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INVESTIGATION OF DRY FRICTION PHENOMENA IN MECHANICAL SYSTEMS: THEORETICAL MODELING AND PRACTICAL APPLICATIONS

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Abstract
This study provides a comprehensive analysis of the role of dry friction in mechanical systems, as well as its theoretical and practical aspects. Dry friction is considered as a complex contact phenomenon that occurs in the absence of a lubricating layer between contacting bodies, and its characteristics in both static and kinetic states are described. The main factors influencing the formation of friction force-surface topography, material properties, adhesion, and environmental conditions-are explained on a scientific basis. In addition, the study examines dry friction not only within the framework of the classical Coulomb model but also from the perspective of modern approaches, including contact mechanics and interfacial energy effects. The necessity of accounting for friction forces in determining the equilibrium of mechanical systems is

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substantiated, and methods for solving various types of static problems are presented. The theoretical principles are supported by practical problems, demonstrating their importance in improving the reliability and efficiency of mechanical systems.

Keywords: Dry friction, friction force, static friction, kinetic friction, coefficient of friction, contact mechanics, adhesion, surface topography, equilibrium equations, mechanical systems, free-body diagram, Coulomb law

Introduction

The phenomenon of dry friction is a complex contact process that plays a central role in determining the performance of mechanical systems. It manifests as a resistive force occurring between contacting surfaces in the absence of a lubricating layer, and it is crucial in defining both the static and dynamic states of mechanical systems. The magnitude of dry friction is determined not only by the microscopic asperities at the interface but also strongly depends on surface topography, the mechanical properties of materials, adhesion, and environmental factors.

From a theoretical perspective, the study of dry friction in mechanical systems requires consideration of the fundamental laws governing friction forces, in addition to the vectorial sum of forces and moments used to analyze system equilibrium. Practically, dry friction is a decisive factor in determining the operational performance, service life, and efficiency of mechanical components. Therefore, both theoretical and experimental analyses of dry friction are of significant importance for scientific research and industrial applications.

In recent years, dry friction has been studied not only within the classical Coulomb framework but also in conjunction with adhesion, interfacial forces, and multiscale contact mechanics. Popov, Li, and Lyashenko have highlighted the role of adhesion in contact mechanics and friction, emphasizing the necessity of accounting for interfacial bonding energy alongside mechanical contact when explaining the coefficient of friction [1]. Another important finding demonstrated experimentally by Huang et al., is that the mutual alignment of surface roughness—referred to as roughness alignment—can significantly control

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frictional strength [2]. This indicates that the quantitative characterization of dry friction depends not only on the degree of roughness but also on the spatial arrangement of surface irregularities [3].

Characteristics of Dry Friction and Its Role in Mechanical Systems Friction is a force that resists the relative motion of two contacting surfaces. It acts tangentially at the contact points, opposing the direction of actual or potential sliding. In this section, the effects of dry friction are discussed. Dry friction is sometimes called Coulomb friction, as its basic laws were first studied by the French physicist Charles-Augustin de Coulomb in 1781 [4]. This type of friction arises in conditions where no lubricating medium exists between bodies.

Table 1. Typical Values of the Coefficient of Friction

Contacting Materials	Static Friction Coefficient (μ_s)	Kinetic Friction Coefficient (μ_k)
Steel – Steel	0.74 – 0.85	0.57 – 0.63
Steel – Cast Iron	0.50 – 0.70	0.40 – 0.60
Steel – Bronze	0.35 – 0.50	0.25 – 0.40
Rubber – Steel	0.60 – 0.85	0.50 – 0.70
Wood – Wood	0.25 – 0.50	0.20 – 0.40
Aluminum – Steel	0.47 – 0.61	0.36 – 0.50

Characteristics of Dry Friction Based on the experimental results discussed above, the following rules can be formulated for bodies subjected to dry friction:

– The friction force acts tangentially to the contact surfaces and opposes the relative motion or the tendency of motion of one surface with respect to the other.

– The maximum possible static friction force F_s does not depend on the contact area, provided that the normal pressure is neither extremely small nor excessively large, which could cause significant deformation or crushing of the surfaces.

– Typically, the maximum static friction force F_s is greater than the kinetic friction force F_k. However, if one of the bodies moves over the other at a very low velocity, F_k approaches F_s $\mu_s \approx \mu_k$.

– At the onset of sliding, the maximum static friction force is proportional to the normal force:

$F_s = \mu sN$ (1)

– During sliding, the kinetic friction force is also proportional to the normal force:

$F_k = \mu kN$ (2)

Problems Involving Dry Friction The equilibrium of a rigid body under conditions involving friction is determined not only by the equilibrium equations but also by the laws describing friction forces.

Types of Frictional Problems In general, static problems involving dry friction can be classified into three types. Once the free-body diagrams are drawn, the total number of unknowns is identified and compared with the number of available equilibrium equations, allowing a clear classification of the problem type.

1. Imminent Motion at Certain Contact Points In this case, the number of unknowns is less than the sum of the available equilibrium equations and the friction or reversal condition equations. Consequently, multiple potential states of motion or impending motion may exist. Therefore, solving such a problem requires determining which type of motion actually occurs in the body. For example, consider the two-member frame shown in Figure 1a. In this problem, it is necessary to determine the horizontal force P required to initiate motion. If each member has a weight of 100 N, the corresponding free-body diagrams are shown in Figure 1b [5].

In this case, there are a total of 7 unknowns. To obtain a unique solution, 6 equilibrium equations must be satisfied, i.e., three equilibrium equations are written for each member. However, for friction, only one of the two possible static friction equations can be applied. This means that as the force P increases, one of the following two scenarios may occur:

- Sliding begins at point A, while no sliding occurs at point C. In this case:

$$F_A = 0.3N_A and\ F_C \le 0.5N_C \quad (3)$$

Sliding begins at point C, while no sliding occurs at point A. In this case:

$$F_C = 0.5N_C and\ F_A \le 0.3N_A \quad (4)$$

The actual state of motion is determined by separately calculating the force P for each scenario. The scenario that results in the smaller value of P is accepted as the

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real type of motion. If, in the rare case, the value of P is the same for both scenarios, then sliding occurs simultaneously at both points A and C. In such a situation, the system has 7 unknowns but satisfies 8 equations.

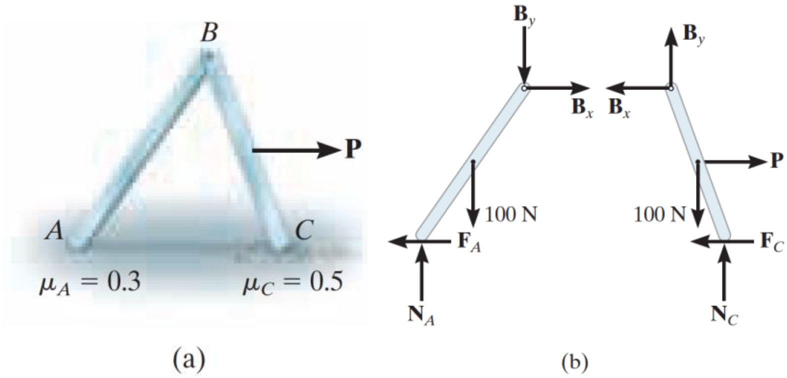

Figure 1. The distinction between equilibrium equations and friction equations.

In problems like those shown in Figure 1, if the friction force F ensures equilibrium and satisfies the condition $F<\mu_s N$, then the direction of F in the free-body diagram can be initially assumed arbitrarily. The actual direction of the force is determined after solving the equilibrium equations. If the calculation yields a negative value for F, this indicates that the true direction of the friction force is opposite to the initially assumed direction. The reason why the direction of the friction force can be assumed in this way is that the equilibrium equations equate the projections of the vectors acting in a given direction to zero. However, in some problems, such as the situation shown in Figure 2, the friction equation $F=\mu N$ is applied directly in the solution. In such cases, the convenience of arbitrarily choosing the direction of the friction force is lost, because the friction equation only expresses the relationship between the magnitudes of two mutually perpendicular vectors, not their directions. Therefore, when the friction equation is used in the solution, the friction force must always be represented in its actual direction in the free-body diagram.

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Depending on the point of application of the push on a uniform block, it will either topple or slide.

Key considerations: Friction is the tangential force that resists the relative motion of one surface over another. If sliding does not occur, the maximum friction force is equal to the product of the coefficient of static friction and the normal reaction force. When a body slides at a small velocity, the friction force equals the product of the kinetic friction coefficient and the normal reaction force. There are three main types of problems related to static friction. When analyzing such problems, the necessary free-body diagrams should first be drawn, and then the equilibrium equations should be applied while taking into account friction conditions or the possibility of toppling.

Procedure for problem analysis: Problems involving dry friction can be solved according to the following sequence:

1. Free-body diagrams: Draw all necessary free-body diagrams. If the problem does not explicitly specify the onset of motion or sliding, always represent friction forces as unknowns; do not assume $F=\mu N$ in advance.

Determine the number of unknowns and compare it with the number of available equilibrium equations.

If the number of unknowns exceeds the number of equilibrium equations, additional equations must be generated by applying the friction equations at one or more contact points, if necessary at all contact points, to obtain a complete solution.

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◦ If the equation F=μN is used, the direction of the friction force F must be correctly indicated in the free-body diagram.

2. Equilibrium and friction equations:

Apply the equilibrium equations together with the necessary friction equations. If there is a possibility of toppling, use conditional equations to determine the unknown quantities.

◦ For problems involving a three-dimensional system of forces, where it is difficult to determine the components of forces or required moment arms, use Cartesian vector representation to apply the equilibrium equations.

Example problem: Problem 1. Consider a uniform block with a mass of 20 kg, as shown in Figure 2a. Determine whether the block maintains equilibrium or topples when a force P = 80 is applied. Take the coefficient of static friction as $\mu s = 0.3$

Solution – Free-body diagram: As shown in Figure 2b, the resultant normal reaction force N_C must act at a distance x from the block's central axis. This position is required to balance the toppling moment generated by the applied force P. The problem has three unknowns: F, N_C and x. All of them can be directly determined using the three equilibrium equations.

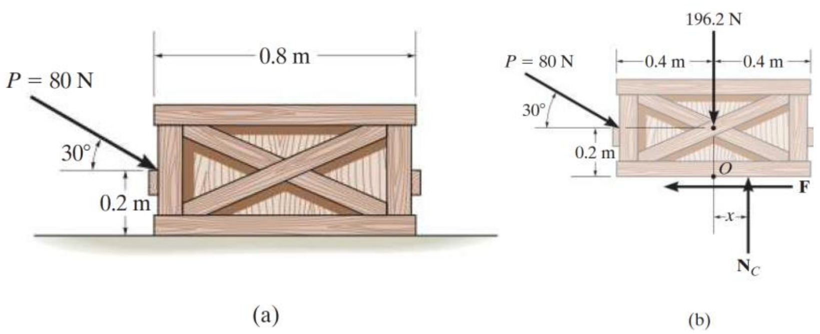

Figure 2. Equilibrium Equations:

$$\overset{+}{\rightarrow}\sum \mathbf{F_x} = \mathbf{0; 80\cos 30° - F = 0}$$

$$+\uparrow \sum \mathbf{F_y} = \mathbf{0;\ -80\sin 30°\,N + N_C - 196.2\,N = 0}$$

$$\curvearrowleft + \sum \mathbf{M_O} = \mathbf{0; 80\sin 30°\,N(0.4m) - 80\cos 30°\,N(0.2m) + N_C(x) = 0}$$

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Solution Based on the Equations:

$$F = 69.3\text{ N};\ N_C = 236.2\text{N}; x = 0.00908\text{ m} = -9.08\text{ mm} \tag{5}$$

Since x is negative, this indicates that the resultant normal force acts slightly to the left of the central axis of the block. Because x<0.4 m, toppling does not occur. Additionally, the maximum possible friction force at the contact surface is:
$F_{max}=\mu_s N_C=0.3\times236.2\text{ N}=70.9\text{ N}$.
Since $F = 69.3\,N < F_{max} = 70.9$ N the block does not slide, although it is very close to the sliding condition.
Problem 3. A uniform ladder of mass 10 kg, shown in Figure 3a, leans against a smooth wall at point B, while its base at point A rests on a horizontal surface with a static friction coefficient of $\mu s = 0.3$. If the ladder is on the verge of sliding, determine its angle of inclination theta θ and the normal reaction at point B.

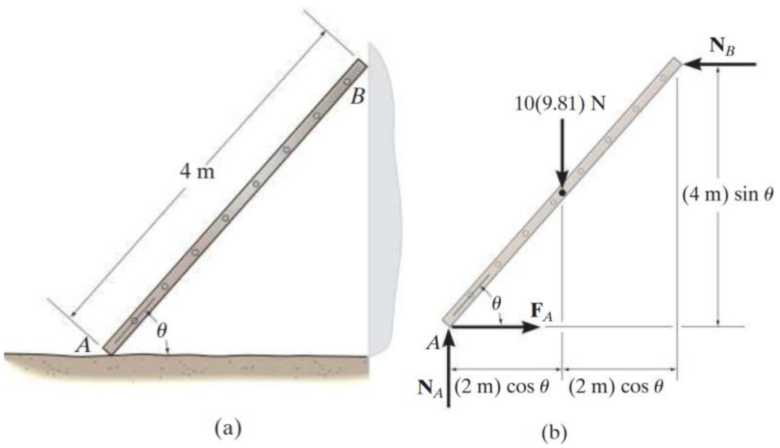

Figure 3.

Solution. Free-Body Diagram. As shown in the free-body diagram in Figure 3b, the friction force at point A, F_A, must be directed to the right, since the expected motion at point A is to the left.
Equilibrium and Friction Equations. Because the ladder is on the verge of sliding, the friction force at point A is taken as: $F_A=\mu_s N_A=0.3N_A$ From observation, the normal reaction N_A can be determined directly.
$+\uparrow \sum F_y = 0;\ N_A - 10(9.81)\text{N} = 0\ N_A = 98.1\text{N}$

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Considering the Result, $F_A = 0.3(98.1N) = 29.43N. N_B$ is determined as follows:

$\overset{+}{\rightarrow}\sum F_x = 0;$ $29.43N - N_B = 0; N_B = 29.43N = 29.4\ N$

Finally, the angle θ can be determined by summing the moments about point A.

$\curvearrowleft + \sum M_A = 0; (29.43N)(4m)\sin\theta - [10(9.81)N](2m)\cos\theta = 0$

$$\frac{\sin\theta}{\cos\theta} = \tan\theta = 1.6667$$

$$\theta = 59.04° = 59.0°$$

Problem 4. The beam AB is subjected to a uniformly distributed load of 200 N/m and is supported at point B by the column BC, as shown in Figure 4a. If the coefficients of static friction at points B and C are μ_B = 0.2 and $\mu C = 0.5$, respectively, determine the force P required to pull the column out from under the beam. The weights of the columns and the thickness of the beam are neglected.

Solution: Free-body diagrams. The free-body diagram of the beam is shown in Figure 4b. By summing moments about point A and setting the sum to zero, the normal reaction at B is found to be $NB = 400$ N. This result is illustrated in the free-body diagram in Figure 4c. There are four unknowns for this element: F_B, P, F_C, and N_C. These can be determined using the three equilibrium equations along with one friction equation applied at either point B or C.

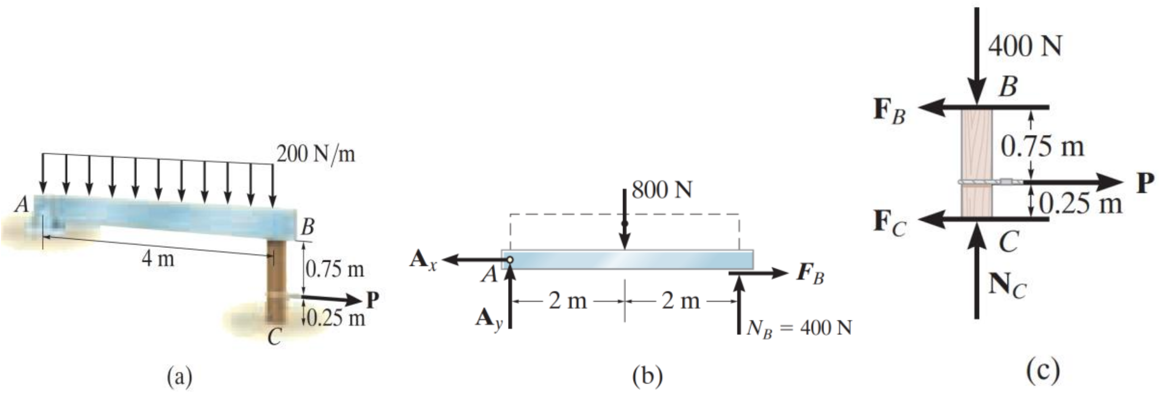

Figure 4. Free-body diagrams and equilibrium with friction equations.

$\overset{+}{\rightarrow}\sum F_x = 0;\ \ P - F_B - F_C = 0$ (1)

$+\uparrow \sum F_y = 0;\ N_C - 400\ N = 0$ (2)

$\curvearrowleft + \sum M_A = 0; \ -P(0.25m) + F_B(1m) = 0$ (3)

It slips at point B and rotates around point C. For this, it is required that $F_C \leq \mu_C N_C$

$$F_B = \mu_B N_B; \ F_B = 0.2(400\ N) = 80\ N$$

Using this result and solving equations 1 through 3, we obtain the following result:

$$P = 320N, F_C = 240N, N_C = 400N$$

$$F_C = 240N > \mu_C N_C = 0.5(400N) = 200N$$

Since this is the case, slipping occurs at point C. Therefore, it is necessary to check the other possible motion scenario as well. The column slips at point C and rotates around point B. Here,

$F_B \leq \mu_B N_B$ va $F_C = \mu_C N_C; \ F_C = 0.5N_C$.

By solving equations (1) through (4), we obtain the following results:

$P = 267\ N, N_C = 400\ N, F_C = 200\ N, F_B = 66.7\ N$

Undoubtedly, this scenario will occur first, as it requires the smaller value of P.

Problem 5**.** Blocks A and B have masses of 3 kg and 9 kg, respectively, and are connected by weightless rods as shown in Figure 5a. Determine the maximum vertical force P that can be applied at hinge C without causing any motion in the system. The coefficient of static friction between the blocks and the surfaces is $\mu_s = 0.3$

Solution. Free-body diagram. The rods are considered as force elements, so the free-body diagrams of hinge C and blocks A and B are shown in Figure 5b.

- The horizontal component of force F_{AC} tends to move block A to the left; therefore, the friction force F_A is directed to the right to resist this motion.
- Similarly, force F_{BC} tends to move block B to the right; hence, the friction force F_B acts to the left to oppose this motion.

The system has seven unknowns and six equilibrium equations: two for the hinge C and two for each block. Therefore, only one friction equation is required. Equilibrium and friction equations. The forces in rods AC and BC can be related to the applied force P by considering the equilibrium of hinge C.

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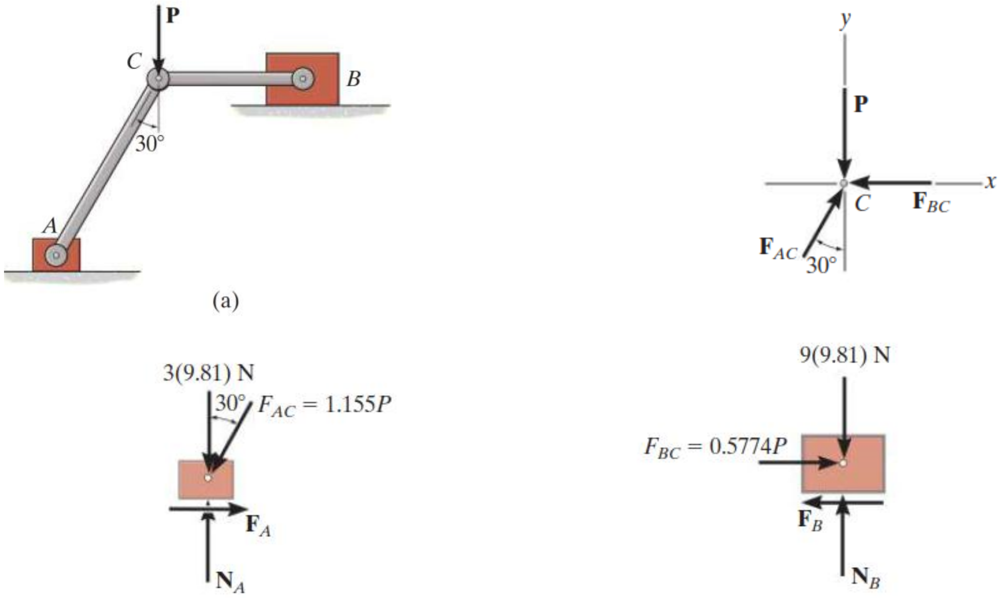

5-Figure

$+\uparrow \sum F_y = 0; \quad F_{AC}\cos 30° - P = 0 \quad F_{AC} = 1.155P$

$\overset{+}{\rightarrow}\sum F_x = 0; \quad 1.155P \sin 30° - F_{BC} = 0; \; F_{BC} = 0.5774P$

F_{AC} Using the result obtained for this scenario, for block A,

$\overset{+}{\rightarrow}\sum F_x = 0; \; F_A - 1.155\,P \sin 30° = 0; \; F_A = 0.5774P$ (1)

$$+\uparrow \sum F_y = 0; \; N_A - 1.155P\cos 30° - 3(9.81\,N) = 0;$$

$N_A = P + 29.43\,N$ (2)

F_{BC} Using the result obtained for this scenario, for block **B**

$\overset{+}{\rightarrow}\sum F_x = 0; \; (0.577P) - F_B = 0; \; F_B = 0.5774P$ (3)

$+\uparrow \sum F_y = 0; \; N_B - 9(9.81)N = 0; \; N_B = 88.29\,N$

The motion of the system can originate from the initial slipping of either block **A** or **B**. If we assume that, block **A** slips first, then

$F_A = \mu_s N_A = 0.3N_A$ (4)

By substituting equations (1) and (2) into equation (4)::

$F_A = \mu_s N_A = 0.3N_A$ (4)

By substituting equations (1) and (2) into equation (4), we obtain:

$$0.5774P = 0.3(P + 29.43)$$
$$P = 31.8\ N$$

Substituting this result into equation (3), we obtain $F_B = 18.4N$ since the maximum static friction force at point B is $(F_B)_{max} = \mu_s N_B = 0.3(88.29\ N) = 26.5N > F_B$ block B does not slip. Therefore, the initial assumption is confirmed to be correct. It should be noted that if this inequality had not been satisfied, it would have been necessary to assume that block B slips first and then recalculate the force P.

Conclusion

Dry friction is one of the fundamental physical factors determining the behavior of mechanical systems. It not only resists motion between contacting bodies but also directly influences the equilibrium, stability, and operational efficiency of the system. Studies show that a complete understanding of friction cannot rely solely on classical models; it also requires consideration of surface microstructure, adhesion, and contact mechanics. In solving practical problems, it is essential to correctly determine friction forces, construct accurate free-body diagrams, and apply equilibrium equations. Moreover, evaluating possible sliding or toppling conditions in advance enhances the reliability of mechanical systems. In general, a thorough understanding of dry friction serves as an important scientific foundation for the design of efficient and stable mechanical systems in modern engineering and industrial practice.

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