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Design of Test Setup for Measurement of Microslip in Clamped Interfaces using a Balanced Heterodyne Interferometer with Picometer-Resolution

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Abstract

This paper introduces a novel experimental approach for characterizing microslip with picometer-level resolution, utilizing the picodrift interferometer, a balanced twin heterodyne interferometric system developed at VSL, the National Metrology Institute in The Netherlands. The instrument provides traceable displacement measurements with a short-term uncertainty of 10 pm and long-term stability below 0.5 nm, enabling unprecedented sensitivity for studying pre-sliding behavior. In this paper the design of a dedicated insert for integration into the interferometer will be presented for applying controlled clamping forces up to 2 kN and tangential loads up to 15 N (push and pull), representative for industrial bolted connections. The setup minimizes environmental influences and ensures alignment within 100 µrad. Preliminary experiments demonstrate stable operation, high signal quality, and inline force measurements. Microslip measurements captured hysteresis loops consistent with pre-sliding behavior of aluminum parts. Under a medium clamping force of 170 N and a tangential load of 7.5 N, a residual offsets of +15.5 nm was observed after a single push-pull cycle (cycle frequency of 1 Hz), confirming irreversible displacement trends that are reduced after repeating motion references, indicating asperity settling. This study establishes a platform for systematic microslip investigation under controlled conditions and opens investigations into future design strategies for picometer-stable clamped interfaces in high-tech systems.

Keywords: microslip, pre-sliding behavior, clamped surfaces, hysteresis loop, metrology, laser interferometer, displacement

1 Introduction

As position requirements for motion stages become more stringent down to subnanometer levels, and at the same time the forces at the interfaces increase due to higher acceleration levels, shortening cycle times, physical phenomena like microslip between clamped parts on the moving platforms become more relevant. Clamped samples on moving stages are exposed to high tangential forces during acceleration phases which induce pre-sliding behaviour due to surface imperfections and irregularities between the clamped surfaces. Typically, high clamping forces prevent macroslip which refers to overall sliding of the surface beyond the global friction force. However, in the regime below stiffer contact points are less likely to deform and may slide, whereas more compliant (flexible) points remain stationary. After the movement at standstill, the compliant points of contact remain unchanged, but the stiffer ones have sled to a new position, changing the average relative position of the two clamped surfaces, and this effect is called microslip.

The goal of this work is to design and develop an experimental setup to characterize microslip in clamped connections to understand and quantify the sensitivity to relevant parameters that determine this pre-sliding behavior. The scope is to study the microslip under typical conditions of firmly bolted connections between flat, industrial machined surfaces. The results will be compared to theoretical models describing the pre-sliding behavior of multi-asperity contacts [1].

Ideally, the global average shift between the asperities, i.e. the displacement between the point of application of the tangential force and the furthest contact point, has to be detected. In three dimensions, the tangential force vector generates a slip front line within a plane perpendicular to the force vector at the contact height. Therefore, measuring the displacement of this line at the force application point is of particular interest when experimentally studying microslip.

2 Picodrift interferometer as metrology platform

Experimental characterization of microslip in clamped interfaces requires a metrology solution that combines extreme displacement sensitivity, long-term stability, and traceability to the SI unit of length. Microslip occurs in the pre-sliding regime, where tangential displacements are typically in the range of nanometers down to sub-nanometer levels, often superimposed on elastic deformation and thermal drift.

To validate analytical models (e.g., Hertzian contact mechanics, Mindlin's theory) and multi-asperity simulations [1], the measurement system must detect irreversible displacements below 1 nm over repeated loading cycles, maintain thermal stability better than 10 mK/h to avoid drift masking microslip, and provide inline integration with force application mechanisms without compromising alignment. These requirements exceed the capabilities of most tribological test benches [2] and necessitate a non-contact interferometric approach with picometer-level resolution.

The picodrift interferometer developed at VSL (National Metrology Institute in The Netherlands), is a balanced twin heterodyne interferometric instrument designed for dimensional stability studies and calibration of displacement sensors with uncertainties in the 10 pm range [3][4]. Its architecture (see figure 1) employs two heterodyne interferometers with equal optical path lengths, cancelling common-mode disturbances such as thermal expansion of the base plate and optical elements. A dedicated refractometer arm compensates for air refractive index variations. The laser source is stabilized using the Pound-Drever-Hall technique [5] and referenced to a stabilized HeNe-laser for SI traceability [6]. In the sample arm the object will be placed and the interferometer beam is reflected off both ends so that only the length change will be measured and not the lateral movement. Sensors monitor the environmental conditions and material temperatures. The entire instrument operates inside a thermally insulated enclosure achieving 1 mK/h stability [4].

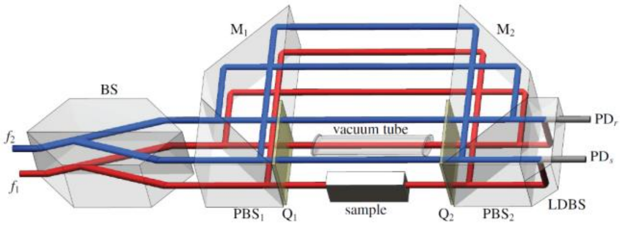

Figure 1: Schematic representation of the balanced double-sided heterodyne interferometer [4], with upper and lower beam at two different modulation frequencies, f_1 and f_2. The beamsplitter BS provides two beams, one into the sample (s) and one into the refractometer (r) interferometer. The polarizing beamsplitters (PBS1 and PBS2), quarter-waveplates (Q_1 and Q_2) and mirrors (M_1 and M_2) make sure the interferometer beam goes around and touches the sample at both reflective ends. In the refractometer, the interferometer beam passes through the vacuum tube to balance the optical path length. The lower and upper interferometer arms are combined in the final beamsplitter optics (LDBS), and the interference signal is detected by photodiodes (PD_s and PD_r). The system is fibre-coupled for receiving incoming laser beams and outcoupling to the photodiodes.

Key performance after thermal acclimatization is on the short-term 10 pm over seconds to minutes, medium-term 100 pm over an hour and long-term < 0.5 nm over 20 hours [7][8]. These characteristics make picodrift interferometer uniquely suited for detecting microslip displacements, which typically range from tens of nanometers in initial cycles to sub-nanometer offsets after asperity settling [9][10]. Previous applications include calibration of piezo actuators (virtual standards) [11][12] and thermal expansion studies of gauge blocks, confirming robustness under controlled environmental conditions.

The microslip test insert in the sample arm of the picodrift interferometer must comply with strict geometric and optical constraints to preserve its intrinsic stability and enable reliable detection of microslip at picometer resolution. The available space between the two polarizing beam splitters (PBS) is only 95 mm and the insert must avoid obstruction of reference and measurement beams with beam separation of 30 mm vertically and horizontally [3]. Reference surface of the clamped blocks should be mirror polished or have bonded mirrors attached to achieve > 70 % reflectivity. Pre-alignment of the clamped blocks and their rotation (pitch and jaw) during force activation should be limited to ±92 µrad to ensure signal integrity [10]. Heat dissipation from actuators and force sensors must be minimized. The Abbe error should be minimal so that the optical axis of the sample arm is as close as possible to the contacting surfaces of the clamped blocks.

3 Microslip test setup design

The microslip test setup for the picodrift interferometer must generate and measure the microslip behavior between two clamped surfaces, allowing for the parameters studies such as dependence on normal and tangential force, and surface and material properties.

Applying the force in-line with the contact plane is crucial. Any deviation introduces a moment arm, resulting in torque and uneven contact pressure distribution which affects microslip behavior. While sample compliance may cause a delay in the slip-line position as it moves away from the contact plane, the samples in this study are sufficiently stiff. Therefore, this delay is negligible, and the key parameter becomes the shift of the global average position after force relaxation. In this relaxed state, the slip-line position remains constant within the slip plane. Nonetheless, real-time microslip characterization is also desirable. Hence, measuring as close as possible to the contact plane is included as a design guideline.

3.1 Design specifications microslip test setup

After evaluation of the working ranges for the microslip experiments and functional conditions of the picometer interferometer the requirements are formulated for the microslip test setup and summarized in **table 1**.

Table 1: Requirements for the microslip test setup

	REQUIREMENTS
1	Measure with high resolution (sub-nanometer displacements)
2	Generate and measure a normal force up to 2 kN between the samples
3	Generate and measure a tangential (push/pull) force up to 15 N between the samples
4	Generate a contact pressure of at least 50 MPa between the samples
5	Ensure accurate alignment between the samples and the picodrift interferometer beams (± 92 µrad)
6	Obtain enough signal power on the detector of the interference of the sample laser beam (100 – 150 mV)
7	Flexibility in the sample geometry and materials
8	Minimize heat dissipation to avoid disturbing the measurement
9	Fit in the available space (95 mm x 50 mm x 40 mm) avoiding beam blockage (beam clearance radius 2.5 mm)

3.2 Metro plate

The metro plate enables the alignment of the clamped sample to the interferometer beams and maintains alignment during the measurement. Therefore, the metro plate must enable sequential alignment of each sample block in two degrees of freedom (DOF), namely *Ry* and *Rz*, for a total of four DOF with high resolution. However, for clamped samples the *Ry* tilt of the top sample is defined by its contact with the bottom sample and is thus coupled. In the microslip test setup design, manufacturing tolerances are assumed to be sufficient to avoid implementing relative *Ry* alignment between the samples.

Alignment is performed sequentially: first the bottom sample (*Rz*, *Ry*), followed by the top sample (*Rz, Ry*), although final alignment of the clamped sample is possible and desired to optimize the signal power.

3.3 Normal force frame

The normal force frame (NFF) is responsible for accurately generating and measuring the clamping force applied to the sample blocks. This force must be strictly perpendicular to the plane of contact and must not interfere with the alignment of the sample blocks. Therefore, the NFF must either be alignable or compliant with the samples' alignment mechanisms. The NFF design is based on the bolt connection concept to directly clamp the sample blocks and generate the required normal force. A load cell (ALTHEN cylindrical load washer M3 type ALF525) is placed in series with the sample blocks to measure the clamping force.

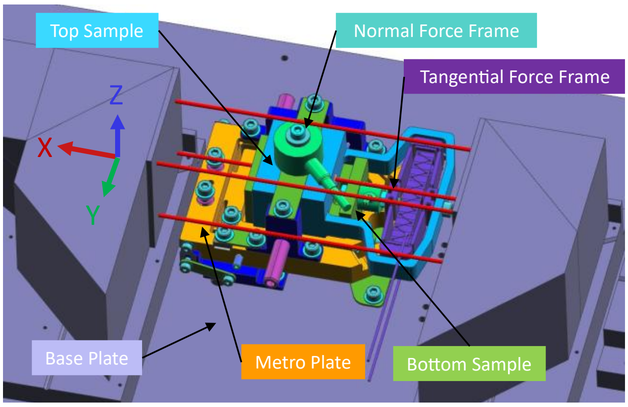

Figure 2: CAD view of the microslip test setup integrated into the picodrift Interferometer with the different functional parts.

To allow sequential alignment of the samples, the clamping force must be applied after alignment. It also serves as a locking mechanism, restraining *Rz* rotation of the top sample. However, torque-based clamping can introduce misalignment during tightening. To mitigate this, a torque release mechanism is implemented. A thin leaf spring is inserted between the top sample and the load cell and fixed in place using bolts at each *Rz* adjustment block. Additionally, a small axial needle bearing is placed between the washer-nut pair and the bottom sample to reduce the impact of the tightening torque in the alignment of the samples.

This setup allows for precise alignment and symmetric stress distribution. Moreover, since microslip is most relevant in bolted connections, this concept closely replicates real-world conditions.

3.4 Tangential force frame

To correctly measure microslip, the relative displacement of the reference surfaces of the clamped samples must be in the direction of the optical axis. This ensures that the true displacement is detected by the interferometer and that the signal remains stable throughout the experiment. While some displacement or tilt in other directions may occur due to the nature of microslip, excessive tilt can lead to signal loss.

Since the actuation surfaces and reference surfaces are not colinear and may differ in orientation due to manufacturing tolerances, applying a force aligned with the optical axis becomes challenging. Only the reference surfaces are aligned precisely using interferometer feedback, so the tangential force frame must accommodate misalignment between the actuation surfaces.

The tangential force frame (TFF) design is based on the car jack concept and utilizes the APF705 amplified piezoelectric actuator from Thorlabs. This actuator features an open frame that preloads the piezoelectric element, which bridges two opposite joints. When voltage is applied, the piezo element expands slightly; this displacement is amplified by the frame, resulting in a noticeable inward movement between the other two joints. Conversely, applying a negative voltage causes the piezo to contract, pushing the actuation faces outward.

Although the APF705 is primarily designed for precise positioning, its force capabilities, amplified range, and compliance in the actuation direction and in *Rz* allows to cope with tolerances in the position of the sample blocks.

To measure the tangential force exerted between the sample blocks, a load cell (ALTHEN load cell type ALF259) is integrated between the actuator frame and the bottom sample. The load cell features threaded studs on both ends, allowing it to measure both compression and tension forces within the force loop.

The actuator is intended to be controlled in closed-loop control using feedback force readings from the load cell. However, during initial experiments it is operated in open-loop mode. A reference voltage signal is applied to the actuator, mimicking the desired force profile. The actual force is measured by the load cell and compared to the displacement recorded by the picodrift interferometer to characterize microslip behavior.

3.5 Sample blocks

The plane of contact is defined by the interface between the top and bottom sample blocks and is characterized by asperity geometry, friction coefficient, shear modulus, surface flatness, and structural stiffness all affecting the microslip behavior. To achieve the required contact pressure while maintaining stability, the nominal area must be carefully dimensioned. The shape should be uniform to ensure the slip front moves directly opposite to the tangential force, avoiding tilt unless caused by asperity distribution. To reach the required contact pressure of 50 MPa with a clamping force of 2 kN, a ring contact area of 27.6 mm^2 is designed, preferred for even pressure distribution, and to minimize the gap between the maximum and minimum contact pressures. The bottom sample includes a compliant extrusion, and the contact area is slightly larger than that of the top sample to maintain consistency during microslip.

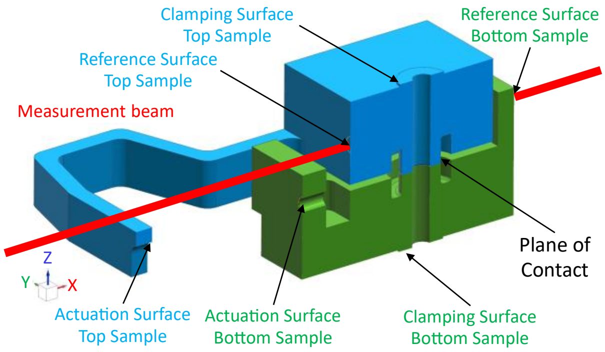

Figure 3: Section view of the sample blocks with detail of the plane of contact and reference surfaces for the interferometer beams.

Each sample block has a reference surface for the interferometer beam. The vertical distance between the plane of contact and the laser beam axis is approximately 10 mm, which is the Abbe offset (see figure 3). Small plane mirrors are glued to the sample block at the reference surfaces.

A number of samples blocks have been manufactured from aluminum 6082 T6. The surface roughness of one bottom sample has been measured using an AFM on 100 x 100 µm^2 measuring areas obtaining an S_q values in the range from 0.05 to 0.09 µm.

4 Experimental results

The microslip test setup is assembled and integrated into the picodrift interferometer. Alignment of the samples to the interferometer is realizable and signal power up to 800 mV is achieved, meaning 61.5 % power of the reference beams. During the microslip measurement, the alignment of the sample blocks is maintained, and the power variation of the signal is negligible. The TFF is able to produce forces up to 15 N for both push and pull between the samples as detected by the load cell. As for the NFF, to evaluate the alignment of this force with the plane of contact wear observation methods could be employed. Nonetheless, the signal of the measurement beam is very stable during the microslip measurements, which means that the clamped samples do not rotate, implying that the alignment of this force is accurate.

Heat sources were minimized in the setup by different design decisions, such as short testing times (≤ 15 min), the use of a piezo actuator at low frequency, turning off the clamping force load cell during the measurement, the use of heat shields and allow for temperature to settle. The temperature variation recorded during experimentation is kept below 5 mK.

4.1 Microslip experimentation

The tangential actuator is energized to complete one full pull-push cycle (1 Hz). Several cycles are repeated reverting the order of actuation (i.e. pull-push, push-pull, pull-push, pull-push, push-pull, push-pull) and increasing the tangential force applied each series (i.e. 2 N, 5 N, 7.5 N, 10 N, 15 N). The clamping force is maintained during this actuation sequence. Different clamping force levels are studied.

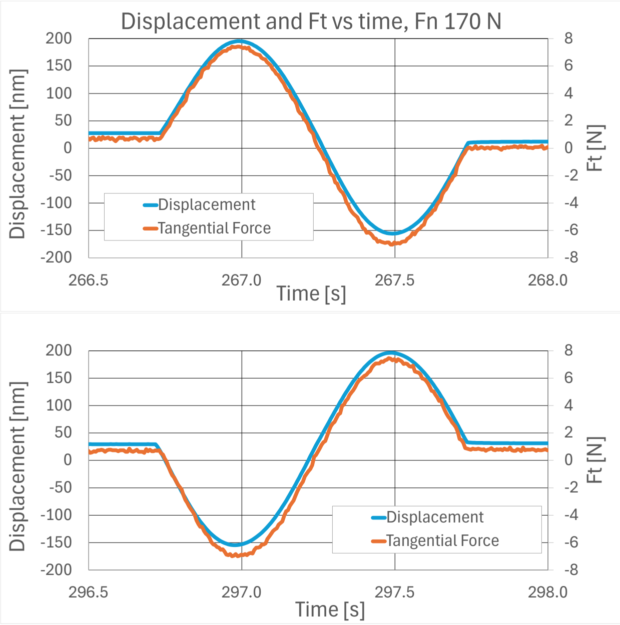

Figure 4: Measured displacement and tangential force versus time during one cycle for 170 N of clamping force: (upper) pull-push reversal resulting in +15.5 nm and +0.63 N, and (lower) push-pull repeated resulting in -1.6 nm and -0.10 N of hysteresis after activation.

After the first cycle (i.e. pull-push), the measured hysteresis displacement between the initial and final position of the reference surfaces of the clamped samples is +15.5 nm (see figure 4 upper graph). This hysteresis captured is consistent in the applied cycles where the order of actuation is reverted, i.e. changing from push-pull to pull-push. For the cycle where the order of actuation is not reverted, the measured microslip displacement is reduced to just -1.6 nm (see figure 4 lower graph). This is consistent with microslip behavior, as asperities find a more stable location.

Because the piezo was operated in open-loop the tangential force reading by the load cell does not drop back to its initial value after activation cycle (see figure 4). Stiffness of the actuator combined with hysteresis in the actuator: when energizing and de-energizing the piezo actuator, it does not return to its initial position. According to spec sheet of the APF705, a 15.4 µm of hysteresis for a full cycle of -30 V to 150 V is expected. This hysteresis combined with the stiffness of the microslip setup could produce a force between the samples. This force can be estimated to 1.03 N. Although it is not fully understood how this effect would show for a constrained displacement of the actuator as it is in this case, the estimated value is very close to that read by the load cell. Therefore, implementation of closed-loop control of the tangential actuator using feedback from the load cell is recommended to improve force accuracy and repeatability.

5 Conclusion and discussion

The realization of the microslip setup meets the majority of the defined requirements: the normal force frame is capable of generating and measuring clamping forces up to 2000 N; The tangential force frame successfully applies bi-directional forces up to 15 N, enabling controlled microslip initiation and measurement; The alignment of the samples to the interferometer was achieved with high precision, maintaining signal power and stability throughout the experiments; The picodrift interferometer provided reliable displacement readings with minimal drift, validating its suitability for microslip characterization; Measurements using the microslip setup captured hysteresis consistent with microslip behavior; The modular design allows flexible adaptation to different materials and geometries of samples, and the use of flexure elements ensures repeatable alignment without mechanical play.

Early testing and final experimentation confirmed the feasibility of the setup and its capability to isolate and measure hysteresis behavior consistent with microslip under controlled conditions.

This result highlights the need for more complete theoretical models and further analysis of the microslip test setup. In summary, this work lays a solid foundation for future microslip research and provides a platform for experimental studies that can inform design strategies in high-precision mechanical systems.

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