Ключові слова: *система регулювання клапанів, фаза газорозподілу, висота підйому клапана, характеристика двигуна*

Цель. Двигатели с системой управления клапанами газораспределения обладают лучшей производительностью по сравнению с двигателями, у которых зафиксированы моменты открытия и закрытия, а также высота подъёма клапанов. В работе предложена гидравлическая система управления клапанами газораспределения, соответствующая требованиям двигателя. Она позволяет регулировать оба клапана: впускной и выпускной.

Методика. Создан испытательный стенд движения клапанов и протестирована эффективность регуляции клапанов системы управления клапанами газораспределения. На основе графиков показателей впускного и выпускного клапанов, регулируемых системой, с помощью программного обеспечения для 1D-моделирования AVL Boost были спрогнозированы рабочие показатели двигателя.

Результаты. Тесты показали, что моменты открытия и закрытия клапанов могут постоянно изменяться системой в соответствии с оборотами двигателя. Результаты моделирования двигателя с регулируемыми клапанами демонстрируют улучшение показателей мощности на единицу рабочего объёма двигателя, мощности торможения, тормозного момента, удельного расхода топлива на тормозном стенде, коэффициента остаточных газов на разных оборотах двигателя по сравнению с исходным двигателем. Улучшения особенно заметны на низких и средних оборотах.

Научная новизна. Предложены новые конструкция и принцип действия гидравлической системы управления клапанами газораспределения, стратегия регулирования клапанов, отличающиеся от известных.

Практическая значимость. Предложенная гидравлическая система управления клапанами газораспределения может использоваться в двигателях для улучшения их рабочих характеристик, отличается простотой конструкции и контроля, низкой себестоимостью.

Ключевые слова: *система регулирования клапанов, фаза газораспределения, высота подъёма клапана, характеристика двигателя*

Рекомендовано до публікації докт. техн. наук В.І. Самусею. Дата надходження рукопису 01.02.15.

УДК 621.85.01

M.O. Lubenets, Cand. Sci. (Tech.), Associate Professor

State Higher Educational Institution "National Mining University", Dnipropetrovsk, Ukraine.

EXPERIMENTAL DETERMINATION OF THE FRICTIONAL PROPERTIES OF THE FLEXIBLE BODY SLIDING OVER A BLOCK

М.О. Лубенець, канд. техн. наук, доц.

Державний вищий навчальний заклад „Національний гірничий университет", м. Дніпропетровськ, Україна

ЕКСПЕРИМЕНТАЛЬНЕ ВИЗНАЧЕННЯ ФРИКЦІЙНИХ ВЛАСТИВОСТЕЙ ГНУЧКОГО ТІЛА ПРИ КОВЗАННІ ПО БЛОКУ

Purpose. Experimental determination of the dependence of the force and the coefficient of friction of the flexible body on the normal reaction between bodies while sliding over the fixed block.

Methodology. The frictional properties of the friction pair "flexible body–block" was determined by means of the test bench with different forces applied to the ends of the flexible body. Then, according to Euler's Solution, the experimental dependence of the force and the friction coefficient on the normal reaction between the bodies was developed and compared with the accumulated data of the theory and practice.

Findings. Experimental dependence of the force and the coefficient of friction of the flexible body on the normal reaction between bodies while sliding over the fixed block was established.

Originality. For the first time, the two-parameter linear dependence of the friction force and inversely proportional dependence of the coefficient of friction of the flexible body on the normal reaction between bodies while sliding over the fixed block were obtained experimentally. This corresponds to Coulomb's law of friction between two solid bodies, new solution of Euler's classical problem of flexible body sliding over the fixed block, and practice data.

Practical value. Research results can be used in mechanical engineering while designing and operating transport vehicles with a flexible traction body as well as in research and education.

Keywords: *law of friction, flexible body, thread, sliding, block, tensile force, frictional properties, friction force, coefficient of friction, normal reaction*

Objectives. The purpose of the article is to define experimentally dependence of the strength and the coefficient of friction of the flexible body on the normal reaction between the bodies sliding over the fixed block.

Previously, the normal reaction between the flexible body and block the has never been defined with the direct method since according to Euler's solution it was determined with the indirect method and depended on the frictional properties of the flexible body – the coefficient of friction.

Problem formulation. Friction of bodies is an extremely complex phenomenon. Mankind faced advantages and disadvantages of the use of friction at the dawn of its existence, long before the understanding of its laws. The first scientific reasoning and results of experiments on the friction of solids were found in the notes by Leonardo da Vinci (1452–1519). The works showed the direct proportion between the resistance force and clamping force (the normal response) while sliding. The proportionality factor between these forces – the coefficient of friction is the ratio of frictional force to the normal reaction between the bodies, which was not then considered to depend on the contact area. Since the know-ledge about friction of solids developed by Leonardo da Vinci was forgotten, 180 years later (in 1699) the law was experimentally reopened by the French scientist Amontons.

In 1775, Leonhard Euler analytically described sliding of an ideal thread over a fixed block (a weightless, inextensible and absolutely flexible thread); it was described through the system of differential equations of equilibrium and solved. The design scheme of the problem is shown in Fig. 1.

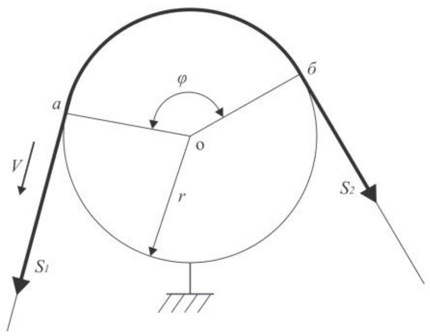

Fig. 1. Design scheme: S_1, S_2 are tensions in the branches of a flexible body leaving and entering the drum; r is the radius of the drum; φ is the angle of the wrap of the drum by the flexible body

According to Euler's conclusion, the ideal thread being under the action of forces S_1 and S_2 applied to its ends slides over the fixed block towards the greater force, exceeding the other one by the magnitude of the total friction force F, which arises between the thread and the fixed block while the ratio of the greater force to the lower force equals

$$\frac{S_1}{S_2} = e^{\mu\varphi},$$

where S_1 and S_2 are tensions in the branches of a flexible body leaving and entering the drum; φ is the angle of the wrap of the drum by the flexible body; μ is the coefficient of sliding friction between the flexible body and the block.

Thus the tension of the flexible body along the line of contact with the block is a non-linear exponential function

$$S(a) = S_2 e^{\mu\varphi},$$

where $S(\alpha)$ is the dependence of the tensile force of the flexible body along the contact line with the drum from the plane angle of the flexible body; α is the plane angle of the flexible body which is in contact with the drum.

Euler's solution (Euler's equation or formula), which has become classic, is the friction law of flexible bodies. The equation is used worldwide in research, education and engineering. Obtaining the equation is a prime example of solving mechanics problems using analytical methods. In spite of the practice data, the correct solution of the problem has never been questioned.

However, Euler's equation, either explicit or indirect, does not contain a recognized factor influencing the friction properties of solids, i.e. the normal reaction between the bodies and the molecular component of the friction force. The equation does not describe the boundary conditions of friction of the flexible body when the minimal force applied to one of its ends is zero. Nonlinear tension of the flexible body along the line of contact with the block does not correspond to the apparent linear relationship, when the friction is determined only by the intermolecular interaction of the friction pair and is proportional to the area of contact. Therefore, the cumulative results of the experimental studies of flexible-body sliding over the block are different from the theoretical prediction [1, 2].

Somewhat later, in 1779, French scientist Coulomb experimentally stated a new friction law of solids functioning to present. Analytical interpretation of the dependence of the friction force between the bodies on the normal clamping bodies (the normal reaction between the bodies) with sufficient accuracy for practical purposes is linked by the linear two-parameter function. However, it is not directly proportional, as Leonardo da Vinci (Amontons) considered. These data have been repeatedly obtained by other investigators.

There are also other hypotheses known regarding the friction of solids by Kragelskiy and Derjaguin. In addition to the frictional force and the normal reaction between bodies, they consider the following: the additional pressure caused by the intermolecular interaction between bodies; the total area of all the direct contacts between the bodies; molecular and mechanical components of the coefficient of friction; the shear strength of a single touch spot when the compressive load does not occur; the actual pressure on the spot of contact; hardening coefficient of a single touch spot when the compressive load does not occur; the coefficient depending on the distribution of roughness heightwise; the coefficient of hysteresis losses; projected range of a single irregularities simulated by the spherical segment. Despite the complexity, these hypotheses correspond to the two-parameter linear dependence between frictional force and the normal reaction of the friction pair, which was first introduced by Coulomb.

Research results. In 2007, the National Mining University proposed a new solution of classical Euler problem of sliding of the flexible body over the fixed block. This decision takes into account the idea of friction of solids – the Coulomb friction law for solids (1779), as well as the latest version of the law of conservation of mechanical energy in a closed mechanical system [2]. The new equation shows two-parameter linear relationship between the friction force and the normal reaction between the flexible body and the block while sliding. The equation is consistent with the generally accepted ideas about the friction of solids – it indirectly includes the force and the normal reaction between the flexible body and block, the molecular component of the friction force, which are interconnected by means of the linear coefficient of friction. Consequently, the new equation of friction of flexible bodies corresponds to the Coulomb friction law for solids and the latest version of the law of conservation of mechanical energy in a closed mechanical system

$$F = F_c + tg\beta \cdot \left(\varphi \cdot \frac{S_1 + S_2 - 2qv^2}{2} \right) = $$
$$= F_c + tg\beta \cdot N = \left(\frac{F_c}{N} + tg\beta \right) \cdot N,$$

where F is the force of friction between the bodies; Fc is the force of friction between the flexible body and the block when the normal reaction between the bodies is zero; $tg\beta$ is the slope ratio of the dependence of the friction force on the normal reaction between the bodies; v stands for the sliding velocity of the flexible body; q is linear flexible body weight; N is the normal reaction between the flexible body and the block.

Moreover, the relationship can be represented using a friction coefficient which is a traditional and widely used parameter in the practice introduced by Leonardo da Vinci (Amontons)

$$F = \mu \cdot \frac{(S_1 + S_2 - 2 \cdot q \cdot v^2) \cdot \varphi}{2} = \mu \cdot N \cdot$$

Thus, applying the coefficient of friction, we artificially convert the two-parameter dependence of the friction force on the normal reaction between the bodies while sliding over the fixed block into proportional relationship. For this reason, the friction coefficient is not a constant, but variable value, which is inversely proportional to the normal reaction between the bodies

$$\mu = \left(\frac{F_c}{N} + tg\beta \right).$$

The variability of the friction coefficient virtually occurs at small values of the normal reaction between the bodies. At medium and high values of the normal reaction the coefficient of friction depends slightly on the normal reaction which asymptotically approaches the value of $tg\beta$.

However, currently in the literature lacks data on the experimental determination of the dependence of the force and coefficient of friction of flexible bodies over a block on the normal reaction between the sliding bodies.

Consequently, to provide support for the new output results of solving the problem of the flexible body sliding over the fixed block it is necessary to conduct the experiment which is covered in the article.

Experimental determination of the dependence of the force and the coefficient of friction between the flexible body and the fixed block on the normal reaction between sliding bodies was carried out on the test bench, Fig. 2.

A flexible cotton thread *3* (0.5 mm thick) was used as a flexible body; it was thrown over the fixed drum *4*. The drum *4* was fixed to the test bench bed (plate) *1* and oriented in a vertical plane. Loads *2* and *5* (from a set of laboratory weights) were attached to the ends of the thread *3*, creating tension forces S_1 and S_2. Diverting pulleys *6* set on the ball-bearings with guards over the working surface are intended to define the angle of the thread 3 wrapping around the drum *4*. The diverting pulleys 6 are separated in space – they are situated in different vertical planes within the height of the drum *4* so that the thread *3* came into contact with the drum *4* spirally, and its windings did not touch each other.

The friction pair – the cotton thread and the turned drum – were subjected to the experiment. The drum diameter was 75 mm and it was 25 mm high. The diameter of the diverting pulleys was 22 mm. The angle of the thread wrapping around the drum was set ranging 45 to 1080°.

The tests were conducted as follows. For a certain wrap angle and less force S_2, applied to one end of the thread, we sorted out bigger force S_1, applied to the other end of the thread so that the sliding speed of the thread over the drum was constant. Sliding speed of the thread over the drum was determined regarding the time of several revolutions of the labelled deflecting roller. The time of a number of turns of the deflecting roller was measured with a stopwatch. The greater force S_1, applied to the other end of the thread, was set with the linear interpolation of the results of several tests at the same sliding speed of the thread over the drum, equal to 46 mm/s.

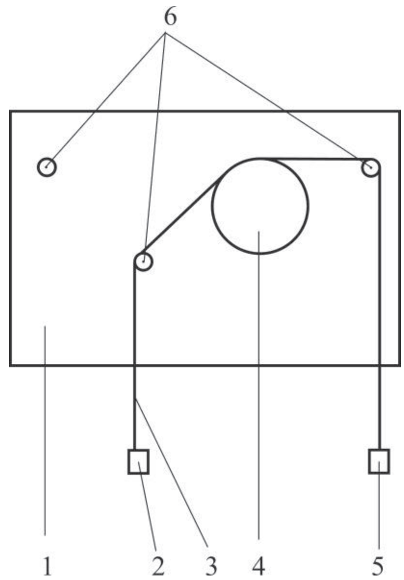

Fig. 2. The kinetic scheme of the test bench to determine the friction force between the thread and the fixed drum of the normal reaction between the bodies sliding over the fixed block: 1 is the test bench bed; 2 is the load; 3 is a thread; 4 is a fixed drum; 5 is the load; 6 stands for diverting pulleys

For the given angle of the thread wrap around the drum and other smaller forces of S_2 (the normal reaction of other bodies) greater forces S_1 were set analogously.

The normal reaction between the flexible body and the drum was defined excluding the centrifugal forces of the thread from the new solutions of classical Euler problem which, unlike the known solution by Euler, does not depend on the frictional properties of the flexible body. Thus, it was determined according to the formula

$$N = \left(\varphi \cdot \frac{S_1 + S_2}{2} \right).$$

According to Euler's known solution, the normal reaction between the flexible body and the drum depends on the coefficient of friction and is determined using the formula

$$N = \int_0^{\varphi} S(\alpha)\cdot d\alpha = \int_0^{\varphi} \left(S_2 \cdot e^{\mu \cdot a}\right)\cdot d\alpha = \left(\frac{S_2}{\mu}\cdot e^{\mu \cdot a}\right)\Big|_0^{\varphi} = \frac{S_2}{\mu}(e^{\mu\cdot\varphi} - 1).$$

The friction force between the flexible body and the drum was determined without taking into account the cross-section of the thread according to the formula

$$F = S_1 - S_2.$$

The coefficient of friction between the flexible body and the drum was first determined with the direct method as the ratio of the frictional force to the normal reaction between the bodies by the formula

$$\mu = \frac{F}{N} = \frac{2\cdot(S_1 - S_2)}{\varphi\cdot(S_1 + S_2)}.$$

According to the Euler's decision, the coefficient of friction between the flexible body and the drum is determined indirectly by the formula

$$\mu = \frac{1}{\varphi}\cdot \ln\frac{S_1}{S_2}.$$

In practice, the coefficient of friction for conveyor belts determined according to Euler's decision is up to 30% higher compared to its actual value.

Fig. 3 shows the dependence of the resulting friction between the thread and the drum on the normal reaction between the bodies.

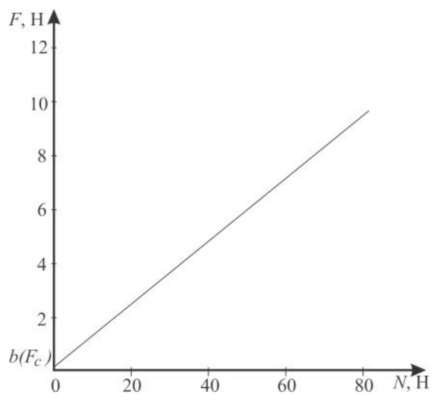

Fig. 3. Dependence of the frictional force between the thread and the drum on the normal reaction between the bodies (sliding speed is 46 mm/s and the wrap angle is 720°)

The analysis of the experimental data shows that the dependence of the friction force on the normal reaction between the bodies is well described with a linear function.

$$F = в + a \times N,$$

where *a* is the slope of the experimental curve *tgβ*; *b* is *const* which is the starting ordinate of the linear function.

The experimental dependence is a two-parameter linear function with positive parameters of *a* and *b* and corresponds to Coulomb's friction law for solids and Euler's new solution of the problem. The value of the parameters *a* and *b* indicates the magnitude of the molecular component of the friction force between the thread and the drum and the slope of the dependence of the friction force on the normal reaction between the bodies

$$F = F_c + tg\beta \cdot N.$$

The linear approximation of the experimental dependence gave the value of *Fc*, equal to 0.066 *N*, and setting *tgβ,* equal to 0.123.

Fig. 4 shows the dependence of the coefficient of friction between the thread and the drum on the normal reaction of the bodies.

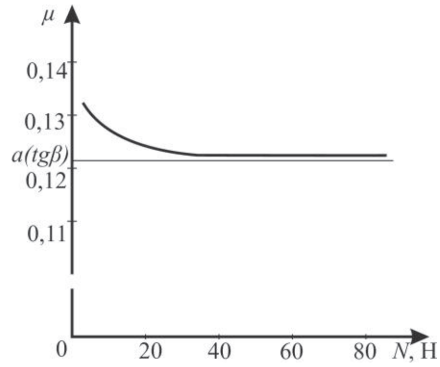

Fig. 4. Coefficient of friction between the thread and the drum on the normal reaction between the bodies (sliding speed is 46 mm/s and the wrap angle is 720°)

The analysis of the data showed that the experimental dependence of the friction coefficient μ on the normal reaction between the bodies *N* while sliding over the fixed drum is described with a monotonically decreasing function. The rate of dependence decay decreases with increasing normal reaction between the bodies, while the friction coefficient asymptotically approaches the value of the parameter *tgβ*.

The dependence of the friction coefficient corresponds to Coulomb's two-parameter friction law for solids, to Euler's new solution [2] and the accumulated data practices. The dependence parameter values indicate the magnitude of the molecular component of the friction force between the bodies *Fc* and the slope of the dependence of the friction force on the normal reaction between the bodies *tgβ*, correspondingly. The coefficient of friction is well described with a two-parameter nonlinear inversely proportional function of the form

$$\mu = \left(\frac{b}{N} + a\right).$$

Conclusions. Thus, for the first time, the linear dependence of the friction force of the flexible body and inversely proportional dependence of the friction coefficient on the normal reaction between the bodies sliding over the fixed block was experimentally obtained. Experimental dependences correspond to currently valid Coulomb's friction law for solids, to the new solution of classical Euler's problem regarding the flexible body sliding over the fixed block and accumulated data of practices.

References / Список літератури

1. Kiriya, R.V. and Stakhovsky, E.A., 2002. The use of the perturbation method of Prandtl to resolve the paradox of N.E Zhukovsky. *Systemni Tekhnolohii,* 4 (21), pp. 33–46.

Кирия Р.В. Применение метода возмущений Л. Прандтля к разрешению парадокса Н.Е. Жуковского / Р.В. Кирия, Е.А Стаховский. // Системні технології. – Днепропетровск, 2002. – № 4'(21).– С. 33–46.

2. Lubenets, N.A., 2014. New solution of the Euler problem about a flexible body sliding over a fixed block. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universitetu*, 3, pp. 45–53.

Лубенец Н.А. Новое решение задачи Эйлера о скольжении гибкого тела по неподвижному блоку / Н.А. Лубенец // Науковий вісник НГУ – Днепрпопетровск, 2014. – № 3. – С. 45–53.

Мета. Експериментальне визначення залежності сили та коефіцієнта тертя гнучкого тіла від нормальної реакції між тілами при ковзанні по нерухомому блоку.

Методика. На випробувальному стенді проведене визначення фрикційних властивостей пари тертя гнучке тіло – блок за різних зусиль, прикладених до кінців гнучкого тіла. Потім, згідно з новим рішенням задачі Ейлера, побудовані експериментальні залежності сили та коефіцієнта тертя від нормальної реакції між тілами й співставлені з накопиченими даними теорії та практики.

Результати. Встановлені експериментальні залежності сили та коефіцієнта тертя гнучкого тіла від нормальної реакції між тілами при ковзанні по нерухомому блоку.

Наукова новизна. Уперше експериментально отримані: двопараметрична лінійна залежність сили тертя та обернено пропорційна залежність коефіцієнта тертя гнучкого тіла від нормальної реакції між тілами при ковзанні по нерухомому блоку. Зазначене відповідає закону тертя твердих тіл Кулона, новому рішенню класичної задачі Ейлера про ковзання гнучкого тіла по нерухомому блоку та даним практики.

Практична значимість. Результати досліджень будуть використані в машинобудуванні при проектуванні та експлуатації транспортних машин з гнучким тяговим органом, наукових дослідженнях і навчальному процесі.

Ключові слова: *закон тертя, гнучке тіло, нитка, ковзання, блок, зусилля натягування, фрикційні властивості, сила тертя, коефіцієнт тертя, нормальна реакція*

Цель. Экспериментальное определение зависимости силы и коэффициента трения гибкого тела от нормальной реакции между телами при скольжении по неподвижному блоку.

Методика. На испытательном стенде проведено определение фрикционных свойств пары трения гибкое тело – блок при различных усилиях, приложенных к концам гибкого тела. Затем, согласно новому решению задачи Эйлера, построены экспериментальные зависимости силы и коэффициента трения от нормальной реакции между телами и сопоставлены с накопленными данными теории и практики.

Результаты. Установлены экспериментальные зависимости силы и коэффициента трения гибкого тела от нормальной реакции между телами при скольжении по неподвижному блоку.

Научная новизна. Впервые экспериментально получены: двухпараметрическая линейная зависимость силы трения и обратно пропорциональная зависимость коэффициента трения гибкого тела от нормальной реакции между телами при скольжении по неподвижному блоку. Указанное соответствует закону трения твердых тел Кулона, новому решению классической задачи Эйлера о скольжении гибкого тела по неподвижному блоку и данным практики.

Практическая значимость. Результаты исследований будут использованы в машиностроении при проектировании и эксплуатации транспортных машин с гибким тяговым органом, научных исследованиях и учебном процессе.

Ключевые слова: *закон трения, гибкое тело, нить, скольжение, блок, усилие натяжения, фрикционные свойства, сила трения, коэффициент трения, нормальная реакция*

Рекомендовано до публікації докт. техн. наук В.В. Процівом Дата надходження рукопису 01.12.14.