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APPROACHES TO STICK-SLIP ANALYSIS IN TRIBOLOGY

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Abstract. The stick-slip phenomenon is a frictional instability frequently encountered in mechanical systems, characterized by alternating phases of static adhesion and sudden sliding. This paper presents two experimental methodologies for analyzing this behavior using the CETR UMT-2 Tribometer. The first method employs a unidirectional linear oscillator with a single degree of freedom, while the second follows a methodology based on the VDA 230-206 standard. These approaches enable controlled tribological testing, facilitating precise measurement of frictional forces, displacement, and acceleration data.

To support data acquisition, an MMA8451Q accelerometer was integrated with an Arduino Nano 33 BLE development board, allowing real-time monitoring of acceleration variations during stick-slip motion. The collected data was used to evaluate the influence of surface roughness and contact pressure on stick-slip dynamics.

By outlining these methodologies, this paper provides a structured framework for studying friction-induced instabilities, contributing to the advancement of tribological research and its applications in mechanical engineering.

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1. Introduction

Stick-slip is a discontinuous motion that arises due to the periodic transition between static and kinetic friction, commonly observed in mechanical and geophysical systems (Baumberger and Caroli, 2006). This phenomenon is characterized by a cyclic variation in friction force, leading to jerky motion that can cause vibrations, noise, and mechanical wear (Persson, 2000). The fundamental cause of stick-slip behavior lies in the difference between static and dynamic coefficients of friction, which results in energy dissipation and unstable sliding conditions (Rice and Ruina, 1983).

Such instabilities are prevalent across a broad range of natural and engineered systems, from seismic faults and geophysical slip events to frictional contacts in industrial machinery and biomimetic surfaces designed to mimic biological friction (Heslot *et al*., 1994). The occurrence of stick-slip motion is driven by the interplay between the applied driving force and the resisting frictional force, leading to oscillatory or irregular movements depending on the system parameters (Scholz, 1998). Various material properties, such as surface roughness, lubrication conditions, and contact stiffness, have been found to significantly influence the magnitude and frequency of stick-slip oscillations (Bureau *et al*., 2002).

Moreover, the characteristics of stick-slip events are highly dependent on the velocity of the driving mechanism, where higher sliding speeds often induce a transition from discontinuous stick-slip behavior to steady sliding motion (Ben-David *et al*., 2010). To systematically study this transition, experimental setups that allow for controlled variations in contact conditions are essential.

Among the available tribological testing methods, the CETR UMT-2 tribometer provides a versatile platform for investigating stick-slip behavior under well-defined conditions. This instrument enables precise control over variables such as load, speed, and material pairing, making it a valuable tool for studying the stick-slip phenomenon (Baumberger *et al*., 2002). Furthermore, tribological testing using the CETR UMT-2 tribometer allows for systematic experimentation under different operational conditions, providing critical insights into the mechanisms governing stick-slip motion (Stempflé and Deyber, 2007).

The following section will delve into the methodologies employed in tribological testing, with a particular focus on the CETR UMT-2 tribometer and its role in characterizing stick-slip behavior under varying experimental conditions.

2. Experimental equipment

Various methods have been previously employed to investigate the stick-slip phenomenon. In earlier research, two distinct types of tests were conducted using the CETR UMT-2 Tribometer in the Tribology Laboratory of the Mechanical Engineering, Mechatronics, and Robotics (IMMR) Department. The author of this paper has utilized these methods in past studies to analyze and characterize this behavior. One approach involved determining the stick-slip phenomenon through the linear oscillator method, using a system with a single degree of freedom. Another method, based on principles similar to those outlined in the VDA 230-206 standard, was also applied in previous research on the CETR UMT-2 Tribometer.

A general diagram of the CETR UMT-2 Tribometer is presented in Fig. 1. This illustration provides an overview of the main components and operational principles of the tribometer, highlighting its capability to perform various tribological tests, including friction, wear, and stick-slip analysis under controlled conditions. This serves as a reference for understanding the experimental setup and the parameters involved in the testing process.

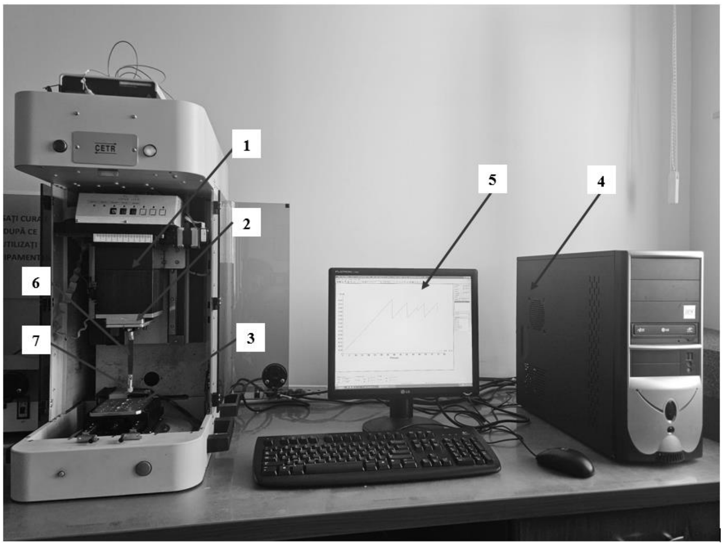

Fig. 1 − A general presentation of the CETR UMT-2 Tribometer.

The tribometer consists of a vertical support for axial loading (force Fz, position 1), a sensor for measuring tangential force (Fx, position 2), and a linear displacement platform with speeds ranging from 0.01 to 10 mm/s (position 3). It is operated through a computer with specialized software (position 4) and features a display for visualizing results (position 5).

The vertical support can move along the Z-axis (vertical loading direction) as well as the Y-axis (transverse direction), while the platform moves back and forth along the X-axis. The tribometer is equipped with three force sensors, capable of measuring forces ranging from 10 μN to 20 N, depending on the required study conditions. These force sensors are attached to the front end of the vertical support.

On the lower surface of the sensor, a support (position 6) is secured using screws. This support includes elastic blades designed to dampen the applied force. A pin (position 7) is then fixed within the support. The measured parameters, including forces (Fz, Fx), displacements (Z, Y), time, the movement speeds of the linear stage (V_2) and transverse support (V_3), as well as the coefficient of friction (COF), are recorded and displayed in the form of diagrams, with options for adjusting various parameters. Details regarding the attachment of the elastic support and the pin are shown in Fig. 6.

3. Testing methods

To investigate the stick-slip phenomenon using a unidirectional linear oscillator with a single degree of freedom, a detailed experimental setup is depicted in Fig. 2. In this configuration, a steel plate (position 6) is securely mounted on the linear platform, while a cylinder with a known mass, m (position 5) is placed on top of it. The cylinder is attached to a pin (position 3) through a tension spring with stiffness k (position 4).

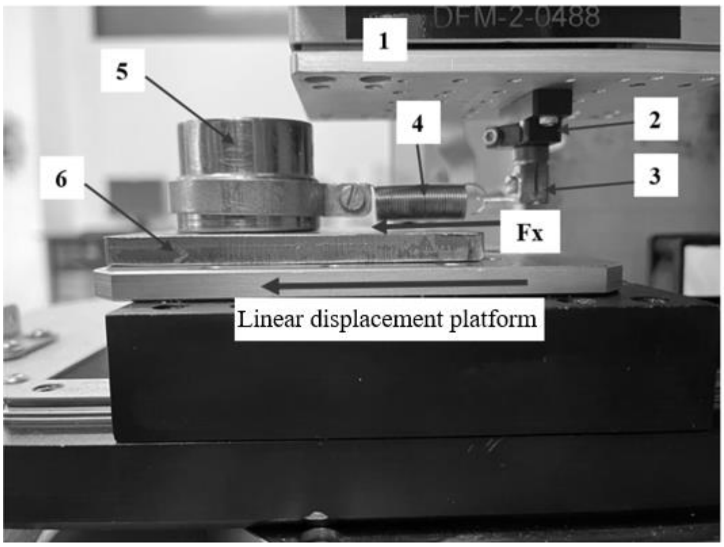

Fig. 2 – Stick-Slip testing with a cylinder placed on a steel plate and connected to a pin via a tension spring.

As the cylinder moves along the metal plate, the adhesion force or frictional force is transmitted through the spring to the pin and subsequently to a support structure (position 2), which then directs the force to the force sensor (position 1). This configuration enables continuous real-time monitoring of the tangential contact force (Fx) between the cylinder and the plate, with data acquisition and analysis performed using the Microtribometer software.

The setup effectively captures stick-slip oscillations by measuring variations in tangential force and displacement, providing critical insights into the development of friction instabilities under controlled conditions.

The experimental tests were conducted under the following conditions:

Three steel plates with varying surface roughness, ranging from Ra = 0.1 µm to Ra = 3.2 µm, were utilized. The cylinder's displacement length on these steel plates varied between 25 mm and 50 mm. For comparative analysis, a glass plate with a thickness of 4 mm and a surface roughness of Ra = 0.03 µm was also included in the study.

The cylinder was manufactured from steel, with its frontal surface precisely ground to achieve a roughness of Ra = 0.6 µm. It had a mass of 242 grams and a contact surface diameter of 38.5 mm with the metal plate. Under these conditions, the contact pressure between the two surfaces in relative motion was calculated to be 0.002 MPa.

Furthermore, three discs with a diameter equivalent to that of the cylinder were employed: one made of aluminum and two made of bronze. The roughness profile. By attaching the discs to the initial cylinder, the total mass of the oscillatory system (cylinder + disc) varied depending on the material composition of the attached disc.

To assess the influence of contact pressure on the stick-slip phenomenon, additional experimental measurements were conducted with the cylinder fixed on the platform using three steel balls with a diameter of 6.36 mm. These balls were mounted into three symmetrically spaced holes (positioned 120° apart) drilled into the frontal surface of the cylinder, as illustrated in Fig. 3. In this configuration, the maximum contact pressure between each ball and the steel plate was determined to be 596 MPa.

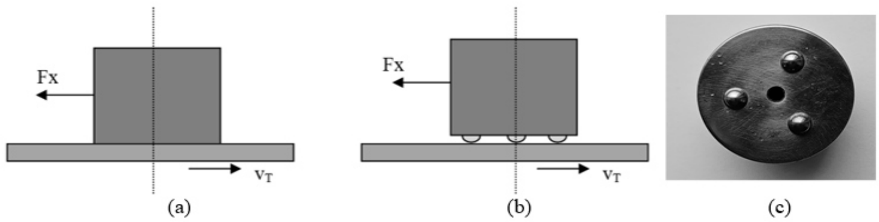

Fig. 3 – (a) Contact on the flat surface with a nominal contact pressure of 0.002 MPa, (b) contact on 3 steel balls with a nominal contact pressure of 586 MPa, (c) front view of the cylinder with 3 balls (c).

The tension spring initially had a stiffness of 40 N/m. However, by constraining a specific number of coils, different stiffness values were achieved, reaching up to 442 N/m. A force sensor (model DFM-2-0488) capable of measuring both normal and tangential forces was employed, with a maximum allowable force of 20 N and a precision of 10 μN.

The majority of the tests were conducted under dry conditions, ensuring that the contact surfaces were degreased using a solvent at the beginning of each test. Each test was systematically coded and later processed in the form of Fx versus time and displacement (Y) diagrams. For a more detailed simulation of the stick-slip phenomenon, additional data processing was performed on the sensor outputs using specialized software. All recorded parameters from each test (Fx, velocity, time, and displacement Y) were transferred to Excel, where the displacement function y(t) over time was extracted.

Based on these diagrams, various models were applied to analyze the variation of the kinetic friction coefficient in relation to the sliding velocity. The models, were evaluated to determine the best approximation for intermittent sliding (stick-slip) for each experimental test performed.

The tests conducted using a method similar to the VDA 230-206 standard were carried out with the help of a specially designed device, similar to the one used by Gavrilă (Gavrilă, 2014). A schematic of the device is presented in Fig. 4, while Fig. 6 shows an image of the device mounted on the testing rig.

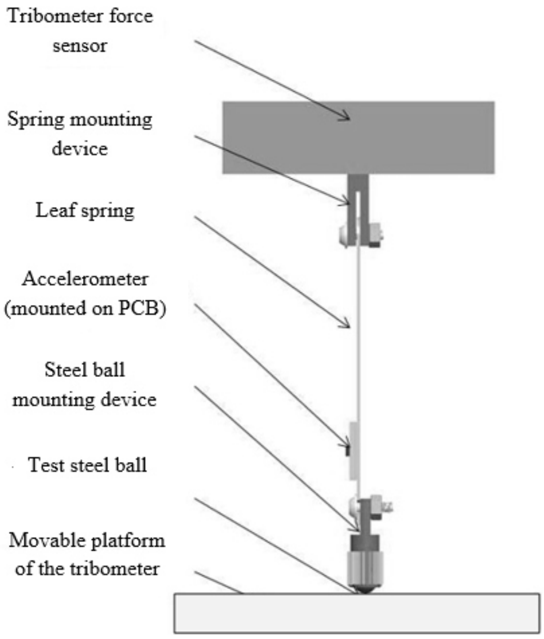

Fig. 4 – General presentation of the device similar to the VDA 230-206 standard.

According to the general presentation in Fig. 4, the friction coupling consists of a steel ball and a metal plate attached to the table's linear stage. The elastic element is made from a spring steel plate with a width of 10 mm and a thickness of 0.8 mm. Positioned 10 mm from the ball fixation device, an accelerometer was mounted, with the upper end of the device connected to the force sensor. The lower end is fitted with a steel ball with a diameter of 6.35 mm.

To provide additional information regarding the stick-slip motion, a specially designed device was used for data collection.

The acceleration measurement system has a two-level structure, as shown in Fig. 5. The Arduino NANO 33 BLE development board is positioned at the upper level, along with the Mini USB power and data transfer cable, while the MMA8451Q accelerometer is placed at the second level. The system features a modular design, which facilitates upgrading and programming.

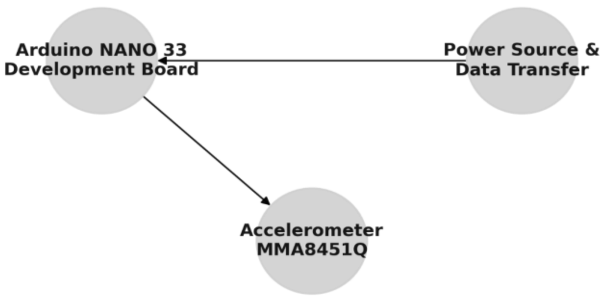

Fig. 5 – Structure of the equipment for experimental data acquisition.

The selection of the capacitive 3-axis MMA8451Q accelerometer was based on several key factors, including its 14-bit architecture, the integration of essential communication interfaces, its compact structural design (measuring 3mm × 3mm × 1mm), its capability to process both digital and analog signals, and its low power consumption, making it an optimal choice for high-precision motion sensing applications.

Data acquisition from the accelerometer was facilitated using an Arduino Nano 33 BLE development board, which was connected to a computer via a Mini USB cable for both power supply and data transfer. The Arduino Nano 33 BLE is a compact electronic development board based on the Arduino platform. It represents an advancement over the traditional Arduino Nano, featuring a more powerful processor, the nRF52840 from Nordic Semiconductors, a 32-bit ARM® Cortex®-M4 CPU running at 64 MHz. Additionally, the board incorporates a 9-axis Inertial Measurement Unit (IMU), which includes an accelerometer, gyroscope, and magnetometer, each providing 3-axis resolution. These characteristics make the Arduino Nano 33 BLE highly suitable for applications in wearable technology, motion tracking, and smart sensing solutions.

The embedded processor is designed to execute code written in a programming language closely resembling C++, ensuring flexibility in software development. The custom-written code for this application initializes the accelerometer and retrieves acceleration data, displaying the measured values in g units (m/s²) along the X, Y, and Z axes. This setup enables precise real-time motion analysis and provides reliable data for experimental studies.

The steel ball is pressed with a force Fz, and the tangential force (adhesion and sliding force between the ball and the plate), Fx, was monitored by the sensor and processed by the Tribometer software. The attachment method of the leaf spring system - accelerometer - Arduino Nano 33 BLE board is shown in Fig. 6 a, b. The components are as follows: spring mounting device (position 1), leaf spring (position 2), accelerometer MMA8451Q (position 3), steel ball mounting device and steel ball (position 4).

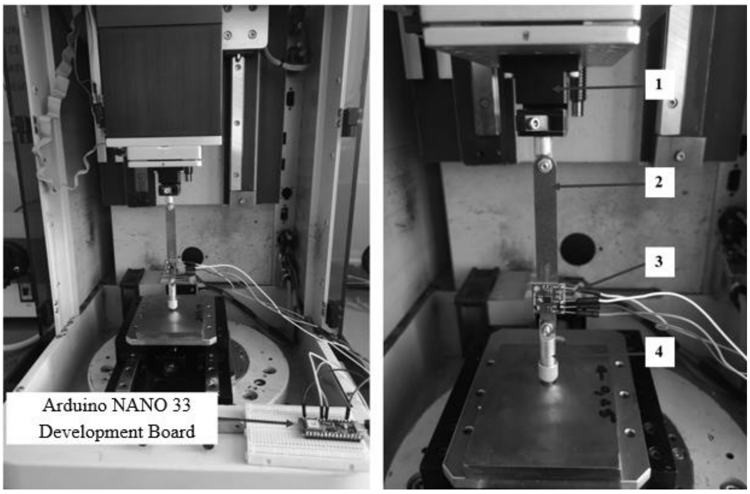

Fig. 6 – Image of the Tribometer with the device similar to the VDA 230-206 standard.

4. Conclusions

This paper presents two distinct experimental methodologies to investigate the stick-slip phenomenon: the unidirectional linear oscillator method with a single degree of freedom and a VDA 230-206 standard-based approach. These methods enabled a systematic analysis of frictional instabilities under controlled conditions using the CETR UMT-2 Tribometer. The experimental setup allowed for precise force, displacement, and acceleration measurements, facilitating a comprehensive assessment of stick-slip behavior.

The integration of the MMA8451Q accelerometer with the Arduino Nano 33 BLE development board provided an efficient and compact data acquisition system, capable of capturing real-time acceleration data with high accuracy. The use of force sensors and motion tracking enabled detailed monitoring of tangential forces and displacement variations, ensuring reliable data collection for further analysis.

Future work may focus on refining these methodologies by incorporating higher-resolution sensors, improving data processing techniques, and expanding the experimental framework to include different materials, lubrication conditions, and varying environmental factors. Additionally, the development of automated data analysis algorithms could enhance the efficiency and precision of stick-slip detection in tribological studies.

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ABORDĂRI ALE ANALIZEI ALUNECĂRII SACADATE ÎN TRIBOLOGIE

(Rezumat)

Fenomenul stick-slip este o instabilitate de frecare frecvent întâlnită în sistemele mecanice, caracterizată prin alternanța dintre fazele de aderență statică și alunecare bruscă. Această lucrare prezintă două metodologii experimentale pentru

analiza acestui comportament utilizând tribometrul CETR UMT-2. Prima metodă utilizează un oscilator liniar unidirecțional cu un singur grad de libertate, în timp ce a doua urmează o metodologie bazată pe standardul VDA 230-206. Aceste abordări permit efectuarea de teste tribologice controlate, facilitând măsurători precise ale forțelor de frecare, deplasării și datelor de accelerație.

Pentru achiziția de date, un accelerometru MMA8451Q a fost integrat cu o placă de dezvoltare Arduino Nano 33 BLE, permițând monitorizarea în timp real a variațiilor de accelerație în timpul mișcării stick-slip. Datele colectate au fost utilizate pentru a evalua influența rugozității suprafeței și a presiunii de contact asupra dinamicii stick-slip.

Prin prezentarea acestor metodologii, această lucrare oferă un cadru structurat pentru studiul instabilităților induse de frecare, contribuind la avansarea cercetărilor tribologice și la aplicabilitatea acestora în ingineria mecanică.