FRICTION FORCES IN NUMERICAL SIMULATIONS OF KINEMATICAL JOINTS OF MECHANICAL SYSTEMS

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Abstract: The paper presents a way of estimation, by simulation, of friction forces that occur in the kinematical joints of mechanical systems. Friction forces between planar surfaces, in revolute joints, and in spherical joints are computed, and the results are compared with the values achieved from simulation. SolidWorks software is used for the simulation process.
Keywords: friction force, kinematical joint, simulation, SolidWorks.

1. Introduction

Friction forces occur to operating mechanical systems, as a result of components interaction, or of mechanical system interaction with external factors.

The numerical simulation is a frequently used instrument for the analysis of mechanical structures behavior in statical or dynamical conditions [11], [12], [13], [14], [16], [17].

For an accurate numerical simulation of real mechanical systems operation, all the conditions have to be considered - including the contact pressure [2], [3], and the friction phenomenon.

The influence of friction forces was studied by numerical simulation for different mechanical systems [15], for fixed robot structures [1], [8], or for mobile robot structures [4], [5], [18], [19].

The friction phenomenon causes local contact erosion, which influences the machine parts operation lifetime [6].

Numerical models, considering the friction forces, are used in the field of robotic surgery, where high accuracy is required [7].

Recently, new methods of studying the friction influence are used, for example the method based on neural networks [9].

The paper presents some cases of friction force calculus for different kinematical joints, motion simulations of the kinematical joints, and the numerical determination of friction forces. The values resulted from calculus are compared with those achieved from simulations, where certain peak values were neglected, being out of usual range. Both for calculus and for simulations, the same friction coefficients are used, given by the software, and according to [10] and [20]. For numerical simulations, SolidWorks software is used.

2. Friction Forces between Planar Surfaces

The simple case of a cube moving on a base plane surface is considered, as shown in figure 1. The forces that occur are as follows: the traction force F, the weight W, the normal reaction N, and the friction force F_f. The cube is set to move at a constant speed v.

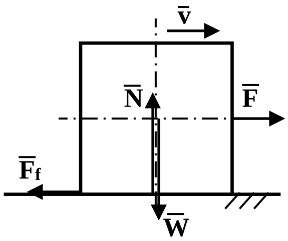

Fig. 1. Friction force F_f occurring between the cube and the plane surface.

The cube's material is considered to be cast carbon steel, with the density $\rho = 7800$ [kg/m^3]; in order to ease the calculus, the cube is set to a volume $V = 1$ [m^3], which means that the cube has the mass:

$$m = \rho \cdot V = 7800 \cdot 1 = 7800 \text{ [kg]}. \quad (1)$$

The cube weight is:

$$W = m \cdot g = 7800 \cdot 9.806 = 76487 \text{ [N]} \quad (2)$$

The expressions of friction force between the cube and the base, in static and kinematical conditions respectively, are as follows:

$$F_{fs} = \mu_s \cdot N = \mu_s \cdot W = 0.3 \cdot 76487 = 22946 \text{ [N]} \quad (3)$$

$$F_{fk} = \mu_k \cdot N = \mu_k \cdot W = 0.25 \cdot 76487 = 19122 \text{ [N]} \quad (4)$$

where: - $\mu_s = 0.3$ is the static friction coefficient in dry friction conditions for steel, provided by SolidWorks software;

- μ_k = 0.25 is the kinematic friction coefficient in dry friction conditions for steel, provided by SolidWorks software;

- N = W is the normal reaction force between the cube and the base surface.

The 3D model of the cube, accomplished in SolidWorks software, is presented in fig. 2.

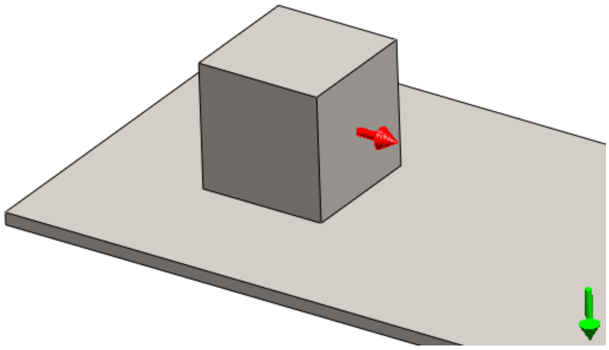

Fig. 2. 3D model of a cube moving on a planar surface.

The cube material, as well as the base material, is Cast Carbon Steel, chosen from SolidWorks materials library.

In SolidWorks Motion module, between the cube and the base there is defined a *Solid Body Contact*, with the same kinematic friction coefficients used in relations (3) and (4).

The cube is set to move with a speed of 2000 [mm/s], in a period of 0.5 [s].

In order to re-create the real conditions, the gravity is applied in SolidWorks Motion module.

Figure 3 shows the variation of friction force, obtained as a simulation result. The friction force value varies very fast at the beginning of motion, because the rest state of the cube instantly modifies to motion state in the simulation.

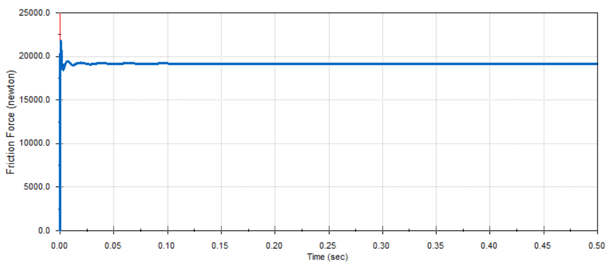

Fig. 3. The variation of friction force between the cube and the base in simulation.

The friction force obtained by simulation has a value of 21704 [N] in static conditions, at the beginning of motion, close to the computed value of 22946 [N], from calculus (3), and a stabilized value in motion of around 19120 [N], very close to the computed value of 19122 [N], from calculus (4).

3. Friction Forces in Revolute Kinematical Joints

The next case studied is that of friction forces which occur between cylindrical surfaces.

The forces that occur are as follows: the axial force F_a, the tangential force F_t, the weight W, the normal reaction N, and the friction force F_f, as shown in fig. 4. The shaft is set to move with a constant angular speed ω, due to a torque M_t.

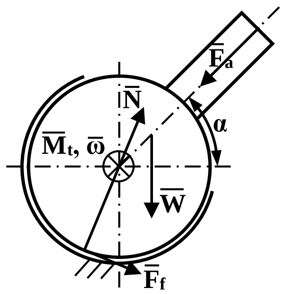

Fig. 4. Forces acting on the shaft of the revolute joint.

The material of the components is considered to be alloy steel, with the density ρ = 7700 [kg/m^3]. The shaft together with the lever have the mass of 12.87·10^{-3} [kg].

The expressions of friction force between the shaft and the bearing, in static and kinematical conditions respectively, are as follows:

$$F_{fs} = \mu_s \cdot N = \mu_s(W + F) = 0.08 \cdot 10.129 = 0.810\ [N] \quad (5)$$

$$F_{fk} = \mu_k \cdot N = \mu_k[F^2 + W^2 + 2FW \cdot \cos(90-\alpha)]^{1/2} = 0.05 \cdot 10089 = 0.504\ [N] \quad (6)$$

where: - μ_s = 0.08 is the static friction coefficient in greasy friction conditions for steel, provided by SolidWorks software;

- μ_k = 0.05 is the kinematic friction coefficient in greasy friction conditions for steel, provided by SolidWorks software;

- N is the normal reaction force between the shaft and the bearing; it is computed in relation (5) for the angle α = 90º, and in relation (6) for the angle α = 45º, as follows:

$$N = [F^2 + W^2 + 2FW\cos(90-\alpha)]^{1/2} = [10^2 + 0,126^2 + 2 \cdot 10 \cdot 0.126 \cdot \cos(90-45)]^{1/2} = 10.089\ N \quad (7)$$

Figure 5 shows the geometrical model of a revolute kinematical joint.

The components material is Alloy Steel, chosen from SolidWorks materials library. In SolidWorks Motion module, between the shaft and the bearing there is defined a *Solid Body Contact*, with the same kinematic friction coefficients used in relations (5) and (6).

The shaft is set to move with an angular speed of π/3 [rad/s], e.g. 60 [°/s], in a period of 0.5 [s].

The gravity is also applied in this case.

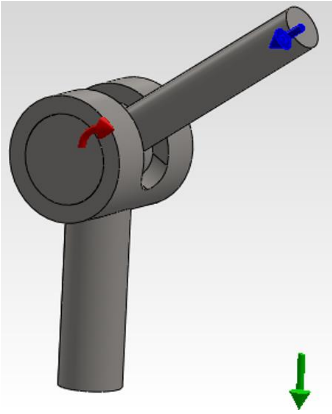

Fig. 5. 3D model of a revolute kinematical joint.

Figure 6 shows the variation of friction force, obtained as a simulation result.

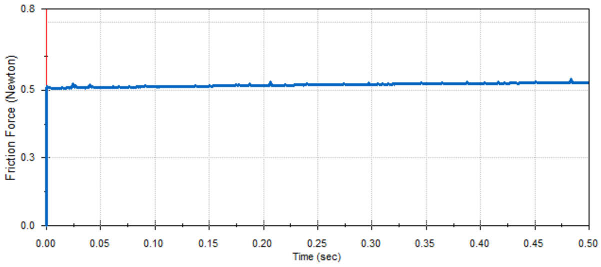

Fig. 6. The variation of friction force between the shaft and the bearing in simulation.

The friction force obtained by simulation has a value of 0.787 [N] in static conditions, at the beginning of motion, close to the computed value of 0.810 [N] from calculus (5), and a value in motion of 0.523 [N] for the position $\alpha = 45^o$, close to the computed value of 0.504 [N] from calculus (6). The exact values of friction force in simulation are taken from a .csv file provided by SolidWorks software.

4. Friction Forces in Spherical Kinematical Joints

The scheme of disposal of forces in this case is similar to the scheme of the previous case, as presented in fig. 4.

The expressions of friction force between the sphere and the spherical shell, in static and kinematical conditions respectively, are as follows:

$$F_{fs} = \mu_s \cdot N = \mu_s(W + F_a) = 0{,}05 \cdot 10.43 = 0.522 \text{ [N]} \quad (8)$$

$$F_{fk} = \mu_k \cdot N = \mu_k[F_a^2 + W^2 + 2F_aW \cdot \cos(90-\alpha)]^{1/2} = 0.03 \cdot 10.43 = 0{,}313 \text{ [N]} \quad (9)$$

where: - $\mu_s = 0.05$ is the static friction coefficient in greasy friction conditions for aluminum, provided by SolidWorks software;

- $\mu_k = 0.03$ is the kinematic friction coefficient in greasy friction conditions for aluminum;

- N is the normal reaction force between the shaft and the bearing, computed, for example, for the angle $\alpha = 45^o$.

Figure 7 shows the geometrical model of a spherical kinematical joint. The components material is Alumina, chosen from SolidWorks materials library.

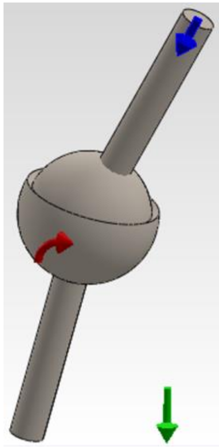

Fig. 7. 3D model of a spherical kinematical joint.

In SolidWorks Motion module, between the sphere and the spherical shell there is defined a *Solid Body Contact*, with the same kinematic friction coefficients used in relations (8) and (9).

The shaft is set to move with an angular speed of $\pi/3$ [rad/s], e.g. 60 [°/s], in a period of 0.5 [s].

The gravity is also applied in this case.

Figure 6 shows the variation of friction force, obtained after simulation.

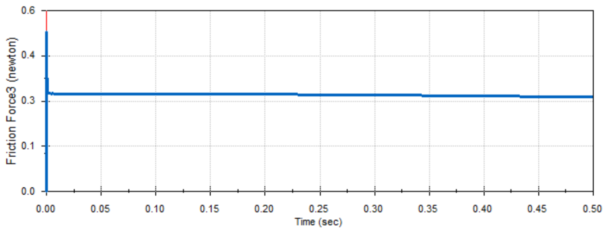

Fig. 8. The variation of friction force between the sphere and the spherical shell in simulation.

The friction force obtained by simulation has a value of 0.526 [N] in static conditions, at the beginning of motion, close to the computed value of 0.522 [N] from calculus (8), and a value in motion of 0.316 [N] for the position $\alpha = 45^o$, very close to the computed value of 0.313 [N] from calculus (6). The exact values of friction force in simulation are taken from a .csv file provided by SolidWorks software.

5. Conclusions

The results of calculus and simulations are shown in table 1.

Table 1. Results comparison

Crt. no.	Joint type	State	Value of friction force [N]		Percent relative difference [%]
			Calculus	Simulation	
1.	Planar surfaces	Static	22946	21704	5.41
		Motion	19122	19120	0.01
2.	Revolute joint	Static	0.810	0.787	2.84
		Motion	0.504	0.523	-3.77
3.	Spherical joint	Static	0.522	0.526	-0,77
		Motion	0.313	0.316	-0.96

It can be observed that the values of calculus and simulation results are very close. The differences occur due to computing approximations.

On these considerations, the use of numerical simulation in the manner presented is an option that must be considered in order to evaluate the friction forces that occur in the kinematical joints of mechanical systems.

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