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FIRST EXPERIMENTAL RESULTS OF A SIMPLE MODULAR APPARATUS FOR FRICTION MEASUREMENTS

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ABSTRACT

The paper describes some preliminary experiments carried out with a simple but very modular apparatus designed and realised for measuring both static and dynamic friction, which has some elements of novelty with respect to other test rigs available on the market or described in the literature. In particular it can be used in two different configurations, i.e. under displacement control of the upper or the lower specimen, the first one connected by an elastic wire to a moving load cell, while the latter connected to a moving plate. The tests were performed to evaluate the capabilities of the apparatus to measure the coefficient of friction by varying many factors that affect its estimation, as normal load, surface conditions, speed of the actuator and type of contact (conformal/non-conformal). Some interesting issues arose that will deserve further investigations.

Keywords: Coefficient of friction, friction test, static and dynamic friction, experimental apparatus.

1 INTRODUCTION

Friction plays a very important rule in our life. Usually, it is considered an unavoidable presence whose effects should be reduced in order to spare energy, having an impact on costs and emissions [1]. This is particularly important for sustainability [2-4]. However, there are also cases where the presence of friction is essential, as for instance in the contact between feet and ground where it is necessary to avoid slipping [5].

The first systematic studies on friction were made by Leonardo da Vinci in the 15th century. They are shown by many drawings in the so-called codices (see for instance [6]). His findings were later confirmed and further developed by Amontons and Coulomb [7, 8], respectively about two and three centuries after Leonardo. Their results are today normally summarized in the three laws that are known as the Coulomb's laws on friction. The most important and valid one is surely the first one, stating that the friction force acting between two sliding bodies is proportional to the force pressing the bodies together.

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CoF is a useful quantity mainly for design purposes, but, despite its easy definition, it is often very difficult to be correctly evaluated, as evidenced in [9]. In fact, friction is affected by several factors, such as the characteristics of the rubbing bodies (e.g. materials, geometry, surface texture) and working conditions (e.g. temperature, humidity, relative motion and velocity, load, etc.). In addition, damaging processes as wear can produce variation of friction during the service lifetime of the coupling. Consequently, a reliable estimation of the CoF is a challenging task. Due to the many factors influencing CoF, its theoretical determination is practically impossible and experimental studies were and still are necessary. Many different experimental rigs, generally called tribometers, have been developed that differ for the specimen geometries, the measuring concept and the operating conditions. Numerous testing methods used to measure friction are reported for instance in [10]. The CoF can be estimated by means of direct or indirect measurements of force or torque typically using load cells, torque meters or strain gauges. Some examples of different test rigs used for measuring static and kinetic CoF are reported in [11-17].

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The different techniques employed in those works are briefly described in [18].

There are many aspects of friction that can be investigated depending on the application. The spread of micromachines lead to studies at micro and nano level with the use of suitable instruments as the Atomic Force Microscope (see for instance [19]). Another aspect that deserved and still deserves attention is the stick-slip phenomenon that is also related to vibration and noise issues [16, 17, 20-22]. Many experiments were also performed with real machine components, as brake pads [23], tires [24] and cams [25].

It is worth mentioning that friction measurements are influenced by the experimental apparatus itself, as shown for instance in [26], where results obtained under the same working conditions with different experimental rigs, a ball-on-ring in two different configurations and a ball-on-disk, are reported. In addition, mounting errors as possible misalignment of specimens and sensors, fluctuations of the electrical signals and sensors calibration lead to measurement uncertainties that affect the estimated values of the CoF as reported in [27].

Friction and wear tests are usually conducted according to specific standards (e.g. ASTM G133 [28], G99 [29] and G115 [30]). Friction typically varies during the test, e.g. due to wear damage, and a sufficient number of test repetitions to achieve statistically significant results are suggested by the standards. Indeed, surface modifications and the formation of wear debris can also occur and are not easy to be controlled during the test replicas. A novel statistical approach aiming to highlight the most significant time intervals during each test replica is reported in [31].

Because of so different approaches and influences, wide ranges of CoF values can be found in the literature for the same material couplings, very often reported without detailing the working conditions. Thus, the understanding, comparison and application of such values is quite hard. The selection of the wrong value of the CoF from published data can have detrimental consequences for engineering industries and should be reduced. Therefore, new rigs for more controlled tests can be useful.

The authors already investigated lubricated [32-34] as well as dry friction couplings [35] with different specimens and two different test rigs, i.e. a reciprocating apparatus and a pin-on-disc machine. Additionally, a new, simple and modular experimental apparatus has been recently developed [18] in order to investigate some of the factors affecting both kinetic and static CoFs. The novel aspect of the apparatus consists in the possibility of performing the same test under two configurations, by actuating one or the other of the coupled specimens.

In this work, after a description of the experimental rig and test procedures, some first results to show the capabilities of the apparatus are described.

2 MATERIALS AND METHODS

2.1 DESCRIPTION OF THE EXPERIMENTAL APPARATUS

2.1.1 Main Features

The experimental rig was mainly designed for investigating the effect of inertial actions on measurements forces used to estimate the kinetic and static and CoFs. Other design criteria in the definition of the apparatus were lightness, simplicity, modularity and cheapness.

As shown in Fig. 1, the experimental apparatus includes a basement that is a legged structure obtained connecting aluminium structural frames. Aluminium, 7075 (Ergal) and 6082 (Anticorodal), was also used for most of the components.

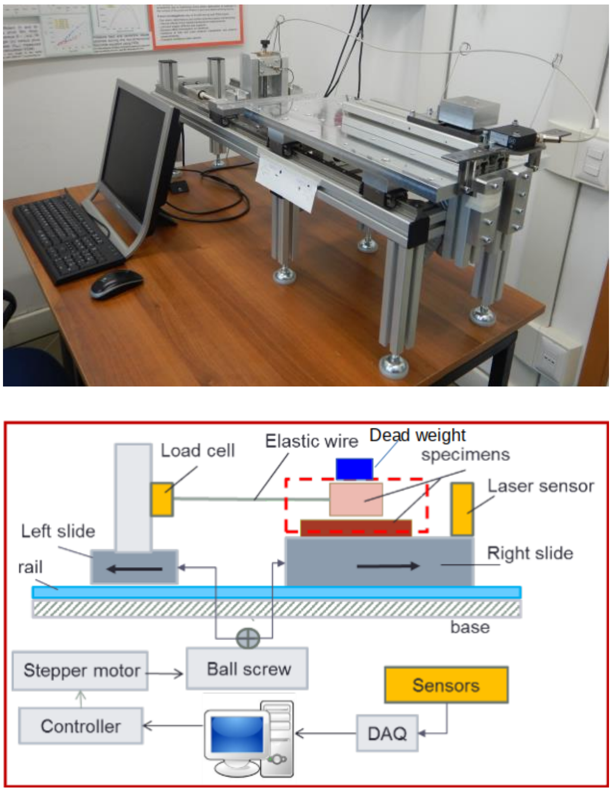

Figure 1 Photograph and scheme of the apparatus.

Two main subgroups can be identified on the top of the basement: a plate over which the lower specimen is fixed on the right, and a ‘tower’ on the left with a load cell connected to the upper specimen through an elastic wire.

The two subgroups can move on two ball rails with very low friction coefficient (0.002-0.003) and can be alternatively connected to the motion transmission system described in the following. This means that when one of the subgroups is moving the other one is fixed. In this way, only one actuator is necessary for all kind of tests .

2.1.2 Functional Schemes

A functional scheme of the test rig is shown in Fig. 2. In the configuration of Fig. 2a the tower is mobile and the load cell is connected to the upper sliding specimen, while the plate with the lower specimen is fixed. In the configuration of Fig. 2b the plate and the lower specimen are mobile while the upper specimen is constrained by the elastic wire connect to the load cell, that is fixed.

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These two different configurations allow to investigate in more detail the influence of the inertial forces.

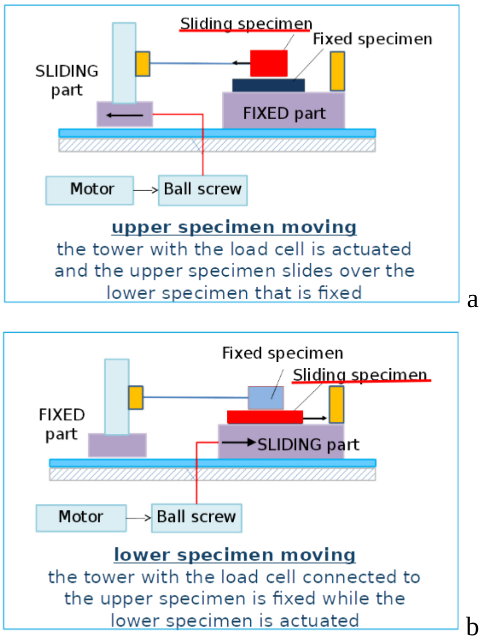


Figure 2 Functional scheme of the apparatus: (a) upper specimen moving; (b) lower specimen moving.

2.1.3 Actuation and Sensors

The motion transmission system is composed by a ball screw supported by ball bearings connected to a step motor through an elastic joint. The linear resolution is 0.025 mm/step and can be improved with the use of a micro-step driver that can electronically split the step in 256 parts.

The friction force is measured by a load cell mounted on an adjusting screw that allows a vertical movement. In this way the load cell can be correctly aligned with specimens of different heights so that the wire remains horizontal (Fig. 3). Depending on the maximum expected friction force to be measured, two different load cells can be alternatively used, with 2 N and 100 N full scale.

Two different laser sensors can be alternatively mounted to detect the beginning of the motion of the specimen and its successive movements. They have measuring ranges of 0.5 and 20 mm respectively. A laser sensor is visible on the top right corner of Fig. 1 and Fig. 3.

Additional details of actuator and sensors can be found in [18].

2.1.4 Fixture for specimens and for load application

Specimens can be metallic and non metallic, with conformal (plane on plane) or non conformal (spheres or cylinders on plane) contacts. The specimens are mounted on suitable fixtures that constitute the upper elements of the couplings. Two examples of specimens and fixtures are shown in Fig. 4.

Normal loads up to 500 N can be applied by using dead weights placed over the specimen fixture, Fig. 5a. In addition, the centre of gravity of the loaded specimen can be adjusted to be as lower as possible, as near as possible to the contact region between the specimens. This can be done through the loading support shown in Fig. 5b. The dead weights are in this case positioned laterally with respect to the specimen fixture and their vertical position can be adjusted as desired by screws.

2.2 TEST PROCEDURE

All electrical and electronic components are managed by an Arduino DUE board through a graphical interface developed in Matlab. User defined motion laws can be easily implemented with full control of speed and acceleration. The apparatus works under displacement controlled conditions and an elastic wire is used to connect the specimen to the load cell in order to obtain a smooth increase of the applied force. The stiffness of the wire has to be properly chosen to control oscillations.

As a first step of the 'standard' test procedure, the specimens are positioned after suitable cleaning of their surfaces. The upper specimen is connected to the supporting block with screws (see for instance Fig. 4a) or glue (Fig. 4b). The lower specimen is fixed to the plate as shown in the detail of Fig. 3 (right) and in Fig. 5.

Then, the upper fixture and the load cell are connected through a wire, Fig. 3. In order to have the desired length and pre-tensioning of the wire, the relative positioning between the fixed and the moving part is chosen.

The desired law of the speed is established using the software interface by assigning time-velocity data pairs and the number of data points to be recorded.

Output data are the force measured by the load cell and the displacement measured by the laser. All data are recorded in a file together with the correspondent time.

In addition, the movement of the block can be recorded by a camera. A high speed camera with a frame rate up to 1000 fps can also be used for the detection of high frequency motions.

A picture of the whole system during a test is shown in Fig. 6. The monitor with the software interface is visible on the left and the camera on the right.

2.3 TEST PLAN AND TEST CONDITIONS

Some experimental tests were carried out in order to check the functionality of the apparatus. In particular, the effect of different quantities on the apparatus was investigated.

2.3.1 Specimens

Most tests were performed with a conformal contact using the specimens shown in Fig. 7a. The upper specimen was made of steel with a 20x20 mm ground surface. The lower specimen was also made of steel but with a lapped surface.

Additionally, some tests were performed on non-conformal contacts, in particular three small ball bearings steel spheres with 3.175 mm diameter were used, Fig. 7b.

2.3.2 Speed and wire

A simple trapezoidal law was chosen for the speed with a linear trend from zero to a desired maximum speed V. V is reached in 1 s as for the deceleration phase. The duration of a whole test was usually 10 s, Fig. 8.

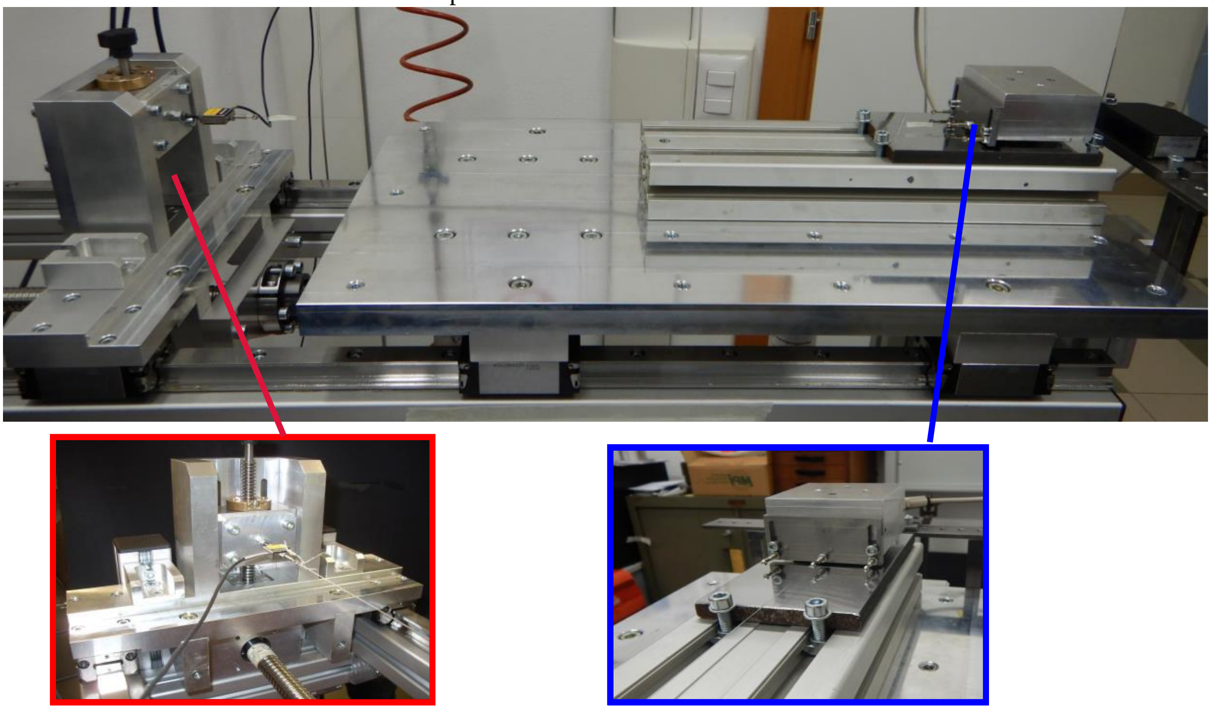
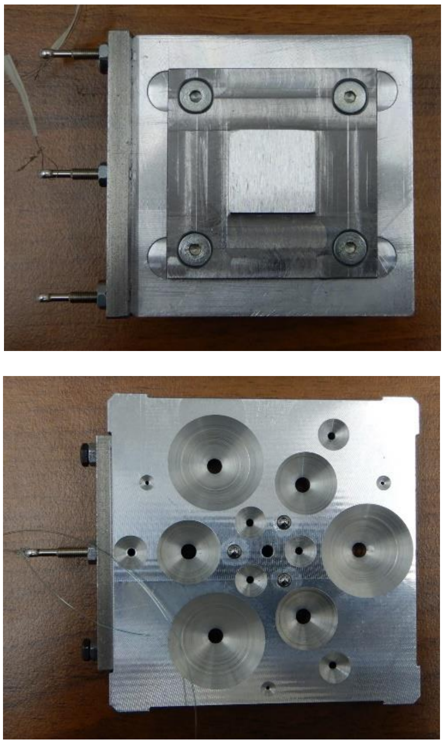


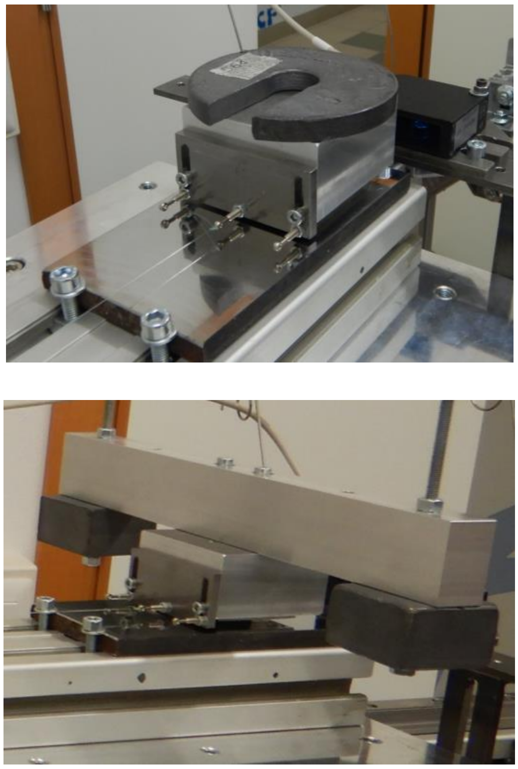
Figure 3 Top part of the experimental apparatus with details of the tower with load cell and elastic wire (left) and of the block with the specimen (right).



a

b

Figure 4 Conformal (a) and non-conformal (b) specimens mounted on their fixture.



a

b

Figure 5 Dead weights load application systems: on the top (a) and lateral (b).

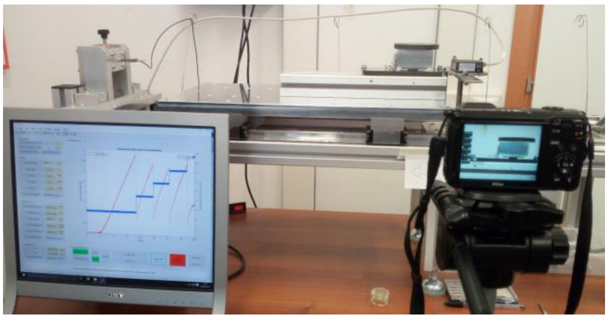
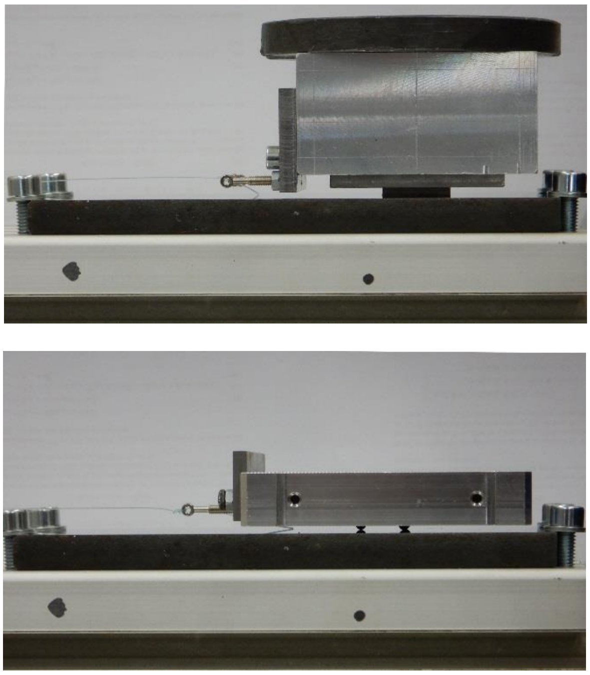


Figure 6 Picture of the apparatus and software interface during a test.



a

b

Figure 7 Pictures taken during tests for conformal (a) and non-conformal (b) contacts.

Three values of V were used to investigate the speed influence on the CoF for the test reported in this work: 0.5, 1 and 2 mm/s.

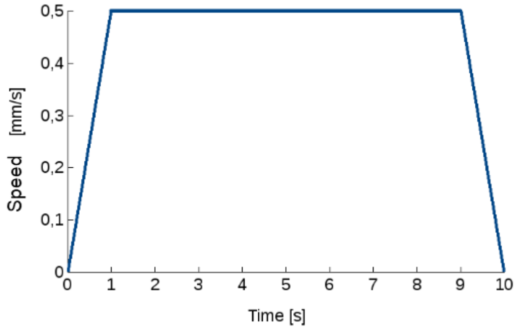


Figure 8 Example of speed law for the mobile part.

However, it must be observed that, due to the presence of clearances and to the compliance of the wire, the effective actuation on the specimen could slightly differ from the profile described above. Thus, two fishing wires were also used, having different diameters and materials, i.e. different stiffness.

2.3.3 Loads

Most tests on conformal contact were carried out with two normal loads: 6 and 11.6 N, correspondent to mean contact pressures of 15 and 29 kPa respectively.
Similarly, tests on non-conformal contacts were carried out with two normal loads: 2.6 and 13.7 N, producing a mean contact pressure 400 and 700 MPa, respectively.

3 EXPERIMENTAL RESULTS

Tests were carried out by combining the three maximum speeds with the two above mentioned loads and also with different actuated part (tower/plate).
Some sample results are reported in the following sections. They were mainly obtained from tests performed with a conformal contact. The behaviour of the apparatus by varying different quantities was investigated. The effect of each quantity will surely deserve specifically addressed investigations in the future. However, some preliminary considerations are reported here.

3.1 EFFECT OF THE STARTING CONDITIONS

The effect of the starting conditions was investigated from two points of view: pre-tension of the wire and time of rest before starting the test. Figure 9 refers to a test with moving tower/upper specimen, maximum speed V=0.5 mm/s and normal load W=6 N. In this figure, as well as in the successive ones, the force measured by the load cell and the displacement measured by the laser sensor are plotted directly from raw data (not post-processed). The sampling frequency was 100 Hz in this case, while 1000 Hz was chosen for most of the successive tests in order to have more recorded data for the signal processing (subject of a future work).
Several observations result from Fig. 9. However, firstly it is worth reminding that with this apparatus tests are performed in displacement-controlled conditions. This explains the rip saw teeth trend of the force vs. time plot in Fig. 9 (i.e. stick slip), while the displacement has a stepwise

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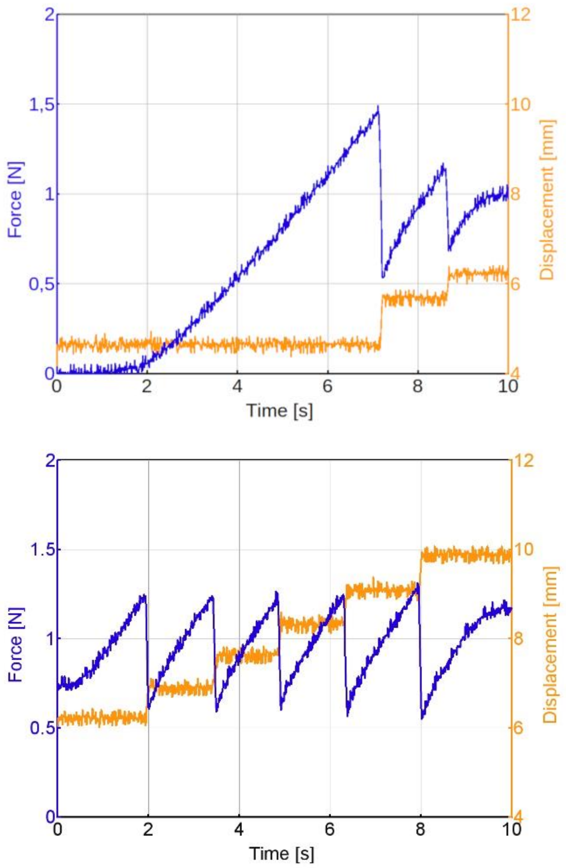
behaviour. Secondly, it must be added that the curves in Fig. 9 were obtained from two subsequent tests performed one after the other with a very short break. In the first test, Fig. 9a, the wire was not initially tensioned. On the other side it can be observed that in the second test, Fig. 9b, started directly from the final position of the previous one, a pre-tension was present. This difference of pretension also causes a different dwell time before a relative motion between the specimens was obtained. In both plots in Fig. 9, the effect produced during the acceleration and deceleration phases, at the test beginning and end respectively, is evident.



a

b

Figure 9 Measured force and displacement vs. time in test on a conformal contact. Beginning of test after a dwell time with no pre-tensioned wire (a) and successive test after a short time with pre-tensioned wire (b). Moving tower, V=0.5 mm/s, W=6 N.

In Fig. 9a it is evident that the force necessary for the initial start of the motion was rather higher than the one for the successive slip. The force value in the second peak on the first test was very similar to the peak values in the second test. Such discrepancy in the peak values can be considered also in relation to several points: pre-tension, time of rest before motion, difference in the local surface conditions (for instance the presence of wear particles or local roughness variations).

It was also observed that the dynamic behaviour of the system is strictly related to the stiffness of the wire. A stiffer fishing wire was used for repeating tests of Fig. 9. The wire's stiffness (about 2000 N/m) was about four times the one of the other wire. By comparing Fig. 9a and Fig. 10, this modification produced an increment in the number of peaks.
In successive tests, the more compliant wire was used.

3.2 EFFECT OF THE SPEED

The effect of the maximum speed of the actuator is shown in Fig. 11 (for the case of mobile tower). Plots obtained from tests at 0.5, 1 and 2 mm/s are shown in Fig. 11a, b and c, respectively.

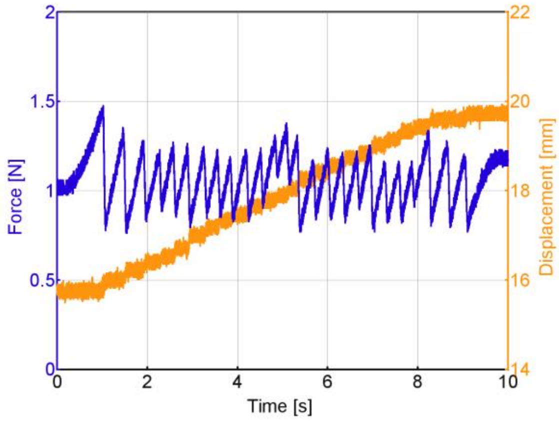


Figure 10 Measured force and displacement vs time with a stiffer wire. Moving tower, V=0.5 mm/s, W=6 N.

In these tests, data were collected at a higher sampling rate (1000 samples/s) with respect to data used in Fig. 9.
It can be observed that, as the speed increases, also the number of peaks increases. A duplication of the speed produces more or less a duplication of the force's number of peaks (note that the fist and the last seconds are not at constant speed). Additionally, the values of the maximum and minimum peaks within each test differ more and more from low to high speed.
It should be reminded that the wire was pre-tensioned at the beginning of the tests of Fig. 11a and Fig. 11b while was not for the test of Fig. 11c. Differences among the three plots depend on the speed but also on other elements as already observed: local surface conditions, pre-tension and in this case also vibrations. Particularly, vibrations became more evident at 2 mm/s through an audible noise. Finally, small differences between Fig. 9b and Fig. 11a do not depend on the sampling rate but mainly on some of the other above mentioned elements.

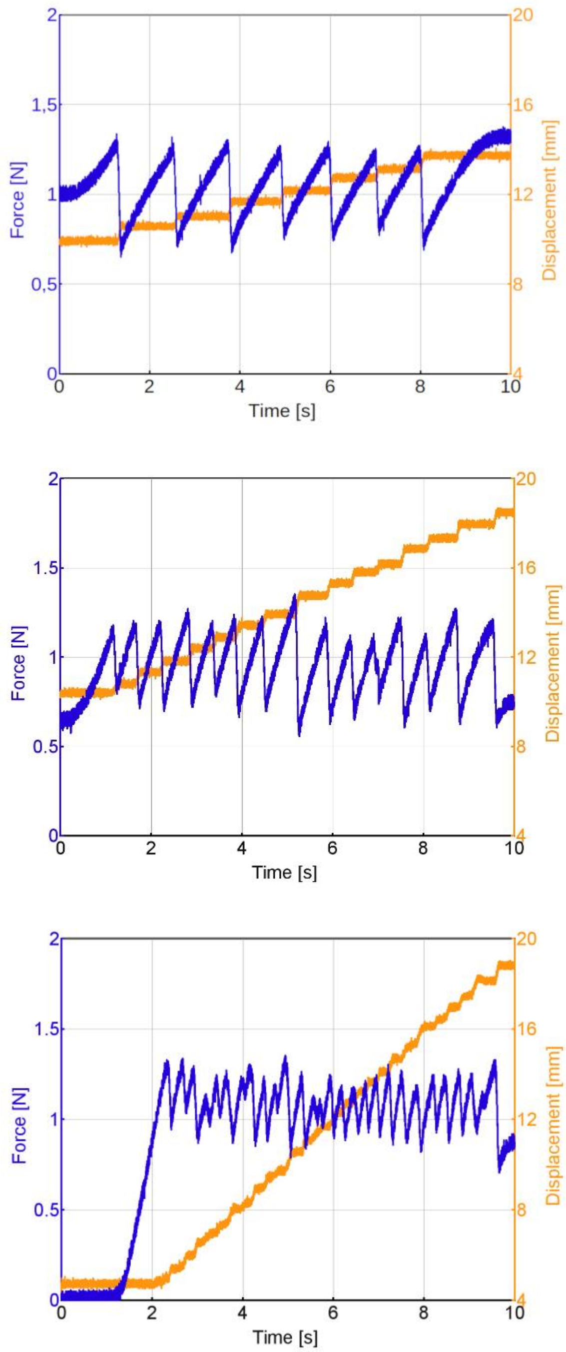
3.3 EFFECT OF THE LOAD

Figure 12 shows the results obtained for the same speed used in tests in Fig. 11 with an almost doubled normal load (W=11.6 N).
As expected, a doubled normal load corresponds roughly to a doubled friction force. It can be noted also that an

increased force results in more stable experimental signals, probably because of a reduced influence of vibrations. As far as the speed influence is concerned, observations similar to those reported in the previous section are confirmed.

3.4 EFFECT OF THE MOVING PART

The role of the moving subgroup is shown in Fig. 13, for test conditions similar to those of Fig. 11 (V=0.5, 1, 2 mm/s, W=6 N) transferring the actuation from the tower to the plane. The measured force is greater than in the case of moving tower, which produces less peaks. This could be due to reduced vibrations, which are usually associated to a decrease of friction, but also to some inertial effects.



a b c

Figure 11 Measured force and displacement vs. time on a conformal contact. Comparison of 3 maximum speeds: 0.5 mm/s (a), 1 mm/s (b) and 2 mm/s (c). Moving tower, W=6 N.

It was found that these differences decrease by increasing the normal load, which should reduce the influence of the vibrations, as already discussed.

Figure 14 compares the results obtained for the cases with W=17.2 N and V=1 mm/s with moving plane (a) and moving tower (two repetitions are shown, (b) e (c)). The test duration was 20 s. In this case differences between results obtained with moving plane or tower are almost comparable to the differences obtained in the repetitions.

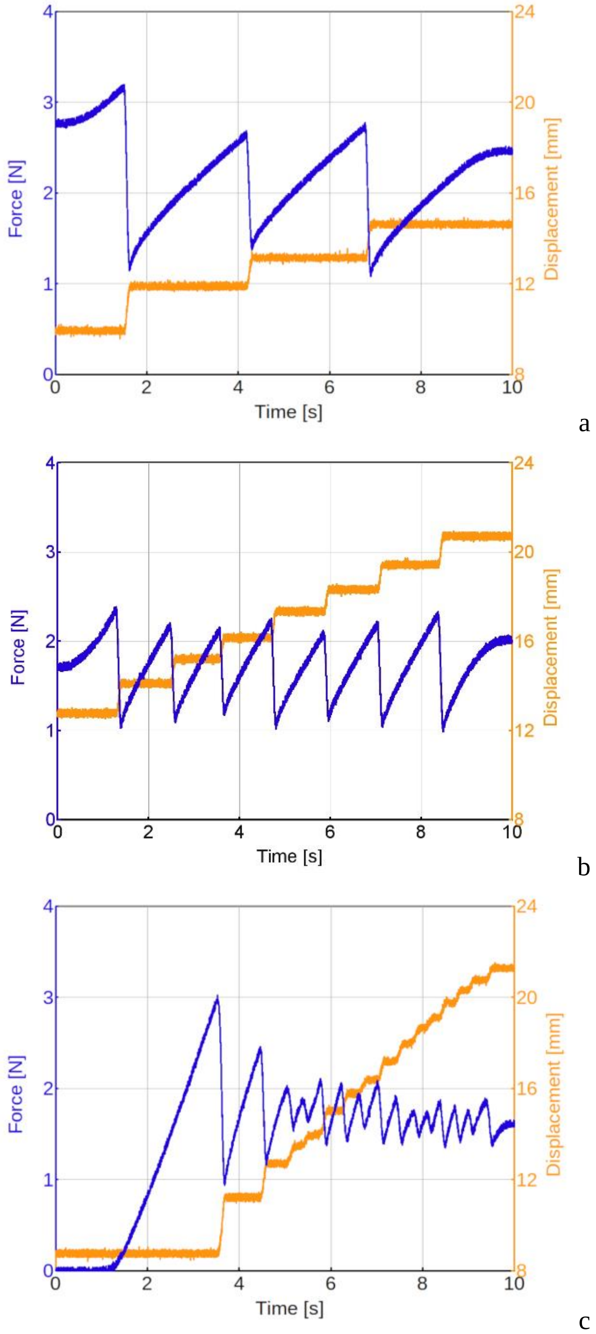


Figure 12 Measured force and displacement vs time for 3 different velocities: 0.5 mm/s (a), 1 mm/s (b) and 2 mm/s (c). Moving tower, W=11.6 N.

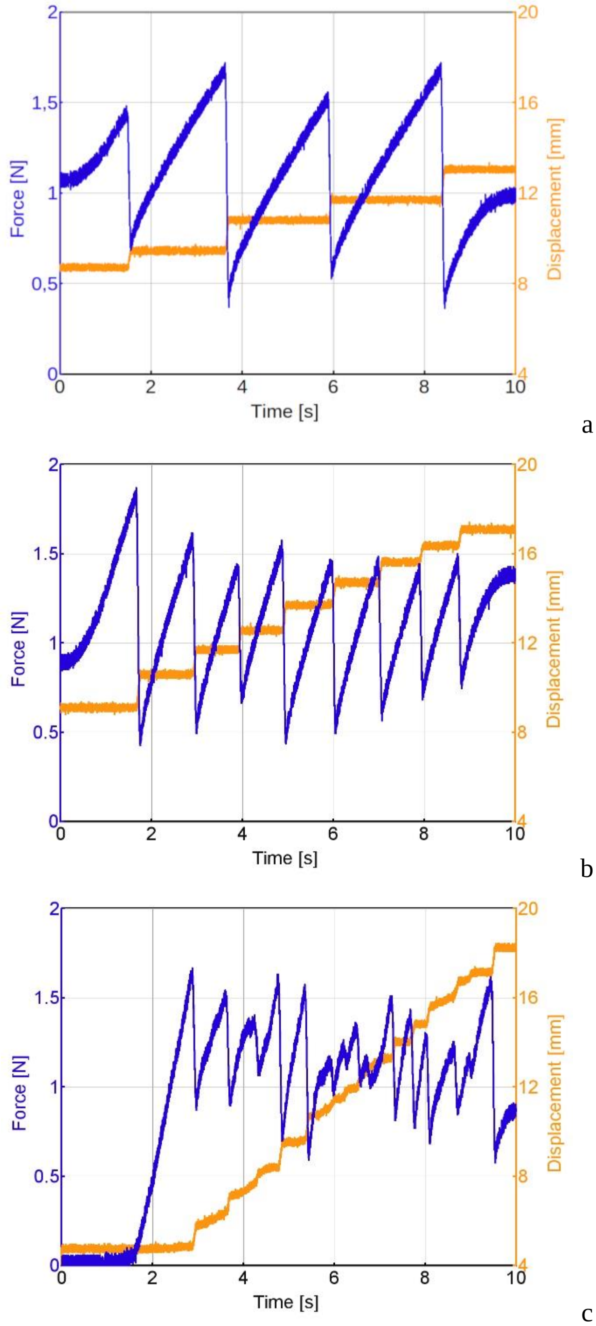


Figure 13 Measured force and displacement vs time for 3 different velocities: 0.5 mm/s (a), 1 mm/s (b) and 2 mm/s (c). Moving plane, W=6 N.

3.5 EFFECT OF THE SURFACE CONDITIONS

As it is well known, friction is markedly influenced by the surface conditions. Modifications of the roughness asperities in the specimen surfaces as well as the presence of particles (e.g. dust or wear) and contaminants yield different behaviours. The results shown in Fig. 15 give an idea of how this effect can be significant. The test of Fig. 15b was carried out after careful cleaning of the surfaces with a cleaning spray mixture of acetone and isopropanol.

3.6 TESTS ON NON-CONFORMAL CONTACTS

Some tests were carried out by using three steel ball bearings spheres with 3.175 mm diameter. They were glued on the block at 120° as shown in Fig. 4b. A picture of the contact during test was shown in Fig. 7b.

Tests were executed with two different normal loads (2.6 and 13.7 N) at 1 mm/s speed. Recorded data are plotted in Fig. 16. For the lower normal load (Fig. 16a), the measured force appears very noisy due to vibrations mixed to stick slip effects.

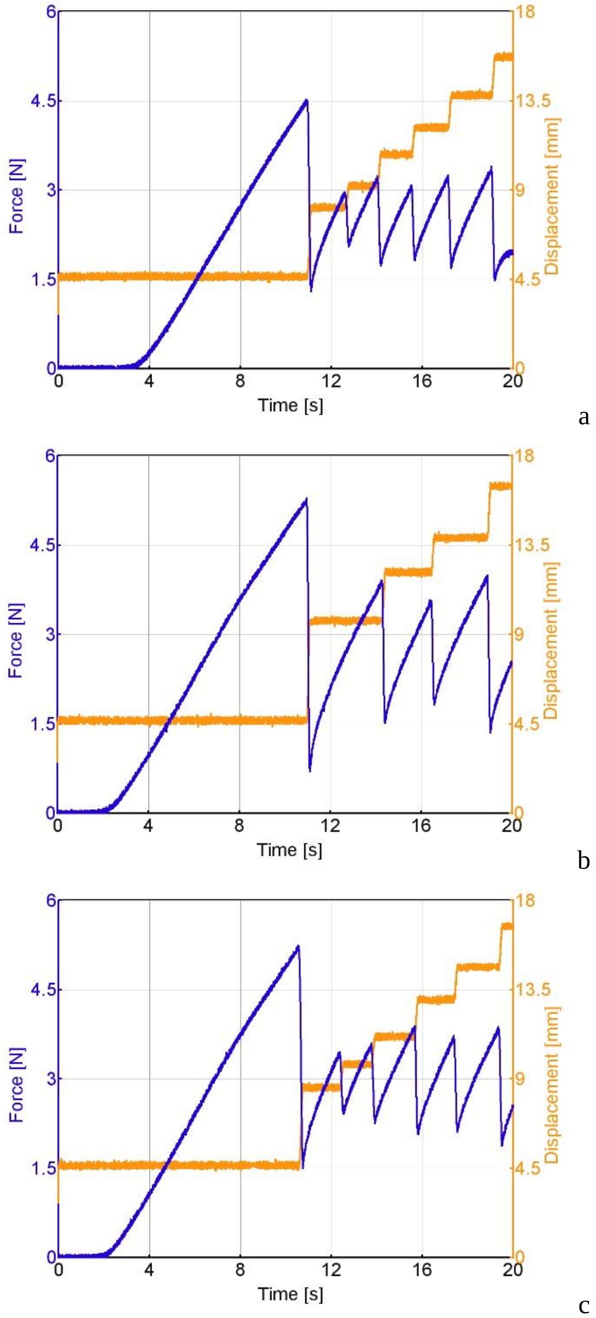


Figure 14 Measured force and displacement vs time for moving plane (a) and tower (b, c). V=1 mm/s, W=17.2 N.

Fluctuations are at higher frequency with respect to the case of Fig. 16b and to results obtained for conformal contacts. Nonetheless, it can be observed that the increment of the measured force appears proportional to the one of the normal load.

A comparison between conformal and non-conformal contact results deserves obviously many additional investigations, because of the very different level of contact pressure and surface conditions (particularly hardness and roughness). However, friction seems to be a little lower in non-conformal tests than in conformal contacts.

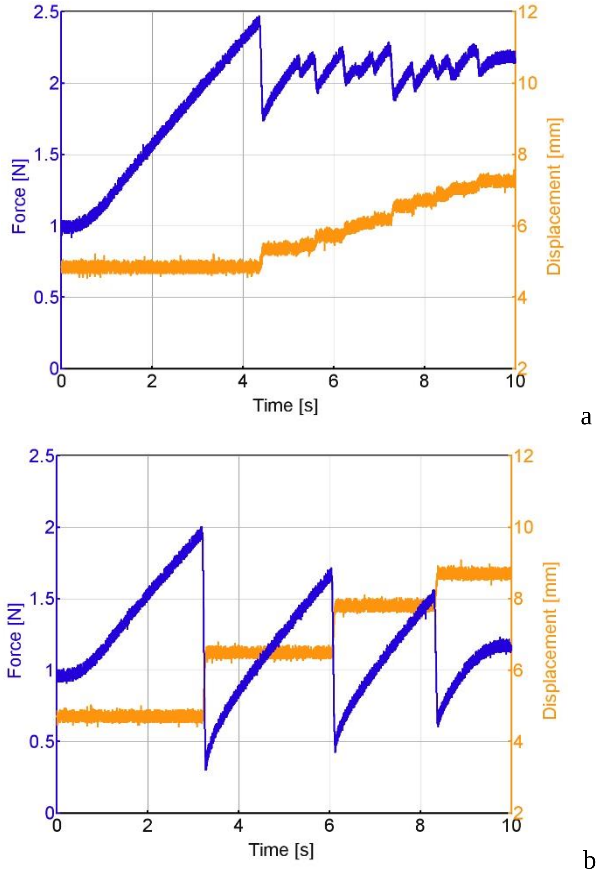


Figure 15 Measured force and displacement vs time in a test without (a) and with (b) cleaning of the specimens surfaces. Moving plane, V=0.5 mm/s, W=6 N.

4 CONCLUSIONS AND FUTURE DEVELOPMENTS

This study reports some preliminary experiments for testing the capabilities of a simple modular apparatus for investigations on static and kinetic friction. The apparatus has some peculiarities with respect to the existing test rigs, in particular the possibility to alternatively control the displacement of an upper specimen connected by an elastic wire to a moving load cell or to control the displacement of a lower specimen connected to a moving plate.

Several factors known to affect the estimation of the coefficient of friction were considered. In particular, tests were performed varying the speed of the actuator, the normal load, the surface condition, the type of contact (conformal/non-conformal). Plots of the measured force and displacement vs. time are reported and discussed.

A comparison of tests can give indication on inertial effects in CoF measurements.

The differences between results obtained in tests with very similar conditions highlight how hard it is to provide reliable values for practical applications from laboratory tests.

Interesting issues arose that indicate the ways of future investigations, as for instance the influence of the dwell time before starting the test, the influence of vibrations, the effect of a deep cleaning of the surface, the different behaviour of conformal and non-conformal contacts.

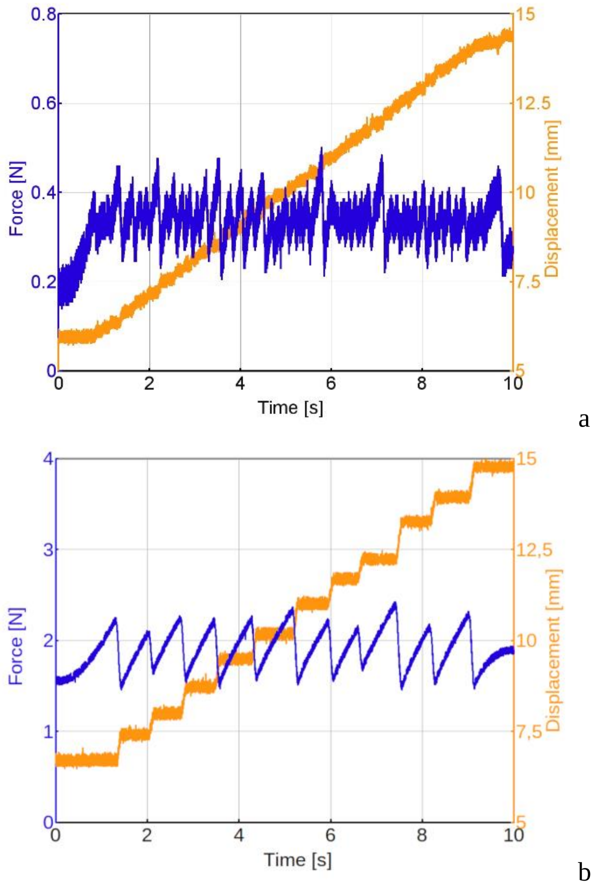


Figure 16 Measured force and displacement vs time for non-conformal contacts for two different loads: W=2.6 (a) and W=13.7 (b). Moving tower, V=1 mm/s.

It is worth recalling that friction is affected by a number of factors and each minor variation of one of them can produce a different value of the CoF. The exact reproduction of what is happening in real machine contacts is quite impossible in laboratory tests. However, an advantage of the laboratory tests is that the influence of each single factor can be deeply investigated. For instance the influence of the idle time before starting can be investigated by carrying out tests with specific different dwell times, and the effect of the surface cleaning can be investigated by using specific different cleaning procedures. A sufficient number of test repetitions will be used in order to achieve statistically significant results.

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