Mechanical stresses in building structures and dry friction - ways to improve the durability of architectural structures

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Abstract-In this work, the authors offer a new approach to the problem of structural strength of architectural constructions and buildings. The authors propose to circumvent the problem of the multiplicity and complexity of numerical methods of calculation by reformulating the problem in terms of the concept of dry friction. A large architectural structure is essentially a combination of solids in contact. Monolithic structures consist of reinforced material, filler and binder, moreover, even the highest quality structure cannot escape systems of developing cracks.In addition, the requirements for seismic resistance and heat resistance make it necessary to introduce gaps, flexible seams and other elements into the structure that do not allow one to consider the architectural structure as an undeformable solid. The proposed approach will allow a deformable body to be considered as a set of connected solids - building elements. Similar approaches in seismology make it possible to obtain reliable results. Reconfiguring problems through a thermodynamic interpretation of the problem of dry friction will radically simplify the mathematical models, more directly introduce empirical parameters (by means of simple and direct measurements, rather than model calculations with discussed accuracy).

Keywords: circumvent, Monolithic, thermodynamic

Introduction

The problem of the strength of architectural structures and buildings has a transparent economic content, social life requires buildings of ever-larger sizes and preferably of less cost. Violation of the balance of the system "society-nature" has led to the fact that the production of any product is usually associated with environmental pollution. The reason is that most technological processes are far from perfect and include the formation of intermediate substances or end products that do not participate in the further production process and, therefore, become waste.It is necessary to minimize waste generation, striving for optimality in the creation of any engineering structures, and architectural structures in particular (Voskresenskaya et al., 2019).With an increase in the size of buildings, the problem of strength acquires an additional dimension - the larger the structure, the greater the requirement for the load on structural materials, the lower floors of high-rise buildings must withstand the weight of all overlying ones, and therefore this weight should be minimized. However, to what extent it must be minimized? Where is the limit after which a decrease in the weight of structures becomes unacceptable due to a drop in strength?For architectural purposes, numerous engineering design methods have been developed, which are overcomplicated with:

- various ways of taking into account mechanical stresses;
- modeling of propagation and dissipation in the structures of these mechanical stresses;
- modeling the behavior of structural materials under a load of mechanical stresses.

However, the authors want to offer a radically different approach, having reconstructed the task of modeling the propagation of mechanical stresses in a building through the forces of dry friction.Dry friction forces and friction forces generally have a strange status in physics. On the one hand, friction is universal and occurs almost everywhere. On the other hand, friction does not belong to the fundamental forces of nature and is usually presented as the result of the action of many random and uncoordinated forces. Physicists today rarely pay attention to friction, believing its study to be purely applied, engineering (Nosonovsky&Mortazavi, 2013).The authors focus on friction and give a detailed justification of their approach. Because friction seems to the authors to be the most general mechanism for representing the interaction of bodies, the fact is that such different

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mechanisms of interaction of contacting bodies can be interpreted mathematically. This is all noteworthy because, with the unity of the mathematical description, the phenomena that take place in practice are extremely heterogeneous.The practical meaning of the authors' approach is to use this phenomenon, to consider the interaction of solid deformable bodies (that make up architectural structures) through the mathematics of dry friction forces. Thereby, the authors want to simplify mathematical models and to get rid of semi-empirical dependencies.Namely, by expanding fundamental concepts in models, not to the detriment of their accuracy.It is known that the law of friction of Coulomb-Amontons, $F=\mu W$, says that friction, F,is proportional to normal load, W.This law is carried out for the most different combinations of materials, for the most different mechanisms of friction, and for very different friction conditions(Nosonovsky&Mortazavi, 2013).According to modern concepts, there are different dry friction mechanisms that have nothing to do with each other. Among these mechanisms are:
- adhesion (which itself is the result of the action of dissimilar forces - van der Waals, electrostatic, covalent bond and capillary effect);
- deformation of roughness protrusions;
- ratchet mechanism of roughness engagement;
- emission of elastic waves (phonons);
- the influence of the so-called “third body” (i.e. debris and lubrication);
- atomic-molecular mechanisms (Tomlinson-Frenkel-Kontorova) (Guo et al., 2011), associated with the elasticity and kinetics of overcoming metastable energy barriers of the lattice. At first glance, there is nothing in common between these mechanisms. Despite such a divergence in mechanisms, friction is a universal phenomenon. For example, for loads from nano-newtons (in nanotribology) to billions of tons (in seismology). For metals, polymers, ceramics, composites, one can safely generalize - for any materials. Moreover, friction is not a single phenomenon. Friction mechanisms can be of a very different nature - deformation, adhesion, fracture, plastic inception, scaling of roughness ledges, chain mechanism (ratcheting), etc.All these mechanisms that seem to have nothing in common, for completely different materials, for completely different situations, are completely randomly described by the same empirical law, and this reflects some fundamental regularity. In order to make it possible to use it in general engineering problems, this regularity needs to be identified and described, and this is precisely what will be the goal of this work.

The dynamic problem of the contact (and uniform motion relative to each other) of two plane elastic bodies (each of which is a half-space characterized by three constant parameters: elastic modulus, Poisson's ratio and density) with a constant coefficient of friction between them is a simple mathematical problem. The latter could have been solved in the 19th century. Despite this, it was studied in detail only in the mid-1990s by G. Adams (Adams, 1995).G. Adams showed that for a wide range of material parameters, such a motion is unstable even in the quasistatic limit of low sliding velocities. In other words, if two bodies glide relative to each other, then friction makes such a movement dynamically unstable. Instability manifests itself in the form of surface elastic waves in a material.The amplitude of such waves decays exponentially with distance from the surface, but grows exponentially with time. This type of frictional instability is now called the "Adams-Martins instability" (Nosonovsky&Mortazavi, 2013).

Materials and methods

To construct the model, the authors use the friction instabilities of Adams-Martins. Such instabilities can play a role in vibrations caused by friction (for example, creaking brakes or even a door hinge). In the case of a linear problem, the amplitude increase is not limited, but in practice, if the amplitude becomes large, the formulation of the linear problem will not be applicable. Either there will be a loss of contact between the bodies, or the system will go into a nonlinear mode and come to a certain limit cycle characterized by twitching (stick-slip mode), by the formation of local propagating slip zones or the like. As a rule, also, if any periodic structures form on the boundary between the bodies, this leads to a decrease in the observed coefficient of friction, since the body cannot move entirely, but by spreading slip zones (like a caterpillar or like a shaken carpet). The existence of Adams-Martins instabilities is, to some extent, a paradoxical result, since no one could have imagined that such a simple phenomenon as sliding with friction is unstable (and, it turns out, should not exist in practice).There are a number of approaches to the regularization of this paradox, in particular, the famous James Rice from Harvard (one of the largest mechanics of our time) in the late 90s became interested in this topic and suggested using dynamic state and friction laws for this purpose (Rice,1993). However, apparently, it is one of the manifestations of the paradoxical nature of Coulomb friction in general(Joughin et al., 2019), for it leads to many dynamic and static paradoxes. The most famous of them are the Painlevé paradoxes (Charles&Ballard, 2016), manifested in the absence of a solution or non-uniqueness of a solution in many friction systems.

Results and Discussion

To test the proposed approach, the authors resort to numerical simulation and consider a system of several concrete monoliths lying on top of each other without a rigid connection, which are in communication only by means of dry friction forces. The authors simulate the passage of a compression wave through this system and the dissipation of the energy of this wave. Figures 1-2-3 show the relative change in size in relative units at the time of the passage of the wave.The dots depict controlled points on concrete products, the circles show the amplitude of the wave, it can be seen that the lower layers are less affected. One can see the relative change in size and deformation of concrete products. The figures differ in wavelength and amplitude; since the values are not absolute, only the relative scale of the values matters. In Figure 2, the wavelength is one and a half times longer than for the first figure, for the third figure, the wave amplitude is twice as large.The circles draw a change in the coordinate during the passage of the wave, it can be seen that these are rather elliptical trajectories and, thus, there is some kind of analog of the Rayleigh waves. These figures demonstrate that the mathematical model built around the forces of dry friction is quite suitable for calculating the parameters of architectural structures.

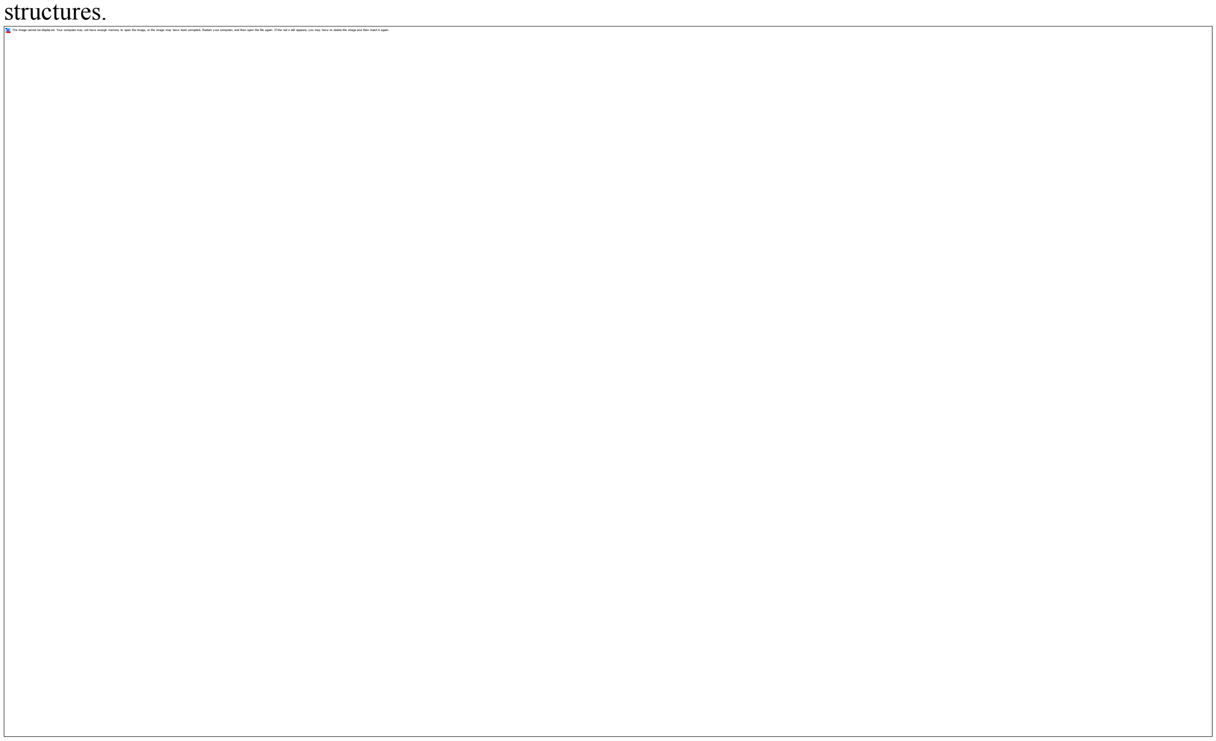

Figure 1. Propagation of compression waves in bonded concrete structures

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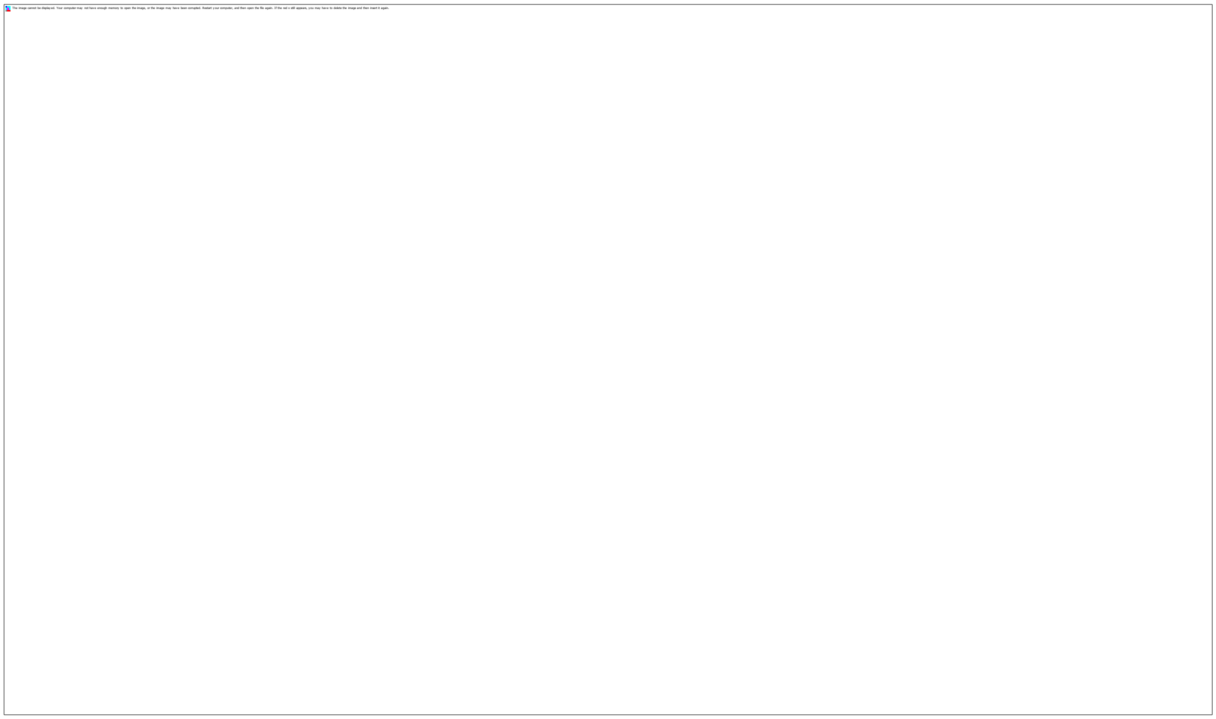

Figure 2. Propagation of compression waves in bonded concrete structures

Figure 3. Propagation of compression waves in bonded concrete structures

In the authors' opinion, Adams-Martins instabilities are a rather important discovery, since they allow one to take a fresh look at such a fundamental phenomenon as friction. It is promising for many industries to look at them through the prism of modern computational methods (such as molecular dynamics) and compare them with experimental observations in modern branches of physics and chemistry. However, the authors will confine this study solely to the case of architectural structures. There are other types of instabilities caused by friction, which can lead to oscillations. The most famous of them are thermoelastic instabilities and instabilities associated with the so-called "negative viscosity". Thermoelastic instabilities, which have been actively studied by prof. J.

Barber since the late 1960s(Barber, 2018), are connected to the fact that from friction the body heats up and expands. From expansion, contact pressure increases, and hence friction increases, and heat generation only increases, creating a positive response in the system. As a result, if due to random fluctuation in some place the temperature is slightly higher than the temperature in neighboring place, the temperature starts to grow, forming a “hot spot”, and friction also grows with it. "Negative viscosity" is the conditional name for the reduction of the coefficient of friction with speed, which is very typical for dry friction. The fact is that with an increase in the sliding speed, individual protrusions of the roughness do not have time to deform, and the adhesion between the bodies, and with it the friction, often decrease. If, with increasing speed, the friction force decreases (albeit insignificantly), this leads to a further acceleration and further decrease in friction. That is, again, leads to instability, which grows in the linear zone of the process until it is compensated by some other process (for example, positive viscosity from air resistance).In all these processes, the common thing is that friction is associated with some other effect (thermal expansion, wear, etc.), which leads to feedback and instability. The formation of spatio-temporal structures on the principle of "sticking-slipping" (Donget al., 2019) is also interesting that it is associated with a very special (and important) type of self-organization called "self-organizing critical behavior" (SOC) (Buck &Endenburg, 2012). This phenomenon was discovered and studied in the eighties of the last century. This phenomenon can be called fundamental for the most diverse branches of nature, society and technology. In a nutshell, SOC manifests itself when the system adjusts itself to a certain “critical mode”, for example, a heap of sand (this is a standard example) thanks to friction maintains the same angle of inclination; exceeding the critical slope leads to a collapse, a decrease leads to the accumulation of sand.Adding a single grain of sand may not change anything (a grain of sand will lie quietly) or cause a large or small avalanche. However, statistically, the amplitudes of avalanches obey very interesting patterns. The same regularities are manifested in the statistics of earthquake magnitudes of the so-called Gutenberg–Richter law (Navas-Portella et al., 2018), since there also takes place the accumulation of elastic energy during plate deformation and its quick release when the threshold is exceeded, i.e. the above-mentioned stick-slip. These laws can be extended to the mechanics of large architectural structures, the laws of accumulation and discharge of mechanical stresses are extremely important for the design of high-rise buildings. All these are purely mechanical examples, but, in the authors' opinion, much more interesting effects can be described if the study of instabilities is combined with a thermodynamic approach.The authors believe that the laws of friction should be derived from the second law of thermodynamics (through the Onsager approach and the principle of co-directionality of thermodynamic forces and flows)(Ławrynowicz et al., 2018), and not empirically introduced, as is usually done. The thermodynamic description makes it possible to include tribochemical reactions, diffusion, and a number of other effects in the picture of instabilities. For example, if friction creates a temperature field gradient, this gradient can be coupled with diffusion and mass transfer in such a way that a protective film is created on the surface from a softer phase of the composite material or alloy.The friction force can locally depend on the film thickness, and, from the point of view of a formal stability analysis, this differs little from the situation when friction depends on speed (the equations look the same, regardless of which parameter is coupled to friction - speed or tribofilm thickness). There is a parallel with a purely mechanical process here along several lines - just like mechanics, there is instability, which leads to the fact that the stationary state (uniform distribution of material) is replaced by the formation of surface structures, which can lead to a decrease in friction. The dynamics of the process here are more important than empirical laws.A classic illustration of the conjugation of thermodynamic forces is the so-called thermal diffusion (thermophoresis or Soret effect) (Koehler&Morozov, 2016). For example, if a red-hot wire is placed in an environment where smoke particles are evenly distributed, then after a while the concentration of smoke particles near the stem decreases (the effect has a characteristic length of about a millimeter). This is because, from the side of the rod, the particles are hit by hotter air molecules. As a result, despite the particle concentration gradient, diffusion does not occur, since it is balanced by the temperature gradient.Heat transfer and diffusion are conjugate, the corresponding forces (gradient T and concentration gradient) cross-influence the corresponding fluxes (heat and mass transfer). This is directly related to friction. For example, instead of a heated body, one can consider a friction interface that also creates a temperature gradient and mass transfer (which, of course, is much less intense in a solid material than in a gas or sol (sol-gel, suspension or similar non-solid phases) but it also takes place).When an electric current is added to this (for example, in a sliding current collector, or, in a more complicated case, in the contact of a microelectromechanical, MEMS device) as well as a chemical reaction, a plasma, and other, the system can become very complex and evolve to the formation of "secondary structures" in the material. These processes depend on the structure of the composite material, thus leading to the establishment of structure-property relationships (Tilley, 2016). At first glance, these systems of interdependence of properties seem very complex, but the authors argue that in the case of solving the problem through friction, the dependencies will become quite accessible for analysis. In other words, the essence of the authors' approach is to describe how material parameters (concentration, magnitude and shape of reinforcing particles, matrix properties, phase boundary

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properties, etc.) affect the ability to form a protective film. Thus, the authors aim to help material scientists create self-lubricating and other anti-friction materials and modify the behavior of a system of solids under the influence of prolonged alternating mechanical stresses.

It must be said that self-organization during friction was actively engaged in the institutes of the former USSR in Russia (as well as Ukraine and Belarus) in the 1980s, where it was a rather large area in which several groups worked, published many articles and wrote dissertations. To a certain extent, this was a reaction to the popularity of Prigogine's synergetics in the USSR. Soviet mechanics created their own terminology (sometimes successful, sometimes not), like "servovite film" (Gerashchenko et al., 2018)and "selective transfer" (Zakovorotny et al., 2019). However, on the whole, no significant results (that is, those included in engineering practices and physics training courses) were produced; these were, as a rule, researchers at the engineering warehouse; today, alas, this is a marginal area of tribology that has not been included in textbooks, which most tribologists are not aware of.Although in the authors' opinion, there is great potential here, especially in connection with modern "smart", "biomimetic" and "meta-" materials.

Another example of self-organization is related to the running-in transition (Cao et al., 2017). The fact is that when the slip begins, often the first time the friction and wear are large, and then it decreases to a stationary value. This is because the surfaces seem to adjust to each other, and in the sense of topography (for example, when the highest protrusions of roughness break), and in the sense of the formation/destruction of surface films. Kragelsky proposed the elegant idea of "equilibrium roughness" (Kragelsky et al., 2013), but in modern tribology, it eventually did not become popular. Quantitatively, this can be described, for example, by determining the Shannon entropy of surface topography (in fact, how many bits of information are needed to describe a rough profile). With self-organization, the number of bits decreases. The principle "friction is large first and then decreases to a stationary value" is very general. For example, static friction (rest friction) is greater than kinetic (sliding friction). As the contact age increases, friction increases (this, by the way, is the reverse side of "negative viscosity").In dynamic friction models (mentioned state-and-rate), the principle is that when the sliding speed changes (it does not matter whether it increases or decreases), the friction increases first, and then decreases to a stationary constant level (which itself may depend on speed). This is a general principle, which, apparently, is associated with (rather unobvious) Prigogine theorem on the minimum entropy production (Vincze&Szasz, 2019). The system itself enters a regime in which energy dissipation is minimal.

Friction and wear reflect the tendency of energy to irreversible dissipation, and the material to irreversible destruction. Both that and another are connected with the second law of thermodynamics. There are four fundamental laws in mechanics. Two laws of motion formulated by Euler (for linear and rotational motion) and two laws of thermodynamics.The law of friction is added to them artificially, as an additional condition. At the same time, there is reason to believe that it is associated with the second law of thermodynamics (which is formulated as inequality). An important feature of friction is also the fact that it is a surface (i.e., fundamentally two-dimensional) phenomenon. The transition from three-dimensional to two-dimensional laws is usually carried out in mechanics by asymptotic expansion (for example, from the 3D theory of elasticity, one can obtain the theory of thin elastic 2D plates and shells).The authors believe that the combination of the Onsager thermodynamic approach (the relationship between forces and flows) and linearization based on the transition to a 2D system should lead to the fact that the law of friction can be formulated in the general case (regardless of the specific mechanism), but this is a topic for further research.

In general, the authors believe that the thermodynamic methods for tribology are quite marginal today, but cause a growing interest, and deserve much more attention. Thus, for example, let us consider wear, power dissipation, and temperature rise; adhesive wear of materials is always accompanied by dissipation of friction energy and, consequently, an increase in contact temperature.Numerous studies suggest a linear correlation between wear rate, power dissipation, and temperature rise (Amiri&Khonsari, 2010; Aghdam&Khonsari, 2014), moreover, the authors recommend the reader to consider the list of mentioned works (references) for a more complete understanding of the topic. In order to better study the correlations between wear rate, power dissipation and temperature increase, the authors propose using two characteristic coefficients for any given slip system.The first one,ψ_w , connects power dissipation with wear and can be obtained in laboratory experiments. The second coefficient, called the power dissipation factor with increasing temperature ψ_T, relates the temperature increase in the system to the heat generated during friction.

The work(Aghdam&Khonsari, 2014)shows that the coefficient ψ_T can be easily obtained by analysis of finite-difference analogues. These correlations can be expressed as follows:

$$w = P_d \psi_w$$

$$P_d = \Delta T \, \psi_T$$

Where, $w - wear\ rate$, expressed through a coefficient ψ_w , andP_d - power dissipated in friction.

Conclusions

Thus, the following provisions become apparent. The wear rate of rubbing surfaces as such can be used to predict or evaluate not only wear but also tribological properties of materials and structures. In fact, this is the basis of the special wear assessment methodology proposed in this study. However, it should be remembered that the coefficientψ_w and the degradation coefficients are by no means universal constants and, like any other material or tribological property, are subject to change. For example, the above coefficients will certainly change if:

- a change in load and sliding speed activates a mechanism of different wear;
- the resulting temperature increase becomes so strong that the thermomechanical properties of the interface are affected by phase transitions in the surface material caused by an increase in surface temperature.

However, in the absence of such effects, it is proposed that by measuring the temperature in a sliding system, power dissipation and ultimately wear can be calculated. For this, it is necessary to consider the coefficients ψ_w andψ_T. Coefficient $\psi_w$is obtained on the basis of independent test data. Besides, the coefficientψ_T can be easily obtained by thermal analysis of the tribocouple. The results presented in this work demonstrate the usefulness of a thermodynamically well-grounded methodology for predicting the behavior of a mechanical system as a whole in a dry slip configuration for two different material pairs. Although temperature measurements have not been originally carried out in an experimental study, modeling provides evidence that this approach can be put into practice.

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