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EFFECT OF ANGLE OF THREAD INCLINATION AND EQUIVALENT RADIUS ON ENERGY DISSIPATION IN SCREW JOINTS

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The paper presents the problem of structural friction appearing in a screw joint with frictional and elastic-frictional effects between its elements. Two mathematical models of the screw joint taking into acount Lame's problem are analysed.

Key words: energy dissipation, structural friction, screw joint, thread, equivalent radius, Lame's problem

1. Introduction

In the paper, the influence of the angle of thread inclination in a screw joint and the effect of equivalent radius on energy dissipation in mathematical models representing screw joints are presented.

Vibrations bring about formation of variable stress in machine elements. They lead to distortions in bearings, joints, etc. Vibrations of machines and vehicles have harmful influence on the human organism. Vibration of gases and mechanical elements are a source of noise.

The largest intensity of vibration appears in resonance states. Therefore, selection of natural vibrations of a given system is very important. Escape from a resonance zone does not solve the whole problem, however. In many cases, designers use special dampers of vibrations. Admittedly, they raise costs and cause additional problems with exploitation. Thus, it seems useful to continue works on suppression of vibrations by natural ways, such as structural friction.

Damping of vibration results from mechanical energy dissipation which is associated with motion of mechanical assemblies. Large vibrations can cause defective operation of equipment (reduced accuracy of performance of elements). Vibrations of a system can result in jam of mechanical elements or it can disturb their operation. This can disconnection of joints (threads).

In the paper, the problem of energy dissipation is presented on an example of structural friction. When small forces are exerted to shift two elements pressed one against the other, elastic deformation of the small contact surfaces follows. On these areas, very small slips appear. When the friction forces work, dissipation of energy appears. In machines and systems, there are many joints that are motionless by definition. Yet, in consequence of the deformations in joint bodies, dissipation of energy appears in them. The resistance caused by friction in motionless joints related to elasticity of the connected bodies is called *structural friction* (Giergiel, 1969, 1971; Osiński, 1986, 1997; Skup and Kaczmarek, 2005).

The problem of energy dissipation in screw joints is not new and was presented by e.g. by Kalinin *et al.* (1960, 1961), Panovko and Strakhov (1959). A new approach to the problem is investigation of elastic-frictional effects with Lame's problem taken into consideration.

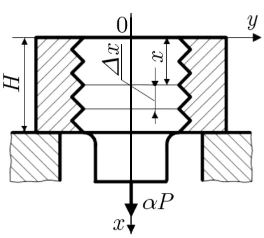

Fig. 1. Physical model of the considered screw joint

2. Mathematical models of screw joints

The purpose of this paper is to show the influence of geometrical parameters on the value of natural dissipation of energy in a screw joint. The paper presents two models of the screw joint. In the first model (Fig. 2), it has been assumed that the interaction between the elements of the screw joint is frictional, and in the second the interaction is elastic and frictional (Fig. 3).

Notations on Fig. 2 and Fig. 3

r_0	–	equivalent radius
r_z, r_w	–	external and internal radii of the surface of segment
r_{z0}	–	external radius of the screw joint

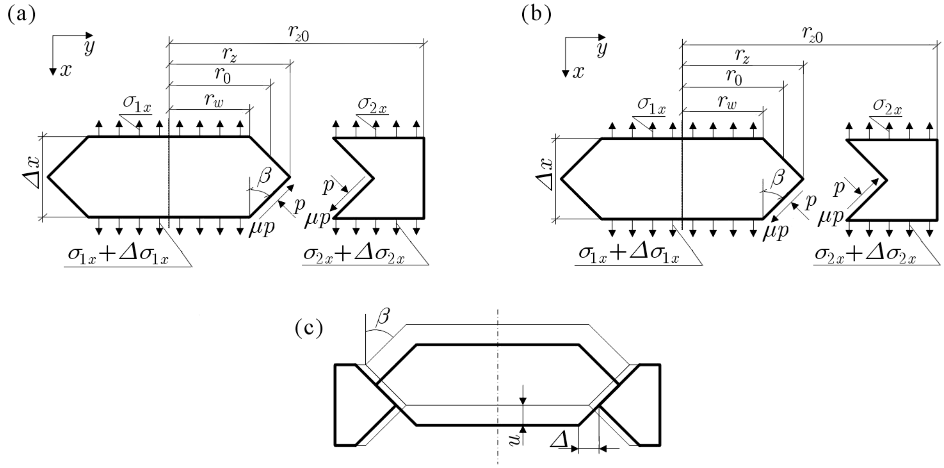

Fig. 2. Model 1 with frictional effects between its elements – segment of the screw joint: (a) axial loading, (b) axial releasing, (c) dislocation the screw joint segment

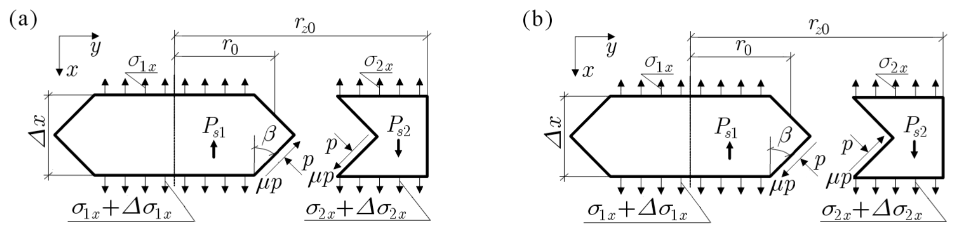

Fig. 3. Model 2 with elastic and frictional effects between its elements – segment of the screw joint: (a) axial loading, (b) axial releasing

p	–	unit pressure
Δx	–	height of the segment
μ	–	friction coefficient
σ_{x1}, σ_{x2}	–	stresses
β	–	angle of thread inclination of the screw joint
u	–	dislocation of the segment
Δ	–	clearance between cooperating elements
P_s	–	force of the elastic resistance.

In the first place, a sector of the screw joint has been analysed (Fig. 2 and Fig. 3). The whole screw joint can be considered as a joint with a large number of such sectors placed in the nut (each sector consists of one coil of thread).

One cycle of loading consist of four stages:

- stage one, the process of loading – the elements of the system get relocated (segment 1 – Fig. 4)
- stage two, the process of unloading – the friction forces change the sign and the elements of the system do not get relocated (segment 2 – Fig. 4)
- stage three, the process of unloading – the elements of the system get relocated (segment 3 – Fig. 4)
- stage four, the process of loading – the friction forces change the sign and the elements of the system do not get relocated (segment 4 – Fig. 4).

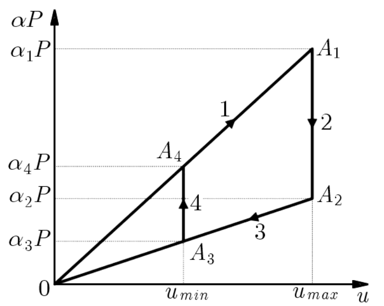

Fig. 4. Hysteresis loop of the screw joint

During one cycle of loading, the energy dissipation in the system is measured by the field of a hysteresis loop in a triangle or quadrangle form (Fig. 4).

In the considerations, the following assumptions have been made:

1. The distribution of the pressure per unit area between cooperating surfaces of the screw joint is even.
2. The joined elements can be characterized by a constant coefficient of friction for any value of the pressure per unit area.
3. Friction forces on the faying surface of mating elements are subject to Coulomb's law.
4. Properties of the material are subject to Hooke's law.
5. Friction is fully developed in the slip zone and amounts to zero outside of it.
6. Changes in the force P are smooth, which justifies the omission of inertia forces.

7. Assumption of plane sections (transverse sections are plane and do not deform under stress) holds.
8. In the model, the role of internal friction is not taken into account.

The conditions for the equilibrium of forces in the sector of the screw joint are (Kalinin *et al.*, 1960)

$$\Delta\sigma_{1x}F_1 = \Delta\sigma_{2x}F_2 \tag{2.1}$$

where: $F1$, $F2$ are the fields of the cross-sectional area of the bolt and nut sectors.

2.1. Model 1

The equation of the equilibrium of forces working in the system (in the direction of the x-axis, Fig. 2) is for the screw sector

$$-\sigma_{1x}\pi r_0^2 - \mu p 2\pi r_0 \cos\beta \frac{\Delta x}{2\cos\beta} - p2\pi r_0 \sin\beta \frac{\Delta x}{2\cos\beta} + (\sigma_{1x} + \Delta\sigma_{1x})\pi r_0^2 = 0 \tag{2.2}$$

The equation of the equilibrium of forces operating in the system in the radial direction (y-axis, Fig. 2) for the screw sector is

$$-\sigma_{1r} + \mu p \sin\beta - p\cos\beta = 0 \tag{2.3}$$

The equation of the equilibrium of forces working in the system (in the direction of the x-axis, Fig. 2) is for the nut sector

$$\begin{aligned}&-\sigma_{2x}\pi(r_{z0}^2 - r_0^2) + \mu p 2\pi r_0 \cos\beta \frac{\Delta x}{2\cos\beta} + p2\pi r_0 \sin\beta \frac{\Delta x}{2\cos\beta} + \\ &+(\sigma_{2x} + \Delta\sigma_{2x})\pi(r_{z0}^2 - r_0^2) = 0\end{aligned} \tag{2.4}$$

In accordance with Lame's problem, the equations of the radial and hoop stresses in the system (Fig. 5) for the nut sector can be expressed as

$$\begin{aligned}\sigma_{2r} &= \frac{p\cos\beta(1-\mu\tan\beta)r_0^2}{(r_0^2 - r_{z0}^2)}\Big(1 - \frac{r_{z0}^2}{r^2}\Big) \\ \sigma_{2t} &= \frac{p\cos\beta(1-\mu\tan\beta)r_0^2}{(r_0^2 - r_{z0}^2)}\Big(1 + \frac{r_{z0}^2}{r^2}\Big)\end{aligned} \tag{2.5}$$

The radial dislocation u_p (in accordance with Lame's problem, Fig. 5c) is equal

$$u_p\Big|_{(r=r_0)} = -\frac{\Delta\sigma_{1x}}{\Delta x}\frac{r_0^2\cos\beta(1-\mu\tan\beta)}{E_2(\mu+\tan\beta)(r_0^2 - r_{z0}^2)}[(1-\nu_2)r_0^2 + (1+\nu_2)r_{z0}^2] \tag{2.6}$$

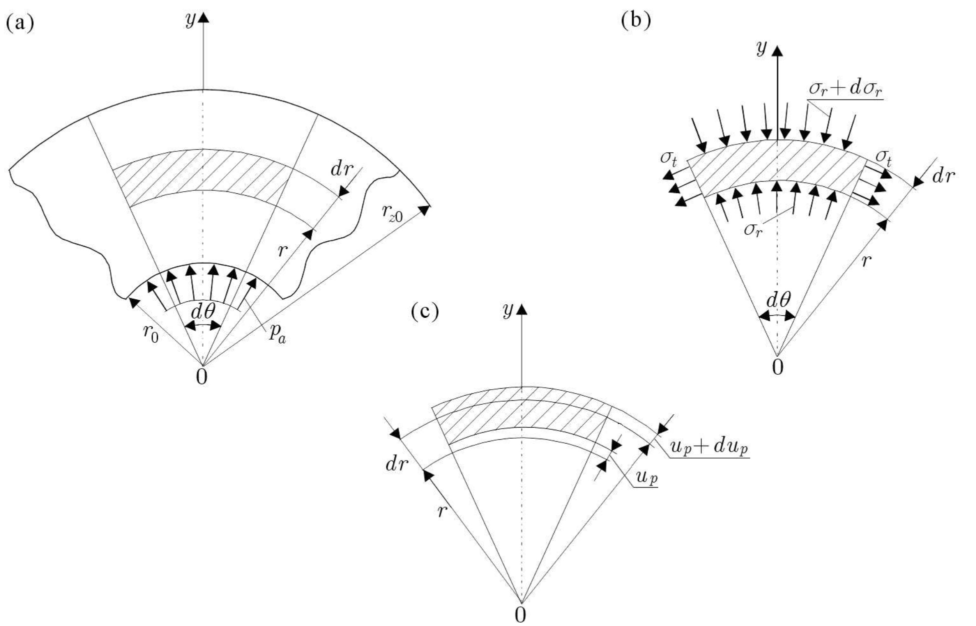

Fig. 5. Stresses and dislocations in the nut sector

It has been assumed that during the loading the sectors do not displace axially, and a margin Δ appears between them (the radius of the screw sector grows and the radius of the nut sector decreases – Fig. 2c).

The displacement of the whole screw joint has been found for the boundary conditions

$$\sigma_{1x} = \begin{cases} 0 & \text{for} \quad x = 0 \\ \dfrac{\alpha P}{\pi r_0^2} & \text{for} \quad x = H \end{cases} \tag{2.7}$$

and can be described as

$$u = \frac{\alpha P}{\pi r_0^2}\Big[w_2 - \frac{a_0}{2}w_1 + \frac{w_1\sqrt{a_0^2 + 4b_0}}{2\tanh\Big(\frac{H}{2}\sqrt{a_0^2 + 4b_0}\Big)}\Big] \tag{2.8}$$

where

$$a_0 = \frac{(w_2 - m_4)}{w_1} \qquad\qquad b_0 = \frac{1}{E_1 w_1}$$
$$m_4 = \frac{2\nu_1 r_0 \cos\beta(1 - \mu\tan\beta)}{E_1(\mu + \tan\beta)}$$

$$w_1 = -\frac{r_0^2 \cos\beta(1-\mu\tan\beta)[(1-\nu_2)r_0^2 + (1+\nu_2)r_{z0}^2]}{E_2 \tan\beta(\mu+\tan\beta)(r_0^2 - r_{z0}^2)} + $$
$$+\frac{r_0^2\cos\beta(1-\mu\tan\beta)(1-\nu_1)}{E_1\tan\beta(\mu+\tan\beta)}$$
$$w_2 = \frac{\nu_1 r_0}{E_1 \tan\beta}$$

where

H	–	height of the screw joint
u	–	axial displacement
P	–	axial force
p	–	pressure per unit area
μ	–	coefficient of friction
E_i	–	Young's modulus
α	–	coefficient which changes from 0 to 1.

Similarly, the dislocation of the extreme cross-section in Stage 3 has been determined

$$u = \frac{\alpha P}{\pi r_0^2}\Big[w_4 - \frac{a_1}{2}w_3 + \frac{w_3\sqrt{a_1^2+4b_1}}{2\tanh\Big(\frac{H}{2}\sqrt{a_1^2+4b_1}\Big)}\Big] \tag{2.9}$$

where

$$a_1 = \frac{(w_4 - m_5)}{w_3} \qquad\qquad b_1 = \frac{1}{E_1 w_3}$$
$$m_5 = \frac{2\nu_1 r_0 \cos\beta(1+\mu\tan\beta)}{E_1(\tan\beta - \mu)}$$
$$w_3 = -\frac{r_0^2 \cos\beta(1+\mu\tan\beta)[(1-\nu_2)r_0^2 + (1+\nu_2)r_{z0}^2]}{E_2 \tan\beta(\tan\beta-\mu)(r_0^2 - r_{z0}^2)} + $$
$$+\frac{r_0^2\cos\beta(1+\mu\tan\beta)(1-\nu_1)}{E_1\tan\beta(\tan\beta-\mu)}$$
$$w_4 = \frac{\nu_1 r_0}{E_1 \tan\beta}$$

The energy dissipation for one cycle of stress (Fig. 4) equals

$$\psi = \frac{P^2\alpha_1^2 m_6}{2\pi r_0^2}\Big(1 - \frac{m_6}{m_7}\Big) - \frac{P^2\alpha_3^2 m_7}{2\pi r_0^2}\Big(\frac{m_7}{m_6} - 1\Big) \tag{2.10}$$

where

$$m_6 = w_2 - \frac{a_0}{2}w_1 + \frac{w_1\sqrt{a_0^2+4b_0}}{2\tanh\Big(\frac{H}{2}\sqrt{a_0^2+4b_0}\Big)}$$

$$m_7 = w_4 - \frac{a_1}{2}w_3 + \frac{w_3\sqrt{a_1^2+4b_1}}{2\tanh\Big(\frac{H}{2}\sqrt{a_1^2+4b_1}\Big)}$$

2.2. Model 2

The dislocation of the extreme cross-section and energy dissipation for one cycle of stress for Model 2 have been obtained similarly, and they have the following form

$$u = \frac{\alpha P}{\pi r_0^2}\Big[w_8 - \frac{a_0}{2}w_7 + \frac{w_7\sqrt{a_0^2+4b_0}}{2\tanh\Big(\frac{H}{2}\sqrt{a_0^2+4b_0}\Big)}\Big] \tag{2.11}$$

$$u = \frac{\alpha P}{\pi r_0^2}\Big[w_{12} - \frac{a_1}{2}w_{11} + \frac{w_{11}\sqrt{a_1^2+4b_1}}{2\tanh\Big(\frac{H}{2}\sqrt{a_1^2+4b_1}\Big)}\Big] \tag{2.12}$$

where

$$\begin{aligned}
w_9 &= -\frac{r_0^2\cos\beta(1-\mu\tan\beta)[(1-\nu_2)r_0^2+(1+\nu_2)r_{z0}^2]}{E_2(r_0^2-r_{z0}^2)(\tan\beta+\mu)} + \\
&\quad + \frac{r_0^2\cos\beta(1-\mu\tan\beta)(1-\nu_1)}{E_1(\mu+\tan\beta)} \\
w_{10} &= \frac{c_{S2}[(1-\nu_2)r_0^2+(1+\nu_2)r_{z0}^2]}{E_2(r_0^2-r_{z0}^2)}\Big(\frac{\cos\beta(1-\mu\tan\beta)}{\pi\Delta x(\mu+\tan\beta)} + r_0\tan\beta\Big) + \\
&\quad + \frac{c_{S1}\cos\beta(1-\nu_1)(1+\tan^2\beta)}{E_1\pi\Delta x(\mu+\tan\beta)} \\
w_{13} &= -\frac{r_0^2\cos\beta(1+\mu\tan\beta)[(1-\nu_2)r_0^2+(1+\nu_2)r_{z0}^2]}{E_2(r_0^2-r_{z0}^2)(\tan\beta-\mu)} + \\
&\quad + \frac{r_0^2\cos\beta(1+\mu\tan\beta)(1-\nu_1)}{E_1(\tan\beta-\mu)} \\
w_{14} &= \frac{c_{S2}[(1-\nu_2)r_0^2+(1+\nu_2)r_{z0}^2]}{E_2(r_0^2-r_{z0}^2)}\Big(\frac{\cos\beta(1+\mu\tan\beta)}{\pi\Delta x(\tan\beta-\mu)} + r_0\tan\beta\Big) + \\
&\quad + \frac{c_{S1}\cos\beta(1-\nu_1)(1+\tan^2\beta)}{E_1\pi\Delta x(\tan\beta-\mu)}
\end{aligned}$$

$$w_7 = \frac{w_9}{\tan\beta + w_{10}} \qquad w_8 = \frac{\nu_1 r_0}{E_1(\tan\beta + w_{10})}$$

$$w_{11} = \frac{w_{13}}{\tan\beta + w_{14}} \qquad w_{12} = \frac{\nu_1 r_0}{E_1(\tan\beta + w_{14})}$$

$$m_8 = \frac{2\nu_1 r_0 \cos\beta(1 - \mu\tan\beta)}{E_1(\mu + \tan\beta)}$$

$$m_9 = \frac{2\nu_1 c_{S1} \cos\beta(1 + \tan^2\beta)}{E_1 \pi r_0 s(\tan\beta + \mu)}$$

$$m_{10} = \frac{2\nu_1 r_0 \cos\beta(1 + \mu\tan\beta)}{E_1(\tan\beta - \mu)}$$

$$m_{11} = \frac{2\nu_1 c_{S1} \cos\beta(1 + \tan^2\beta)}{E_1 \pi r_0 s(\tan\beta - \mu)}$$

$$a_0 = \frac{1}{w_7}(w_8 - m_8 + m_9 w_7) \qquad b_0 = \frac{1}{w_7}\Big(\frac{1}{E_1} - m_9 w_8\Big)$$

$$a_1 = \frac{1}{w_{11}}(w_{12} - m_{10} + m_{11} w_{11}) \qquad b_1 = \frac{1}{w_{11}}\Big(\frac{1}{E_1} - m_{11} w_{12}\Big)$$

The energy dissipation for one cycle of stress (Fig. 4) equals

$$\psi = \frac{P^2\alpha_1^2 m_{12}}{2\pi r_0^2}\Big(1 - \frac{m_{12}}{m_{13}}\Big) - \frac{P^2\alpha_3^2 m_{13}}{2\pi r_0^2}\Big(\frac{m_{13}}{m_{12}} - 1\Big) \tag{2.13}$$

where

$$m_{12} = w_8 - \frac{a_0}{2}w_7 + \frac{w_7\sqrt{a_0^2 + 4b_0}}{2\tanh\Big(\frac{H}{2}\sqrt{a_0^2 + 4b_0}\Big)}$$

$$m_{13} = w_{12} - \frac{a_1}{2}w_{11} + \frac{w_{11}\sqrt{a_1^2 + 4b_1}}{2\tanh\Big(\frac{H}{2}\sqrt{a_1^2 + 4b_1}\Big)}$$

3. Simulation results

Simulations have been carried out with the help of a professional software (Mathematica 4.1).

The main purpose of the simulations was to show the influence of the angle of thread inclination in the screw joint and of the equivalent radius on energy dissipation for the assumed frictional models of bolted joints. Table 1 shows parameters of the screw joint which were used in computer calculations.

Table 1

Parameter [unit]	Value
Maximum stress σ [N/m^2]	$158.126 \cdot 10^6$
Maximum axial force P [N]	8000
Parameter α_1	1
Parameter α_3	0.125
Poisson's ratio ν	0.32
Young's modulus E [N/m^2]	$2.1 \cdot 10^{11}$
Coefficient of friction μ	0.166
Angle of thread inclination of the screw joint β [°]	45; 50; 55; 60
Outer diameter of the screw d_z [m]	$10 \cdot 10^{-3}$
Inner diameter of the screw d_w [m]	$8.026 \cdot 10^{-3}$
Equivalent diameter of the screw joint d_{z0} [m]	$13 \cdot 10^{-3}$
Height of the screw joint H [m]	$20.03 \cdot 10^{-3}$
Pitch of thread s [m]	$1.5 \cdot 10^{-3}$
Equivalent radius r_0 [m]	$4.525 \cdot 10^{-3}$

The area of the hysteresis loop and the maximal values of displacement for different angles of thread inclination are presented in Table 2 and Table 3.

Tabela 2

Angle	Hysteresis area ψ [Nm]		In percentages [%]	
β [°]	Model 1	Model 2	Model 1	Model 2
60	0.00268301	0.00223170	100	83.18
55	0.00337004	0.00274716	100	81.52
Angle	Displacement u [mm]		In percentages [%]	
β [°]	Model 1	Model 2	Model 1	Model 2
60	0.00214850	0.00187719	100	87.38
55	0.00285121	0.00247360	100	86.93

Simulations show (Fig. 7) that the relations between the angle of thread inclination and the field of the hysteresis loop are not linear. Similarly is with the dependences between the angle of thread inclination and the displacement of the extreme cross-section. They are not linear too (Fig. 6).

Tabela 3

Model	Hysteresis area ψ [Nm]		In percentages [%]	
	$\beta = 55°$	$\beta = 60°$	$\beta = 55°$	$\beta = 60°$
Model 1	0.00337004	0.00268301	100	79.61
Model 2	0.00274716	0.00223170	100	81.24
Model	Displacement u [mm]		In percentages [%]	
	$\beta = 55°$	$\beta = 60°$	$\beta = 55°$	$\beta = 60°$
Model 1	0.00285121	0.00214850	100	73.35
Model 2	0.00247360	0.00187719	100	75.89

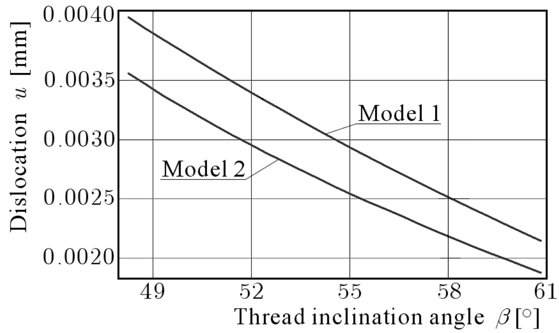

Fig. 6. Screw joint dislocation versus thread inclination angle

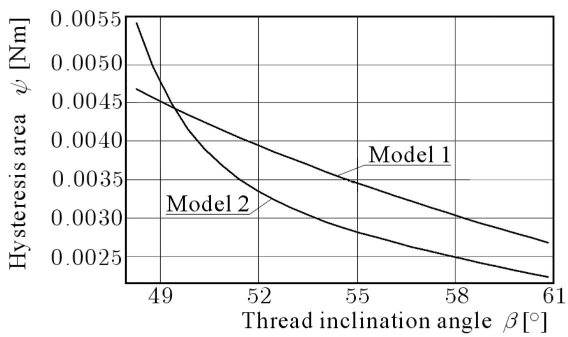

Fig. 7. Energy losses versus thread inclination angle $\psi(\beta)$

Moreover, one can easily notice that (for both models Fig. 6) it is very important to remember that every screw joint should be self-locking and changes of the angle should be limited.

Another problem is the equivalent radius r_0. In frictional models of screw joints, its effect on the displacement of the extreme cross-section is not linear

(Fig. 8). Similarly, the influence of the equivalent radius on energy dissipation (Fig. 9) non-linear too.

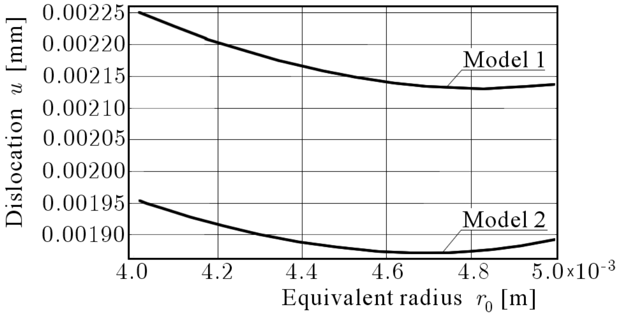

Fig. 8. Dislocation of the screw joint versus equivalent radius r_0

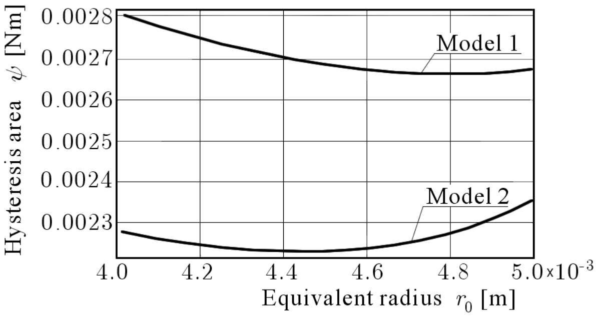

Fig. 9. Energy losses versus equivalent radius of a screw joint r_0

The range of the equivalent radius is limited by the external and internal radius of a screw. Figures 8 and 9 show that for both mathematical models, the displacement and dissipation energy decrease at first and grow afterwards.

All diagrams (Fig. 6-9) show that the displacement as well as the area of the hysteresis loop are larger for the frictional than for the elasto-frictional model.

4. Conclusion

The problem of energy dissipation in screw joints is not new and was presented e.g. by Kalinin *et al.* (1960, 1961), Panovko and Strakhov (1959). A new approach to the investigation of the problem is the study elasto-frictional effects between cooperating elements (screw-nut) with Lame's problem taken into consideration at the same time.

Structural friction in screw joints can be used to damp vibrations in systems subject to dynamic loads. Moreover, it is a natural way of energy dissipation. In the paper, basic laws of mechanics have been applied for the determination of the distribution of stresses and deformations at tension and compression. The assumptions are presented in Section 2, and the results of simulation in Section 3.

The paper presents two mathematical models of screw joints, in which Lame's problem is taken into consideration. The main purpose is to show the influence of the angle of thread inclination of a screw joint and of the equivalent radius on energy dissipation in frictional models of screw joints. Calculations have been conducted with the professional software Mathematica 4.1, which enabled quick analysis. The area of the hysteresis loop and the maximal values of displacement for different angles of thread inclination are presented in Table 2 and Table 3.

Simulations showed that (for both models Fig. 6) with a growth of the thread inclination angle leads to decrement of both quantities. It can be concluded that in inch screw joints, in which the thread angle amounts to 55 degrees, the natural dissipation of energy is larger than in metric threads, in which this angle amounts to 60 degrees.

One can formulate a theorem that the design of machines, devices and structures aimed to optimally exploit natural properties of vibration damping in screw joints, requires incorporation of screw threads with the smallest angle of thread inclination β (Fig. 6) with all geometrical parameters and the property of self-locking taken into consideration.

Mathematical models are created based on the concept of the equivalent radius. The value of the equivalent radius depends on the character of pressure per unit area. In the paper, it has been assumed that the distribution of the pressure per unit area between cooperating surfaces of the screw joint is even (2.1)-(2.13). This is not true. In real mechanical systems, the distribution of the pressure per unit area can have different shapes (triangular, parabolic, etc.), and this makes the value of the equivalent radius different too.

Figures 8 and 9 show (for both mathematical models) that if the equivalent radius grows, the displacement and energy dissipation decrease at first but then grow as well. All figures (Fig. 6-9) show that the value of the displacement as well as the hysteresis loop area are larger for the frictional model than for the elasto-frictional model of the joint. The obtained results confirm that research in this direction is purposeful and structural friction in screw joints can be used to damp vibrations in dynamic systems containing such joints.

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Wpływ kąta pochylenia gwintu i promienia ekwiwalentnego na rozpraszanie energii w połączeniu gwintowym

Streszczenie

W artykule przedstawiono problem tarcia konstrukcyjnego w aspekcie rozpraszania energii w połączeniu gwintowym. Rozpatrzono dwa modele matematyczne połączeń gwintowych: czysto- i sprężysto-tarciowy z uwzględnieniem twierdzenia Lame'go.

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