Y axis.

Ultra-accurate strain-gauge sensors precisely perform measurements of loads in two axes with a resolution ranging from 1 μ N to 1 mN. A normal-load sensor provides feedback to the vertical motion controller, actively adjusting the sample position to ensure a constant load during testing.

The UMT Viewer allow the user to visualize the test parameters in real-time and to control all the modules in both semi-automatic and fully automatic modes with easy to write test scripts.

2.2. Experimental procedure

The experimental procedure consists in performing friction tests between two contacting surfaces in a reciprocating sliding motion under dry and lubricated conditions. By using UMT-2 Tribometer tangential friction force was recorded during the transient sliding friction between hard and viscoelastic materials such as steel on steel, steel on finger skin and glass on finger skin. The friction tests were realized by imposing a normal load to the contacting surfaces and perform lateral cyclic displacements during a specified time.

Firstly, it was studied the friction between hard materials, and it was used a steel ball that was placed in contact with a steel plate. The steel ball with a diameter of 6.3 mm was placed in a ball holder that was fixed into an elastic adapter and attached to the load sensor of the tribometer. A steel plate was fixed on the bottom linear table of the tribometer that was moved with a specified velocity. In Fig. 1 it is shown the experimental setup for friction test between hard materials in dry conditions at room temperature conditions.

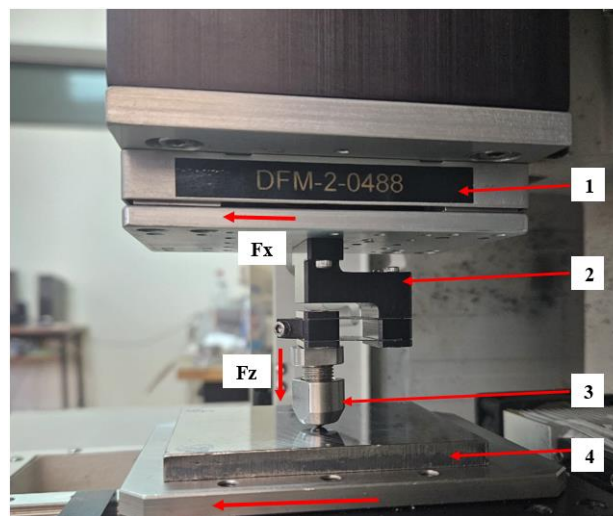


Fig. 1 – Experimental setup for friction tests between hard materials:
1 – load sensor, 2 – elastic adapter, 3 – ball holder, 4 – steel plate.

The second scenario is referred to the contact between a hard body and a soft material. For this friction tests, a steel cylinder with a diameter of 6.96 mm and length of 40 mm was attached to the load sensor and put in contact with the human finger skin that stay rest on the linear table of the tribometer. The cylinder was laterally moved in a reciprocating-sliding fashion under different normal loads and sliding velocities. Figure 2 shows the experimental setup and the contact between the probe cylinder and the finger skin.

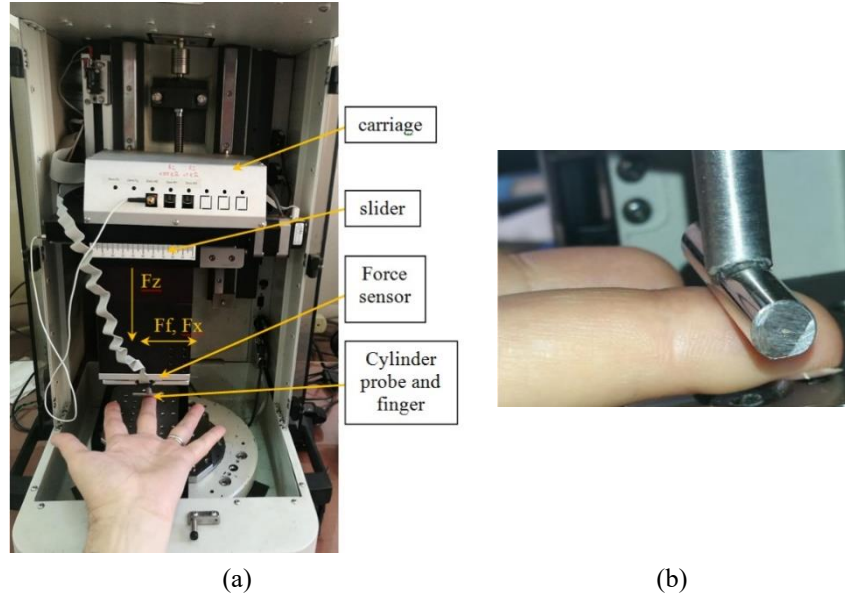


Fig. 2 – Experimental setup for friction tests between a steel cylinder and human finger skin: a) general view of UMT-2 Tribometer with the human hand on the lower specimen table; b) contact between the steel cylinder and the fingertip.

The last scenario is referred to the contact between a glass plate and human finger skin (Fig. 3). The experimental setup is similar to the previously one, except that a glass plate was used in contact with the finger skin. The sliding friction of the glass plate onto the finger skin was studied in dry and lubricated condition at room temperature.

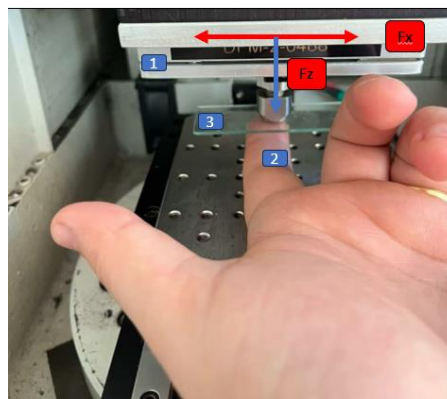


Fig. 3 – Experimental setup for friction tests between a glass plate and finger skin:
1 – load sensor, 2 – finger, 3 – glass plate.

In all three scenario the testing procedure imposed to define a script that composed a series of sequences and steps that define the mechanical actions of the tribometer modules such as speed, load, distance, and duration. In the first sequence was defined a pre-load by defining the normal force to be applied on the contacting surfaces. After the force is stabilized, in the next sequence of the script are defined the distance, sliding velocity and time needed to perform the cyclic movements. Also, in this sequence were selected the test parameters to be recorded during the friction test, such as tangential force (F_x), normal force (F_z), sliding velocity (v), and distance (Y) on the sliding direction.

3. Results and discussions

3.1. Sliding friction in steel-on-steel contact

In Fig. 4 is presented an example of the transient sliding friction between two steel contacting surfaces at a normal force of 1 N and a sliding velocity of 1 mm/s in dry conditions. It can be observed the step trend of both the tangential force and the sliding velocity, respectively, with variations from positive to negative values and pass through zero, due to the change in sliding direction. The tangential force shows to varies symmetrically in the range of 0.12 N to -0.12 N.

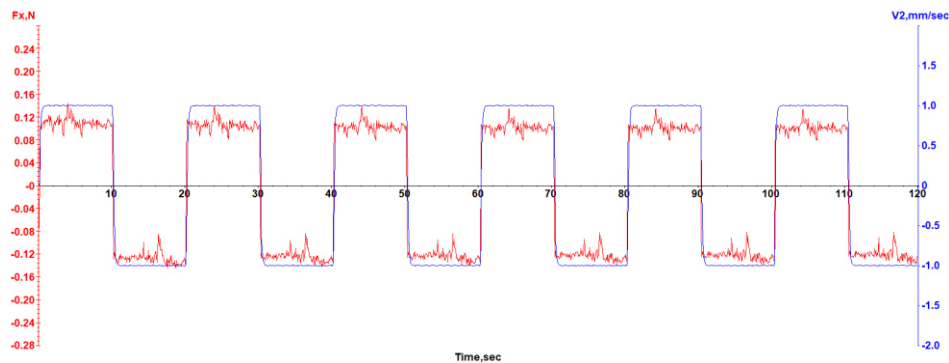


Fig. 4 – Step variation in sliding transient friction of the tangential force and sliding velocity versus time for dry steel-on-steel contact at $F_z=1$ N and $v=1$ mm/s.

From Fig. 4, if we extract a short period of time, for example the first 20 seconds, in order to capture two sliding phases, it can be clearly observed the transition of both the tangential force and the velocity, respectively, from positive to negative values when sliding direction is change (Fig. 5a). Also, if we refer just on the time when the transition is made, it can be observed that both the tangential force and the velocity, respectively, have a short transition time to pass from positive to negative values of about $T_f=0.13$ seconds and $T_v=0.46$ seconds,

respectively. The delay time between the points of passing through zero of tangential force and velocity is about $T_d=0.105$ seconds.

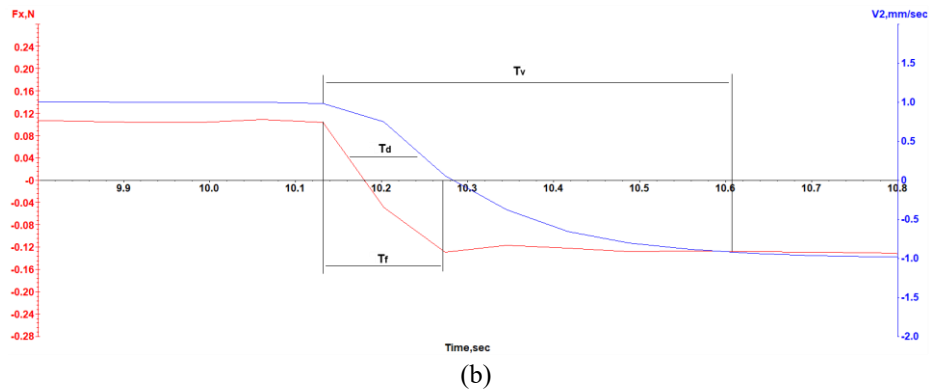
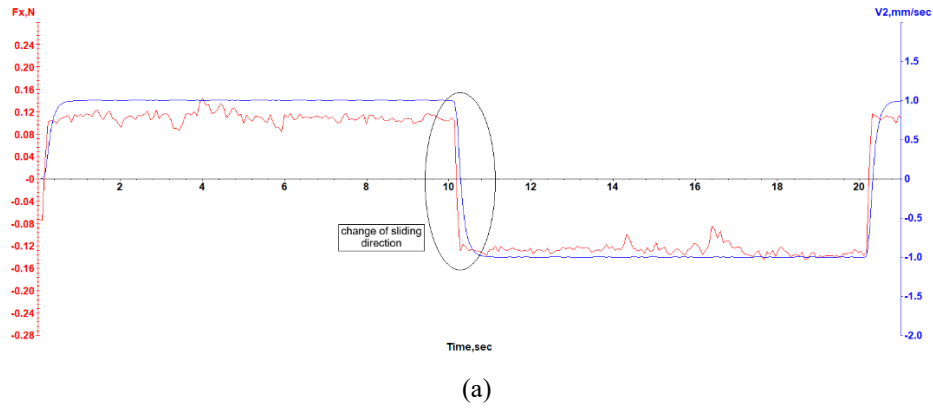


Fig. 5 – Details of a sliding cycle: a) transition step phase; b) showing the period of time in transitions of the tangential force and sliding velocity.

Figure 6 shows the variation of the tangential friction force and velocity at a normal force of 1 N and velocity of 1 mm/s with respect to a total stroke of 120 mm. At the ends it can be observed the rapid slope transition for both tangential force and the velocity, respectively.

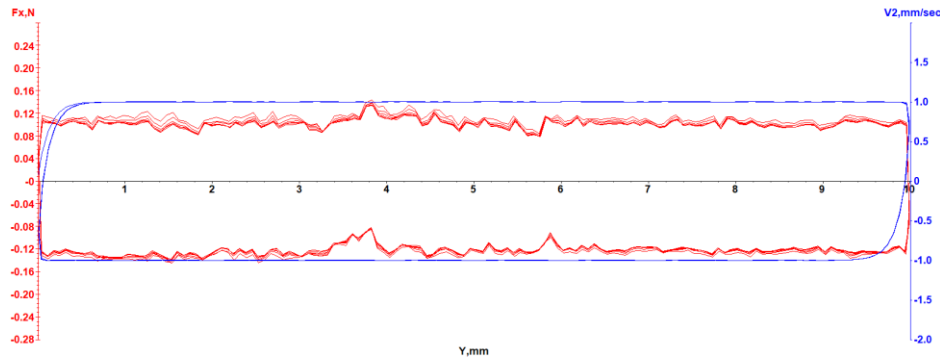


Fig. 6 – Variation of the tangential friction force and velocity with total stroke for steel-on-steel contact sliding friction.

If we relate the tangential force to the normal force, it can be obtained the variation of the coefficient of friction (COF) during the transient sliding friction in steel-on-steel contact surfaces, as is showed in Fig. 7. It can be observed that the values of the coefficient of friction are varying in the range 0.1 to 0.15, which is typically for steel-on-steel contact in dry conditions.

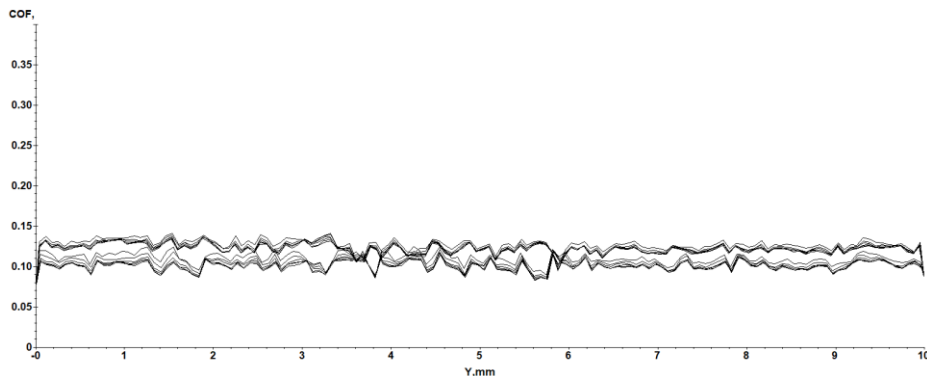


Fig. 7 – Variation of the coefficient of friction with displacement for dry steel-on-steel contact.

3.2. Sliding friction in steel-on-skin contact

Skin tribology is important to study since the skin plays a critical role in many tasks of our daily living and leisure activities that involve gripping, feeling, and manipulating objects (Lewis *et al.*, 2007, 2012; Tomlinson *et al.*, 2009). Skin friction is governed by both adhesion and deformation phenomena and is depending on many factors related to mechanical contact parameters and skin conditions (Derler *et al.*, 2012, 2015; Veijgen, 2013).

Some results regarding the friction of finger skin in sliding contact with different materials were previously reported by the authors (Cârlescu *et al.*, 2017,

2019, 2020, 2022; Oprisan *et al.*, 2016; Chiriac *et al.*, 2022). Thus, the authors proposed a methodology based on the Hertz contact theory to determine the Young's modulus from the force-displacement curve recorded by indentation tests.

In this paper the authors focused on modelling the transition of tangential force in a sliding contact between a steel cylinder and finger skin. Figure 8 illustrate the results of dry friction between a steel cylinder in a transient sliding motion with the finger skin at a normal force of 1 N and a sliding velocity of 1 mm/s.

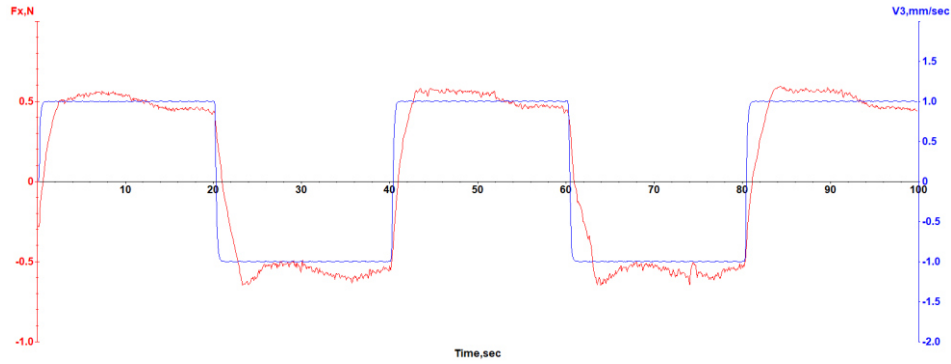


Fig. 8 – Step variation in sliding transient friction of the tangential force and sliding velocity versus time for dry steel-on-skin contact at $F_z=1$ N and $v=1$ mm/s.

From Fig. 8 it can be observed that the tangential force has a symmetrically step variation, similar to steel-on-steel contact in Fig. 4, with limits from 0.5 N to -0.5 N. Figure 9 shows more clearly the step transition regions from positive to negative values (Fig. 9a) and from negative to positive (Fig. 9b) in a sliding motion of a steel cylinder in contact with the finger skin. Because of the visco-elastic behavior of the skin it can be observed that the tangential force has a much larger transition time $T_f=3.15$ seconds to pass from positive to negative when the sliding direction is changed, compared to the velocity transition time $T_v=0.55$ seconds. Also, the delay time between the points of passing through zero for both tangential force and velocity, respectively, is about $T_d=0.65$ seconds.

A similar step transition from negative to positive values of both the tangential force and velocity, respectively, can be observed in Fig. 9b. Again, due to the elastic deformation and adhesion of the skin, the transition time $T_f=2.7$ seconds of the tangential force is larger the transition time of velocity $T_v=0.7$ seconds and time delay is $T_d=0.6$ seconds.

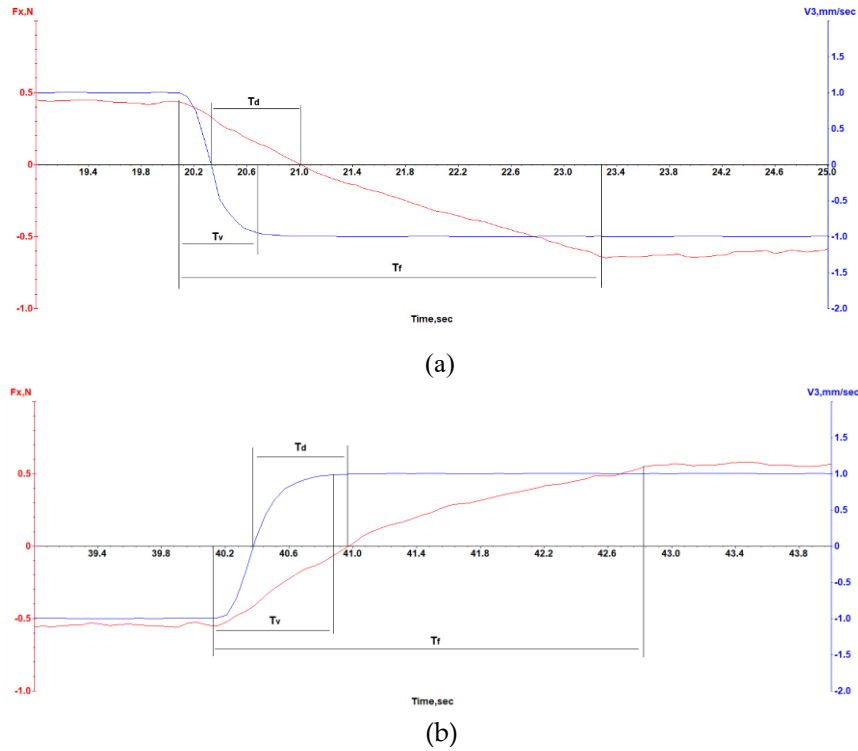


Fig. 9 – Details of step sliding transition for steel-on-skin contact:
a) positive to negative transition; b) negative to positive transition.

Figure 10 shows the variation of the tangential force of 1 N and velocity of 1 mm/s with respect to a total stroke of 100 mm. It can be observed the large sliding phases and at the ends a slow slope transition of the tangential force due to the adhesion (stick) and elastic deformation along with the change of sliding direction.

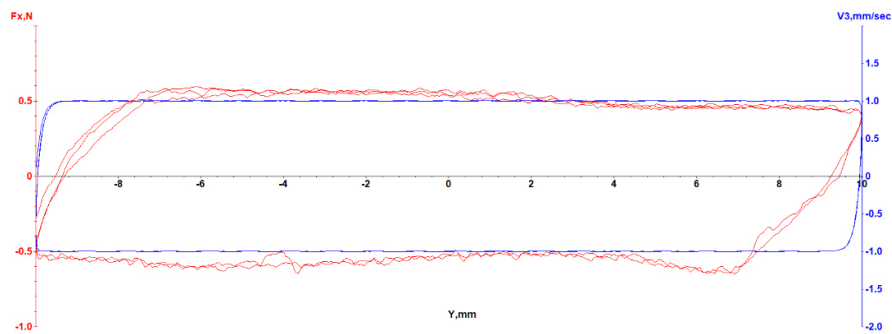


Fig. 10 – Variation of the tangential friction force and velocity with total stroke for dry steel-on-skin contact sliding friction.

The viscoelastic behavior of the finger skin can be also evidenced if relate the tangential force to the normal force and obtained the coefficient of friction (COF) during the transient sliding friction in steel-on-skin contact surfaces, as is showed in Figs. 11 and 12. These regions are becoming much larger if both the sliding velocity (Fig. 11) and normal force (Fig. 12) increase, respectively, along with the reduction of the sliding phases because the finger skin doesn't have time to recover the deformation. It is also evidenced that the coefficient of friction increases with the sliding velocity and decrease with normal force. These specific curves were previously reported by the authors that was named "butterfly" curves (Oprisan *et al.*, 2016).

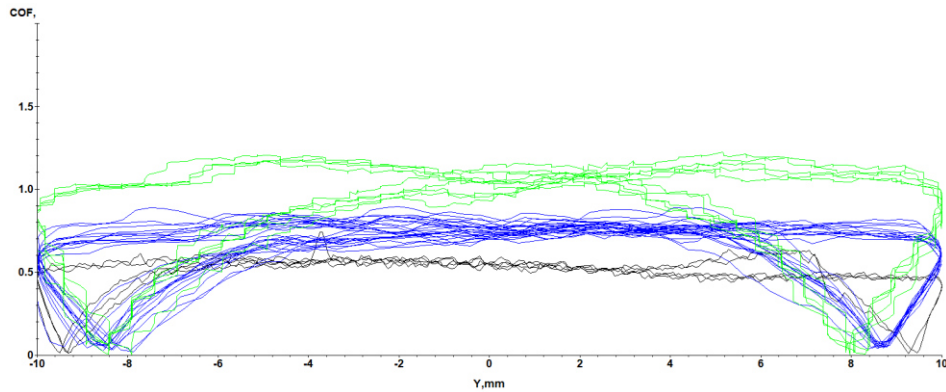


Fig. 11 – Variation of the coefficient of friction with sliding velocity and displacement for dry steel-on-skin contact at normal force of 1 N: 1 mm/s (black); 5 mm/s (blue); 10 mm/s (green).

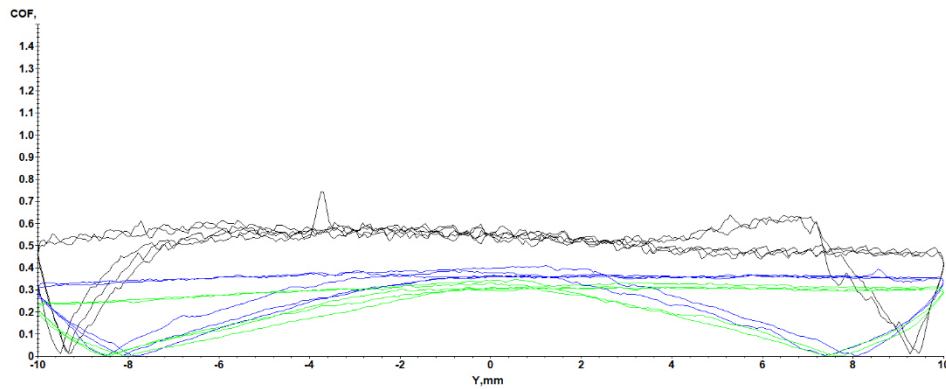


Fig. 12 – Variation of the coefficient of friction with displacement and normal force for dry steel-on-skin contact at a sliding velocity of 1 mm/s: 1 N (black); 5 N (blue); 10 N (green).

3.3. Sliding friction in glass-on-skin contact

Sliding friction experiments between glass and finger skin were also previously reported by the authors in dry and lubricated conditions (Chiriac *et al.*, 2022). Similar to the above-mentioned sliding friction contacts between steel-on-steel and steel-on skin, also for glass-on-skin contact was observed a transient sliding step response of the tangential force, as can be seen from Fig. 13. The tangential force in dry friction conditions varies within a range of 1.2 N to -1.2 N and shows a transition time $T_f=9.4$ seconds from positive to negative and $T_f=10.6$ seconds from negative to positive values and a time delay of $T_d=3.6$ seconds and $T_d=2.5$, respectively. The transition time of the tangential force are bigger than that for steel-on-skin contact in dry friction possible due to a pronounced adherence within the glass and finger skin.

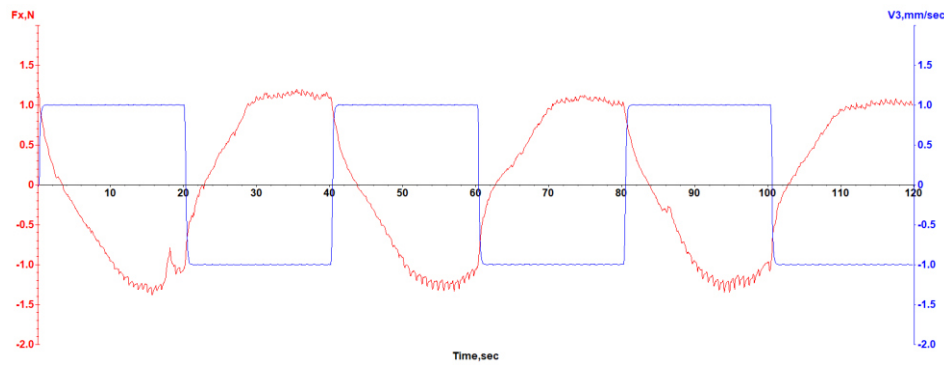


Fig. 13 – Transient step variation of the tangential force versus time for dry glass-on-skin at 1 N and 1 mm/s.

The influence of the lubricants on the sliding friction contact is evidenced in Fig. 14 that shows the variation of tangential force in time at a normal force of 1 N and a velocity of 1 mm/s for dry, water and grease conditions.

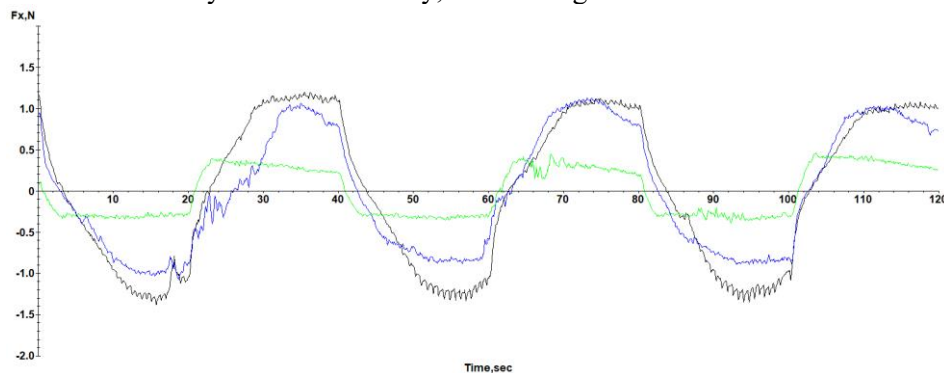


Fig. 14 – Tangential force versus time for glass-on-skin contact at 1 N and 1 mm/s under different lubricated conditions: dry (black); water (blue); grease (green).

Figure 15 shows the variation of the coefficient of friction with the sliding distance for all lubricated conditions and it can be observed the same “butterfly” curves reported for steel-on-skin contact with the values that are in accordance.

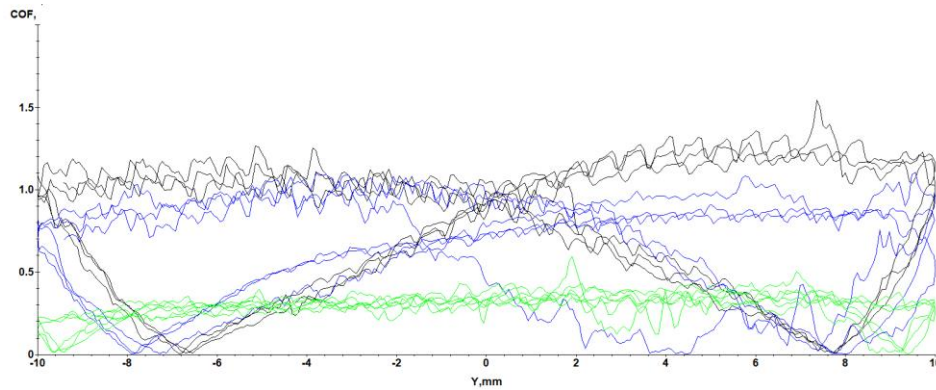
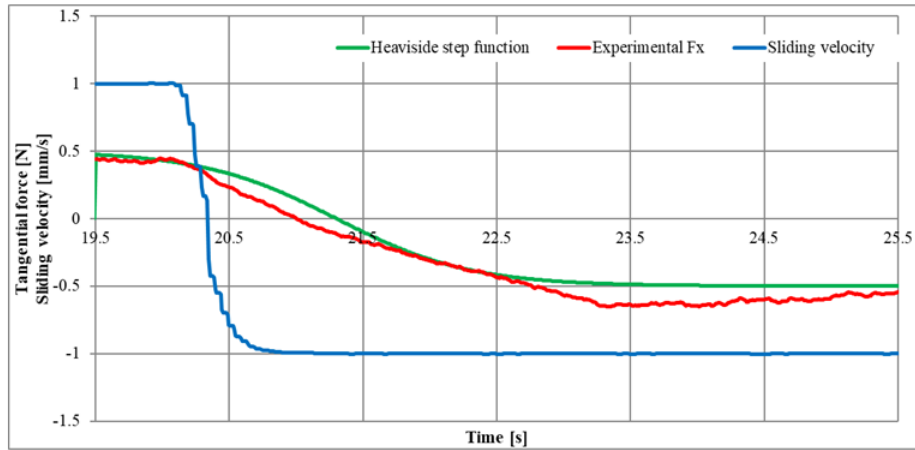


Fig. 15 – Variation of the coefficient of friction on sliding distance for glass-on-skin contact at normal force of 1 N and velocity of 1 mm/s under different lubricated conditions: dry (black); water (blue); grease (green).

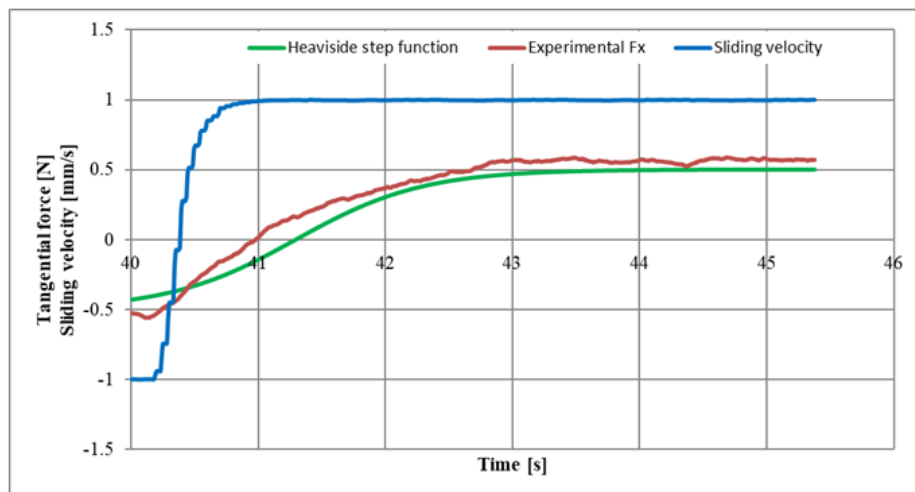
3.4. Experimental results validation with the proposed model

The proposed model based on the Heaviside step function was used to validate the transient phases of the tangential force against experimental data. In Fig. 16 it can be observed the experimental tangential force that goes from positive to negative values (a) and from negative to positive (b), for sliding friction between a steel cylinder and finger skin fitted with the modified Heaviside step function previously proposed.

From the Fig. 16 it can be observed a good correlation between experimental and theoretical results. The modified step function offers good results if the tangential force is symmetrically in the transition sliding friction process. Fig. 17 illustrate the experimental data for tangential force fitted with step function for glass-on-skin contacting surfaces under grease lubricated conditions.

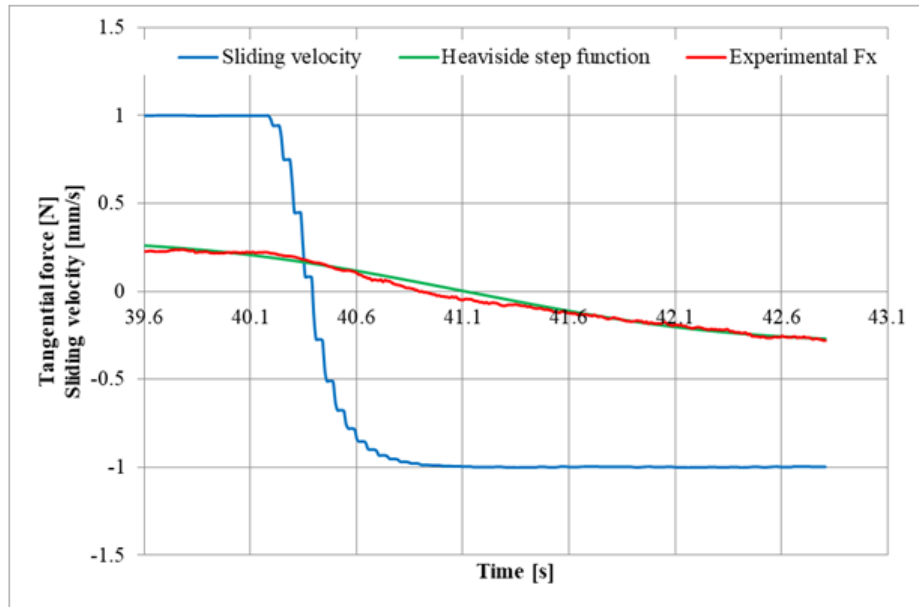


(a)

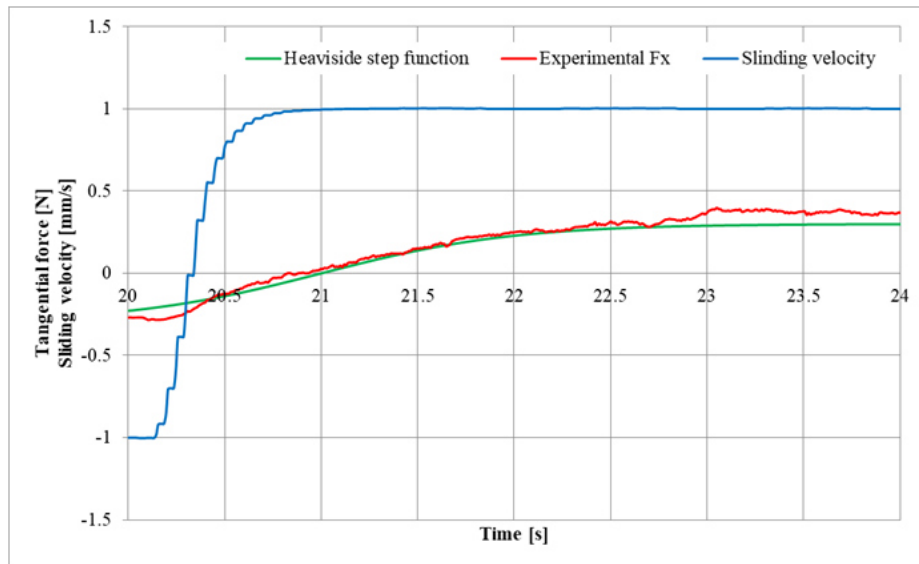


(b)

Fig. 16 – Experimental data for tangential force fitted with modified step function for steel-skin contacting surface.



(a)



(b)

Fig. 17 – Experimental data for tangential force fitted with modified step function for glass-skin contacting surface.

From Figs. 16 and 17 it can be observed that the model is better fitting the experimental tangential force in sliding a glass on skin contacting surfaces due to the grease effect that reduce the adhesion force.

4. Conclusions

The present paper is a study regarding the transient sliding friction that occur in many mechanical systems. Static friction models had some limitations due to the discontinuity of the friction force when the relative velocity is zero. The authors perform experimental friction tests by reciprocating sliding of different contacting surfaces at both low load and velocity, respectively and different lubricated conditions. Using a CETR-UMT2 Tribometer three scenario was studied: a steel ball sliding against a steel plate, a steel cylinder sliding against a viscous material such as finger skin and a glass plate sliding also on skin. The transient step variation in the sliding friction process was put in evidence in all three scenarios. Tangential force showed to have a transition time much larger than the velocity when pass from positive to negative values or vice versa especially for skin contact due to the viscoelastic properties. By using a step function, named Heaviside step function, the authors modeled the transition of the tangential force from positive to negative and vice versa during the sliding friction for steel-on-skin and glass-on-skin contacting surfaces. A modified step function was proposed that showed good correlation when fitted with experimental results.

Acknowledgements. This paper was realized with the support of Doctoral School from “Gheorghe Asachi” Technical University of Iași.

REFERENCES

- Brown P., McPhee J., *A continuous velocity-based-friction model for dynamics and control with physically meaningful parameters*, Journal of Computational and Nonlinear Dynamics, **11**(5), 054502, Sep 2016.
- Cârlescu V., Oprisan C.M., Ianus G., Olaru D.N., *Evaluation of friction behaviour on human finger skin considering precision grip task*, IOP Conf. Series: Materials Science and Engineering **997**, 012007, 2020.
- Cârlescu V., Olaru D.N., Prisăcaru G., Oprisan C., Știrbu R.Ș., Machado J., *Influence of the Indentation Speed on Viscoelastic Behavior of the Human Finger*, In: Machado J., Soares F., Veiga G. (Eds.) Innovation, Engineering and Entrepreneurship HELIX 2018, Lecture Notes in Electrical Engineering, vol **505**, 143-150, 2019.
- Cârlescu V., Oprisan C.M., Chiriac B., Ianuș G., Olaru D.N., *Influence of Hand Sanitisers on the Friction Properties of the Finger Skin Amid the COVID-19*

- Pandemic*, 1st International Conference on Innovation in Engineering, ICIE 2021 Guimarães 28 June 2021 through 30 June 2021, In: *Innovation in Mechanical Engineering, Lecture Notes in Mechanical Engineering*, Pages 420-428, 2022.
- Cârlescu V., Olaru D.N., Prisăcaru Gh., Opreșan C., Machado J., *Sensors and Actuators on Determining Parameters for Being Considered in Selection of Elastomers for Biomimetic Hands*, SENSORS **17**, 1190, 2017.
- Chiriac B., Oprisan C.M., Carlescu V., Olaru D.N., *Friction coefficient between glass surfaces and soft materials*, The 10th International Conference on Advanced Concepts in Mechanical Engineering (ACME 2022) 09/06/2022 - 10/06/2022 Online, IOP Conf. Ser.: Mater. Sci. Eng. 1262 012004.
- Derler S., Gerhardt L.-C., *Tribology of skin: review and analysis of experimental results for the friction coefficient of human skin*, Tribol Lett **45**, 1-27, 2012.
- Derler S., Rossi R.M., Rotaru G.-M., *Understanding the variation of friction coefficients of human skin as a function of skin hydration and interfacial water films*, Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology Vol. **229**(3), 285-293, 2015.
- Kang W.S., Choi C.K., Yoo H.H., *Stochastic modelling of friction force and vibration analysis of a mechanical system using the model*, J Mech Sci Technol., **29**(9), 3645-3652, 2015.
- Lewis R., Carré M.J., Abu Bakar A., Tomlinson S.E., *Effect of surface texture, moisture and wear on handling of rugby balls* Tribol. Int. **63**, 196-203, 2012.
- Lewis R., Menardi C., Yoxall A., Langley J., *Finger friction: grip and opening packaging* Wear **263**, 1124-1132, 2007.
- Marques F., Flores P., Pimenta Claro J.C., Lankarani H.M., *A survey and comparison of several friction force models for dynamic analysis of multibody mechanical systems*, Nonlinear Dyn **86**, 1407-1443, 2016.
- Marques Filipe, Łukasz Woliński, Marek Wojtyra, Paulo Flores, Hamid M. Lankarani, *An investigation of a novel LuGre-based friction force model*, Mech. Mach. Theory **166**, 104493, 2021.
- Opreșan C., Cârlescu V., Barnea A., Prisăcaru G., Olaru D., Plesu Gh., *Experimental determination of the Young's modulus for the fingers with application in prehension systems for small cylindrical objects*, IOP Conf. Series: Materials Science and Engineering **147** (1), 012058, 2016.
- Tomlinson S.E., Lewis R., Ball S., Yoxall A., Carré M.J., *Understanding the effect of finger-ball friction on the handling performance of rugby balls*, Sports Eng **11** (3), 109-118, 2009.
- Veijgen N., *Skin friction: A novel approach to measuring in vivo human skin*, PhD Thesis, University of Twente, Enschede, 2013.

MODEL SIMPLIFICAT PENTRU REGIMUL TRANZITORIU AL FORȚEI DE FRECARÉ LA CONTACTUL DINTRE SUPRAFEȚE DURE ȘI MOI

II. Validarea rezultatelor experimentale cu modelul funcție treaptă propus

(Rezumat)

În lucrarea de față autorii și-au propus să valideze modelul funcție treaptă propus anterior cu rezultate experimentale. Astfel, autorii au realizat teste de frecare cu alunecare alternativă utilizând diferite tipuri de suprafețe de contact, cum ar fi bilă de oțel pe placă de oțel și cilindru de oțel, respectiv sticlă, pe pielea degetelor, în condiții uscate și lubrificate. Testele experimentale au pus în evidență regimul tranzitoriu al forței tangențiale și al vitezei relative în timpul mișcării alternative a celor două corpuri în contact. În cazul contactului oțel-pe-oțel cu frecare uscată, tranziția forței tangențiale prezintă aproape aceeași tendință ca și viteza relativă. În cazul frecării de alunecare dintre un cilindru de oțel, și respectiv o placă de sticlă pe piele s-a observat că forța tangențială a prezentat o întârziere în timp, trecerea de la valori pozitive la valori negative, spre deosebire de viteză, datorită proprietăților vâscoelastice ale pielii degetelor. Rezultatele experimentale au fost validate cu un model simplificat bazat pe funcția treaptă Heaviside și au arătat o corelație bună, în special pentru contactul de alunecare cu lubrifiere. Metodologia propusă dă rezultate satisfăcătoare numai dacă forța de frecare tangențială variază simetric în procesul de frecare tranzitorie de alunecare.