

## EXPERIMENTAL DETERMINATION AND STUDY OF STRUCTURAL DAMPING AND DRY FRICTION

Ognjen Mijatović<sup>1</sup>  
Zoran Mišković<sup>2</sup>  
Ratko Salatić<sup>3</sup>  
Rastislav Mandić<sup>4</sup>  
Matija Guzjan-Dilber<sup>5</sup>  
Goran Jotić<sup>6</sup>

UDK: 539.67

DOI: 10.14415/konferencijaGFS2021.29

**Summary:** *The challenge that will be posed to researchers for an even longer period is the development of a predictable model for describing mechanical connections, their variable stiffness and dissipative contact interaction processes. The main challenge to this goal lies in the lack of understanding of how friction behaves on a small scale. Coulomb friction, a large heuristic model is not predictable and has actually been proven to be untrue in many modes. Expecting a universal law of friction for all types of materials and therefore contact interactions is not very realistic. Instead, the goal of the international research community is to develop a predictable model for a limited range of cases. So far, the metal-metal contact is most often tested, respectively the contact interaction behaviour of aluminium and steel elements of different quality. We also know that in the application those two metals are most often found in making mechanical connections. The aim of this paper is to make a brief overview of some of the previous tests and approaches to the study of contact interaction in mechanical connections and the role of friction in energy dissipation.*

**Keywords:** *contact interaction, damping, dry friction, mechanical connections.*

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<sup>1</sup> Ognjen Mijatović, Civ.Eng., DNEC - Construction Engineering Consultancy, Bulevar Mihajla Pupina 115v, Belgrade, Serbia. Faculty of Civil Engineering University of Belgrade, Bul Kralja Aleksandra 73, Belgrade, Serbia, tel: ++387 65 765 484, e – mail: mijatovicognjennada@gmail.com

<sup>2</sup> V.prof. dr Zoran Mišković, Civ.Eng., University of Belgrade, Faculty of Civil Engineering, Bulevar kralja Aleksandra 73, Belgrade, Serbia, tel: +381 11 3218 620, e – mail: mzorani@imk.grf.bg.ac.rs

<sup>3</sup> F.prof. dr Ratko Salatić, Civ.Eng., University of Belgrade, Faculty of Civil Engineering, Bulevar kralja Aleksandra 73, Belgrade, Serbia, tel: +381 11 3218 580, e – mail: [ratko.salatic@gmail.com](mailto:ratko.salatic@gmail.com)

<sup>4</sup> F.prof. dr Rastislav Mandić, Civ.Eng., University of Belgrade, Faculty of Civil Engineering, Bulevar kralja Aleksandra 73, Belgrade, Serbia, tel: +381 11 3218 544, e – mail: [rale@grf.bg.ac.rs](mailto:rale@grf.bg.ac.rs)

<sup>5</sup> Matija Guzjan-Dilber, Civ. Eng., Peter the Great St. Petersburg Polytechnic University, Polytechnicheskaya 29, 195251, St. Petersburg, Russia, tel: +387 65 569 529, e-mail: [nikobelic025@gmail.com](mailto:nikobelic025@gmail.com)

<sup>6</sup> Goran Jotić, Mech.Eng., Faculty of Mechanical Engineering of University of Banja Luka, Bulevar vojvode Stepe Stepanovića 71, Banja Luka, BiH, tel: +387 66 703 246, e-mail: [goran.jotic@mf.unibl.org](mailto:goran.jotic@mf.unibl.org)

## 1. INTRODUCTION

In order to better understand the challenge presented by the defining and examination of structural damping, we need to take into consideration the bigger picture along with all the factors and parameters which could influence the behaviour of contact interaction, Fig. 1, [1]. As we will see in contact interaction it is not just a problem of pure friction represented over Coulomb's law and coefficient of friction. The problem is material change, plasticization and degradation. Unpredictable changes in the total-real contact area involved in the interaction and changes in "stick and slip conditions". Defining the connection and separation of contact on some parts or the whole surface is nonlinear and requires a massive algorithm for solving "Contac search and Contact detection" [2], [3].

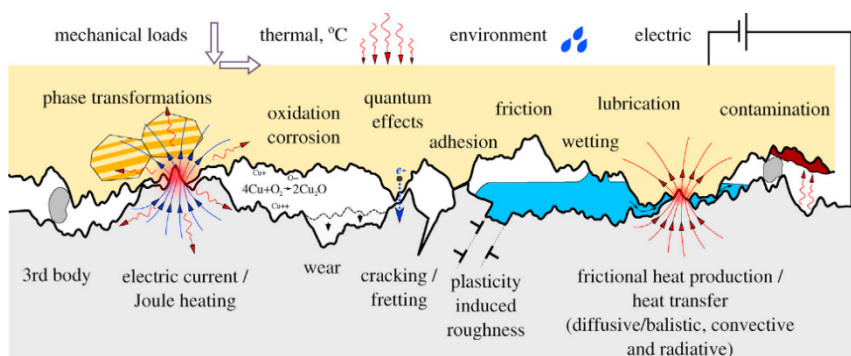


Figure 1. A scheme representing the multiphysical nature of contact interactions: two different bodies with rough surfaces and relevant material microstructures are brought into mechanical contact and exposed to various loads: mechanical, thermal, electric, and environmental. [1]

The complexity of the contact problem increases with decreasing of scale. The contact interaction of the two most general bodies at the atomic or nano-level is a multi-physical problem in which several different scientific disciplines are involved, Fig. 1. From a mechanical point of view, when studying structural damping in mechanical connections as a consequence of dry friction (possibly slightly contaminated contact), the change and deformation of contact interaction surfaces, including friction (possibly adhesion), is of the utmost importance. The process of plasticization of contact micro asperity (individual points in contact), where at higher pressure and number of cycles of micro and macro slipping in a unit of time, micro asperity melt, which includes thermodynamic processes and further complicates the contact mechanics of dry friction. Local heating and melting of micro asperity known as "flash-heating" is a previously known problem that significantly reduces friction and has a significant impact on dry contact. Further observing the contact microstructure, heating can occur due to the electrical conductivity of "Joule heating". In addition to the already mentioned phenomena, the following should be taken into account: different types of materials, some of which can be porous and saturated with water, the influence of lubrication and the presence of different types of fluids, changes in phase and structure of materials due to heating or radiation, quantum

effects. All of these effects significantly complicate the description of contact problems. It is interesting to note that phenomena that occur at the nano and atomic levels have a significant impact on the system's response on a macro scale.

## 2. AN OVERVIEW OF THE ANALYSIS AND EXAMINATION OF MECHANICAL CONNECTIONS

Even though the methods of establishing connections have been studied in depth in cases where the main function of the connection was to create a whole by transferring the load from one element onto another, this brings up the question of how such a connection would behave. Problem which arise is related to amplitude dependent stiffness and amplitude dependent damping. Structural damping (not exclusive to the joints and connections) is a phenomenon in the field of structural dynamics that has been described and defined the least, despite being crucial when it comes to predicting and understanding the behaviour of structural systems. Depending on their applications, there are different kinds of mechanical connections as depicted in Fig. 2. In practice, the connections most commonly used are the different type of bolted splice connection joints, Fig. 2 (b), (c), (d). It should be noted that the processes of energy dissipation, wear, and damaging are extremely important in mechanical connections between the turbine blades and the mounting disc Fig. 2 (a).

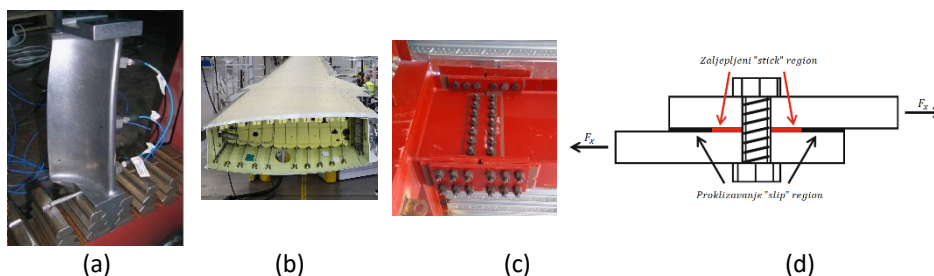


Figure 2. Turbine blades fir-tree connected (a), splice connection in the aviation industry (b), splice connection in steel structures (c), simple overlap connection (d)

Bolted cover plate splice connection joint are projected by introducing a large enough pressure force between the elements in contact interaction so that they would prevent macro slips and partly micro slips which are more or less always present. The micro slips are characteristic for the contact interaction parts of bolted connections which are separate from the body area of the bolt Fig. 2 (d). As the disturbing force increases, so does the micro slip area spread towards the body of the bolt until the force becomes so powerful it causes macro slipping of a contact surface against another contact surface. As previously noted, the function of the joints and the splice connection is to transfer the load which was already well defined and clear.

The main topic of this paper are the secondary phenomena arising in bolted connections that can significantly influence the dynamic response of a construction. The issue of the contact of two bodies and the description of a process, taking place within the interaction

of their contact surfaces can be classified as a exceedingly non-linear dynamic problem for which no single, uniform solution has been reached.

A good demonstration of this issue can be found in a recent research conducted by Segelman 2013, where twenty researches were asked the following question: “What are the ways in which you define and model mechanical connections?” The results of the survey showed that there were more ways to describe mechanical connections than there were survey participants [4]. This only serves to demonstrate that there truly is no uniform solution or agreement when it comes to the issue of mechanical connections modelling and structural damping.

### 3. UNIVERSALLY INDEPENDENT SYSTEMS AND MODELS OF STUDYING THE BEHAVIOUR OF MECHANICAL CONNECTIONS

As regards the current research of mechanical joints, two dominant approaches are prevalent: the first – based on the measuring and predicting of structural damping and energy dissipation, and the second which is based on the hysteresis loop of different mechanical connections. At the moment, the focus of attention is on studying simple connections where only two elements (parts) are connected using bolts or examining two elements that are in simple contact interaction without bolts. Simple experimental settings are intentionally used instead of complex structures in which the separation of different physical phenomena would prove to be too complex.

#### 3.1. Experimental settings for hysteresis measuring

The experimental settings called „rigs“ ( London Imperial College ) represent experimental settings used to research the hysteresis loops that emerge when friction is present in the system. After the issue had been defined, a detailed plan was constructed for the purposes of analysing the friction coefficient change in behaviour depending on the type of material or conditions of the experiment such as: pressure, temperature and velocity, [5].

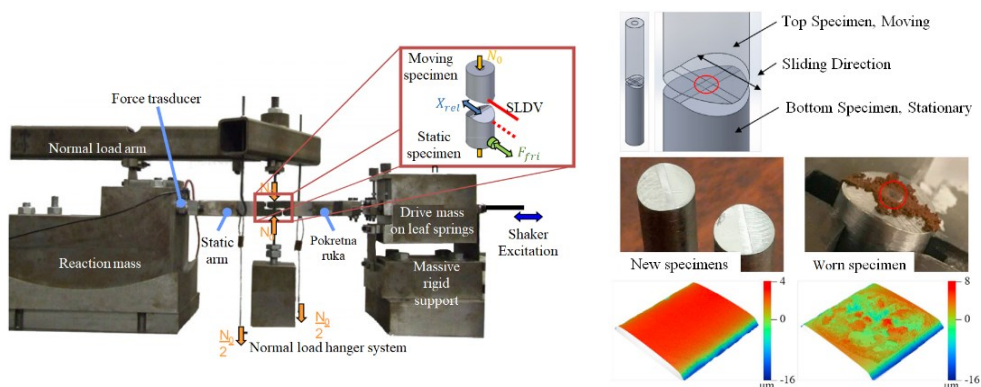


Figure 3. Experiment for measuring of the friction hysteresis “Friction Rigs” [6]

The first attempts of constructing and applying the aforementioned experimental setting at the Imperial London College took place in 1990, and later culminated in the form of the “First Generation Rig” [6] in 1998. The general intention behind the construction of this experimental setting was to develop a mechanism that will have two separate parts that would be able to move relative to each other in an oscillatory way. In order to accomplish this the experiment needed to ensure that two bodies in contact have relative one-dimensional sliding  $X_{rel}$  under a known normal force acting on the contact surface  $N_0$ , Fig. 3. Simultaneously measuring the relative displacement of the two bodies and frictional force  $F_{fri}$  (determined with the use of a force measuring probe), we can extract the basic parameters of the contact interaction between the two bodies, i.e. the friction coefficient  $\mu$  and tangential contact stiffness  $k_t$ . Depicted in Fig. 3 are an experimental system and details of two cylindrical specimens with wedged shape ends. The width of the straightened wedge top is 1 mm which creates an effective contact surface equal to 1 mm<sup>2</sup> when placing the wedge tops orthogonally from each other. A 3D model of the test specimens is also represented in the picture, along with a marked area of contact interaction and the direction of movement of the specimen in motion. Also depicted in the Fig. 3 (right) are the test specimens constructed from a high value steel SS 304 (EN 1.4301) before and after the testing procedure. By scanning the contact surfaces with an optical interferometer the material wear after a repeated cycle of horizontal movement due to dry friction between the contact surfaces becomes clear, [7]. The wear, that is, a change in the geometry of contact surface, directly affects the friction coefficient and structural damping. The bottom specimen is stationary and connected with girder-Static arm to a massive rigid support which is considered absolutely rigid, while the other specimen is mobile and moves in a horizontal direction being connected to the moving mass via Moving arm, Fig. 3. The moving mass is connected through leaf springs to the rigid steel support in order to enable the oscillation of the mass in a horizontal direction. A shaker is linked to the moving mass in order to enable the excitation of specimens at a specific frequency of the oscillation. The relative displacement amplitude ranges from 20 to 40  $\mu\text{m}$ , when the test specimens are compressed via the mounting bracket with a normal force that ranges from 5 to 75 N. The relative displacement  $X_{rel}$  between the slipping contact surfaces was measured with the Scanning Laser Doppler Vibrometer (SLDV) and the friction force was measured with the use of a measuring probe set between the Static arm and rigid support, Fig. 3. By depicting the friction force  $F_{fri}$  in the relation to the relative displacement  $X_{rel}$  we create a hysteresis loop that describes the behaviour of a contact interaction between two specimens of the tested material, as is evident in Fig. 4. On the hysteresis loop one could differentiate between three phases of the stick-slip motion within a contact interaction:

(I) – the first phase applies to the very beginning of the slipping where a fixed stick state within contact interaction is immediately activated. During the first phase the horizontal force is still not strong enough to induce plastic deformation of the asperities between the two contact surfaces so only elastic deformation is present. In the first phase the contact interaction can be said to act as a load on the elastic support where  $k_t$  represents elastic stiffness of the support. (II) – during the second phase, a phenomenon known as *microslipping* occurs. Microslipping represents an “in-between” or a transitional state between the sticking process of the contact surface and the final macroslipping or the full sliding of the two contacting surfaces. The microslipping phase is the hardest one to physically describe because some parts of the contacting surfaces may be in the state of

„stick stage“ while other parts could be in a state of „slip stage“ at the same time. (III) – an increase in the horizontal force shifts the process into its third phase, when, due to increased tangential stresses between the contacting surfaces and the subsequent reaching of the maximum tangential stress value, the contacting surfaces start to slide one over the other. Once the sliding occurs, the friction coefficient stays more or less constant. The surface under the hysteresis loop represents the energy that dissipated during contact interaction while the span between the horizontal lines of the same loop represents the friction coefficient  $\mu$ , Fig. 4. During the testing and comparison of 15 different heat-resistant materials it was determined that the value of the friction coefficient changes slightly depending on the normal pressure and temperature in which the experiment was conducted. The names of the types of materials examined during these experiments were not published, as per request of Rolls Royce, the investor of the project.

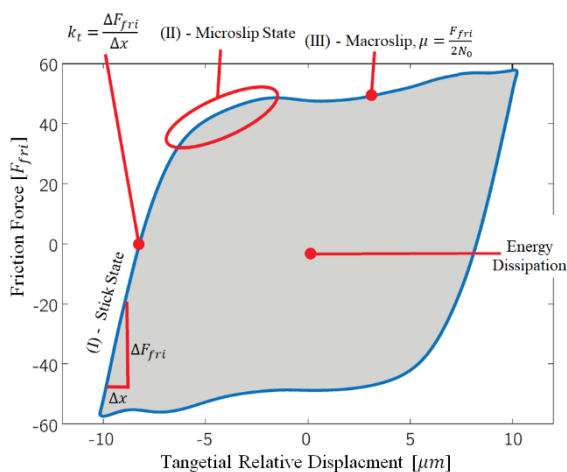


Figure 4. A typical hysteresis loop caused by friction

By examining of the different material specimens it was determined that the friction coefficient does not change considerably with increasing of pressure between the contact surfaces, this assumption is already proven before. An interesting to note was that deferments in specimens change in the friction coefficient caused by a change in temperature. Namely, it was discovered that the friction coefficient decreases as the temperature increases. Depending on the material's properties, at a temperature of 20°C, for example, the friction coefficient varies between 0.4 and 0.8, while at a temperature of 600°C, the coefficient of friction ranges from 0.2 to 0.35 for all tested materials.

It is important to mention the impact of the roughness on the behaviour of the experiment setting before and after the testing. As we can see in Figure 3, a significant change in the geometry of the contacting surfaces as the consequence of the wear and tear of the material specimens can be clearly observed. This also lead to a change of the real contact surface, consequently resulting in the change in friction-induced stresses within the contact interaction [7], [8].

### 3.2. An experimental investigation of dissipation and damping in bolted connections

The principal rule when developing a universally accepted experimental model, in this case, a model for testing bolted connections, is that it must be replicable – different teams of experts must be able to obtain the same results and arrive at same conclusions. The aim of such a model would be to enable the study of non-linear behaviour of bolted connections without the uncertainty and parasitic effects that can easily occur while constructing and preparing experimental specimens. The main question to be asked here is what can we observe when experimenting with simple bolted connections and how can the results we receive be applied to real structural connections. The difficulties that arise when choosing a representative of the connections to be tested are:

- the system that is being tested doesn't possess the required non-linear behaviour because of the joints, connections, or supporting construction that serve to support the experimental model. One of the issues here can also be due to the spurious stiffness of the bolted connections and the resulting impossibility of inducing the sliding between the elements of the bolted connection. One example of this behaviour can be observed in the Sumali beam.
- Many systems with suitable characteristics that also behave similar to real connections have numerous parts where it is difficult to avoid the overlapping of element solutions. An example of such a model is the Ampair 600 W Wind Turbine.

The presence of bolted connections inside a structure can significantly impact the structure's behaviour which is not the case when the structure is monolithic. As was already described in Section 1 structural damping is a direct consequence of the friction between two parts of a bolted connection. Despite the knowledge that the cause of the friction is attributed to the deformation of asperities between two contact surfaces and a change of geometry of contact surfaces, the nature of friction is still not fully understood. Due to this, we are unable to determine the damping characteristics of structures with bolted connections nor to describe the behaviour of these structures in precise terms.

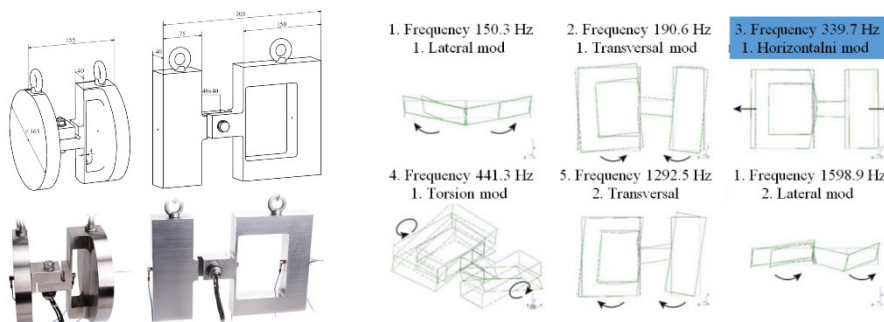


Figure 5: A schematic illustration of the Gaul resonator with a circular and rectangular base and the first six oscillation mods [4].

The basic concept of simple bolt connection joint is founded on the previous studies of the Gaul resonator Fig. 5. The Gaul resonator consists of two circular masses connected with the use of a single bolt in the middle [4]. One side of the connection is monolithic with a rigid mass, while the other is connected with the mass using a flexible spring that also serves to lower the oscillation frequencies of the first six modes. The system was designed to have an operating point near its resonant frequency. Seeing as the main points of interest are the displacements (slipping) between two parts of the system, the third natural frequency (339.7 Hz) is the one that drives the system because it has the correct form of oscillation (horizontal displacements), Fig. 5. So, as to obtain unambiguous results, the Gaul resonator is hangs by thin flexible threads that enable us to consider this system free of boundary conditions. The shaker is attached horizontally in order to provide sinusoidal excitation to the resonator with a frequency of 339.7 Hz (the first horizontal mod). The dynamical response of the system was measured using three accelerometers while the normal pressure between two contacting surfaces was induced as a pretension of the bolts and was measured using a probe placed between the body and the head of the bolt. The discrepancies in the obtained results are the consequence of micro slipping between contacting surfaces. In addition to the aforementioned experiment, there are others based on the same idea, such as "Dumbbel oscilator", for example, the experiments is conducted by Sandia National Laboratories, [4]. Also, in the study of constructive damping in bolted connections, the research performed on the experiment called "Big Mas Device" is of great importance.

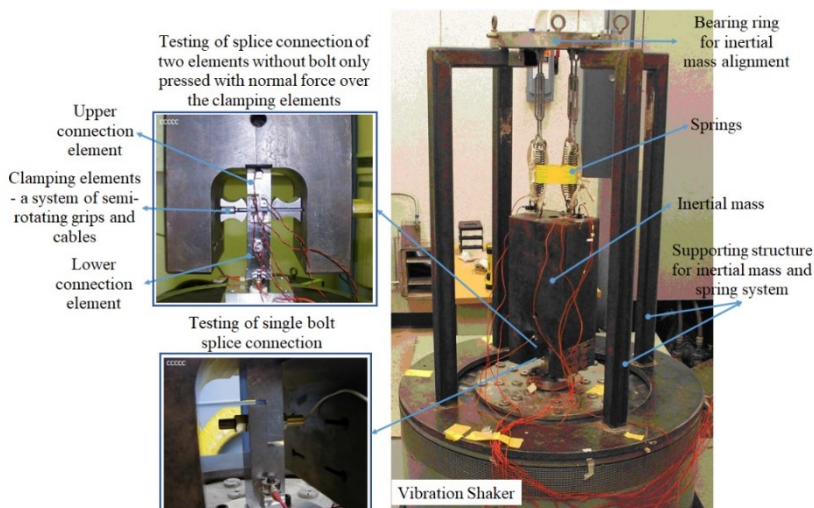


Figure 6: An experimental setting for the Big Mass Device [4].

The main idea behind the Big Mass Device is founded on a simple connection with and without bolts to connect the two parts of the assembly. The simplest experimental setting for the study of constructive damping consists of only two elements that overlap each other without using bolts. The normal pressure is induced by using a system of semi-rotational clamps and steel wires that can press together with adequate force the two elements of the connection and are come with the ability to adjust the alignment of the parts as well as the



clamps themselves. The tightening force between the parts is determined by use of measuring probes. In order to ensure a high enough intensity of the force in the system, a massive steel block weighing 93 kg was introduced into the setting Fig. 6. In Fig. 6, one can observe an example where the upper element of the connection is rigidly connected to the steel block while the lower element of the connection is rigidly connected to the simulator. The challenging aspect of this type of experiment was finding the ways to adequately secure the supporting of the steel block connected to the upper element and at the same time ensure the precise alignment of all three axes with the lower element rigidly connected to the simulator. The issue was resolved using elastic springs and a support construction by which the steel block was hanged. The spring stiffness was positioned in such a way so as to set the first natural oscillation frequency at approximately 2 Hz, and by selecting springs of lesser stiffness the overlapping of the supporting structure frequencies and the planned simulated frequencies (10 – 3000 Hz) was prevented.

The system described above was used to explore a wide scope of different specimens of overlapping connections with or without bolts. The variations of the tested specimens were as follows: in different treatment of contact surfaces, the area of contact interactions, the geometrical characteristics of contacting surfaces, the values of the normal pressure, etc..

#### 4. CONCLUSION

This paper represents the part of the research dedicated to the study of behaviour of bolted and mechanical connections in general, with an emphasis on the micro effects that happen within a contact interaction. The question of the nature of friction and behaviour of two bodies in contact is significantly more extensive than described in this paper through the micro and macro levels. In an attempt to answer this question behind the nature of friction, one must observe the contact between two bodies at the nanoscale, until finally instead of observing two bodies one starts observing contacts at an atomic level. Even though the research on the subject of and the study of the behaviour of friction and mechanical connections have become intensive during the last twenty years, there are still many unanswered questions. The study of mechanical connections is not only physical but rather multidisciplinary, meaning it represents a fertile ground for further examination from many different aspects, economic aspect included. The usefulness of exploring the matter from the economic aspect becomes clear when one takes into consideration the incidents and accidents caused by loose connections, like, loosened connections breaking happened in Russia at the Sayano Shushenskaya hydroelectric power station which subsequently also caused the sinking of the entire building and for the power plant to cease operation. The total cost of the damage was approximately three billion dollars. Another well-known example of this happened in 2012 when the connections between the airfoils and the fuselage of an Airbus A380 got loose. The financial losses in this case were over one billion dollars. As we see further study of the behaviour of mechanical connections is necessary in order to improve the usability and predictability of mechanical systems and assemblies, on the other hand, it presents a demanding but exciting challenge for the scientific community.

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## ЕКСПЕРИМЕНТАЛНО ОДРЕЂИВАЊЕ И ПРОУЧАВАЊЕ КОНСТРУКТИВНОГ ПРИГУШЕЊА И СУВОГ ТРЕЊА

*Резиме:* Изазов који ће бити постављен пред истраживаче још дужи низ времена јесте развој предвидљивог модела за описивање механичких веза, њихове промјенљиве крутости и дисипативних процеса контактне интеракције. Главни изазов овом циљу налази се у недостатку разумијевања како се трење понаша у малим размјерама. Цоулоново трење, велики хеуристички модел није предвидљиво и заправо доказано је да у многим режимима није истинито. Очекувати универзалан закон трења за све врсте материјала самим тим и контактних интеракције није баш реално. Умјесто тога, циљ међународне истраживачке заједнице је развити предвидљив модел за ограничен низ случајева. До сада се најчешће испитује контакт метал-метал, односно најчешће понашање контактне интеракције алуминијумских и челичних елемената различитог квалитета. Такође знамо да се у примјени ова два метала најчешће срећу код израде механичких веза. Циљ овог рада јесте направити кратак преглед неких од досадашњих испитивања и приступа проучавању контактне интеракције у механичким везама те улоге трења у дисипацији енергије.

*Кључне речи:* контактна интеракција, пригушење, суво трења, механичке везе