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TRIBOMECHANICAL SYSTEMS IN TIMING BELT DRIVES

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ABSTRACT

Timing belt drive, as relatively new concept in power transmission, uses the lithe element (timing belt) for realisation of its basic function. Kinematics of coupling between the timing belt drives and trapezoidal teeth profiles is explained in detail in the paper. Combining of chain, toothed and belt transmissions has brought a series of different motions, in tangential, radial and axial directions, especially in the period when the belt and the belt pulley enter the coupling. Identification of main tribomechanical systems and their detailed analysis are conducted based on kinematic analyses.

Keywords: timing belts, friction, wear.

AIMS AND BACKGROUND

Belt and strap drives transmit the power and motion from a drive shaft to a driven shaft. The basic elements of the belt drive are the belt pulleys and the belts. Drive belt pulley drives the driven belt pulley through the tractive branch, while the other branch is free.

The timing belt drives, in contrast to belt and strap drives, belong to synchronous drives, that is, they provide constant transmission ratio. The transmission of power is done through shape, while only a fraction of power is transmitted by friction.

The timing belt drive is relatively young drive, designed by Richard Case in 1946 (Refs 1 and 2). That was a rubber belt with trapezoidal teeth profile, used as a drive in sawing machines.

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The timing belt drives with trapezoidal teeth profile of the belts and the belt pulleys are the most frequently used in exploitation. The largest application of these belts is found in automobile industry. Considering that experimental tests were performed on a timing belt drive with trapezoidal teeth profile, the total kinematic analysis is linked to these belts.

Transfer of power and motion via timing belt is conducted by shape and by friction. During the power transfer, the belt teeth enter the coupling with the pulley groove and thereat the lateral and radial plays appear (Fig. 1). During the contact between the belt and the belt pulley, there are belt motions in tangential, radial and axial directions.

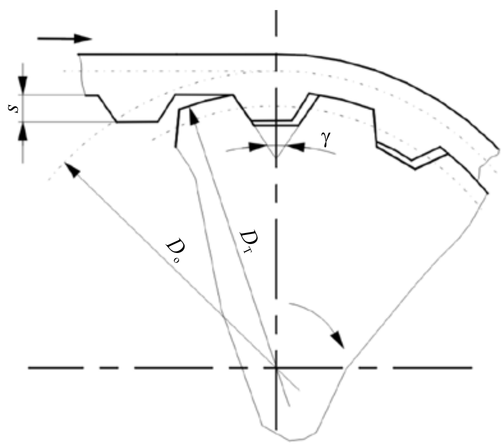


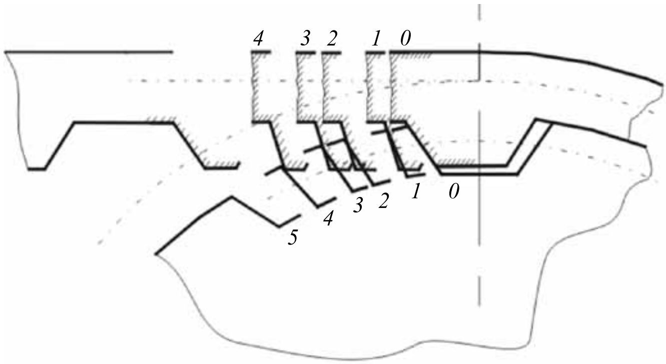
Fig. 1. Layout of coupling between the belt and the drive belt pulley

These motions are due to torque, circumferential force, previous tension, radial force, centrifugal force, air, belt deformation due to bending and tension, belt design, tractive element and the belt pulley, precision of manufacture and assembly, quality of contact surfaces machining, etc. Considering the large number of parameters influencing the transmission of power and motion, kinematic analysis of the coupling is a very complex process.

The side surface of the belt teeth makes contact with the side surface of the belt pulley teeth, after entering the coupling. Besides, the inner surface of the belt groove and the outer surface of the belt pulley and, from time to time, the front surface of the belt pulley with the flange ring, are in contact.

The belt tooth enters the coupling with the drive belt pulley, maximally strained due to previous tension. During entering the coupling, the belt tooth apex contacts the side surface of the belt pulley tooth. At that moment, a line contact occurs. Due to interference, the belt tooth cuts into the side surface of the belt pulley tooth. Due to elastic properties of the belt and the large stiffness of the belt pulley, deformation of the belt tooth occurs (Fig. 2, position *4*). Deformation of the belt tooth grows, while, at the same time, the contact surface between the belt and the belt pulley increases. The contact point between the belt tooth and the belt pulley tooth moves from the belt pulley tooth apex towards its root.

Fig. 2. Layout of belt teeth entering the coupling with the teeth of the drive belt pulley



Maximum tooth deformation takes place in position *2* (Fig. 2). The reduction of deformations occurs due to action of internal stresses and turning of the belt and the belt pulley. Full coincidence of the side surfaces of the belt teeth and the belt pulley teeth occurs in position *1* (Fig. 2). Now, contact over surface occurs. Relative sliding of their side surfaces, with appearance of the friction force, follows the process of belt teeth entering the coupling with the belt pulley. The value of normal force varies according to parabolic law, which leads to variation of the friction force. The greatest values of normal force and friction force are at the teeth roots.

Coincidence of inner belt surface and the outer surface of the belt pulley lasts very shortly. Due to actions of radial and centrifugal forces, the contact surface moves in radial direction (Fig. 3). During belt motion in radial direction, the friction force occurs in contact.

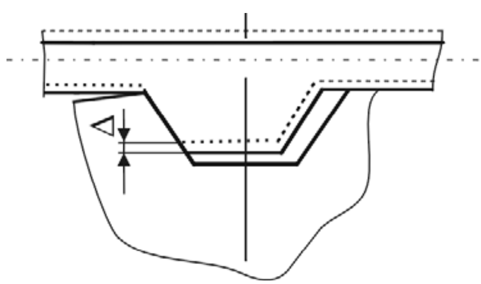


Fig. 3. Radial motion of the belt

Total motion reaches 1/5, that is 1/3 of the teeth height if friction force is neglected. Previous tension influences the most the motion in radial direction, because, with insufficient previous tension, radial forces may induce the exiting of the belt from the coupling with the belt pulley.

Certain amount of air is introduced into the coupling during contact of the belt and the belt pulley. A fraction of air exits the coupling in axial direction, while the rest of it remains trapped. Considering the existence of radial and side play between the teeth of the belt and of the belt pulley, the air remains within that space.

Radial component of air additionally loads the inner belt surface and tries to eject the belt out of the coupling. The air component in direction of motion additionally loads the belt and increases the pressure on contact surface (Fig. 4) which

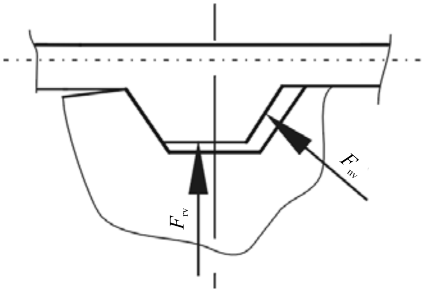


Fig. 4. Radial and tangential component of air additional load

leads to additional deformation of the belt teeth.

Due to action of radial force, centrifugal force and air, additional radial motion of the belt occurs. Relative sliding of side surfaces of the belt teeth and of the belt pulley teeth occurs during this motion. Motion is followed by the appearance of the slide friction force with values less than values of the friction force that appears during the entering of the belt teeth into the coupling with the belt pulley.

During the motion of the belt along the envelope angle of the belt pulley, bending and tension of the belt occur. In contrast to flat belts, where bending occurs along even curve, bending of timing belts occurs along polygonal profile. Bending of the belt leads to internal losses as well as to fatigue of the belt or the tractive element. Bending and tension of the belt along the envelope angle leads to the belt deformation. Besides, the load of the belt tooth decreases as the tooth enters the coupling with the belt pulley, until it comes out of the coupling. The first tooth in the coupling is the most loaded and the greatest deformations occur on it. Considering different teeth loads, uneven deformations of the belt teeth occur along the envelope angle. Difference of deformations leads to relative motion of the belt in tangential direction. In addition, the belt enters the coupling with the belt pulley maximum strained and leaves it unloaded. Due to these motions of the belt, a motion relative to the belt pulley along the envelope angle occurs. The friction forces between the inner belt surface and the outer belt pulley surface occur during this motion. Since these are the first order motions, values of the forces are very small, but their influence is not negligible.

In addition to motions in tangential and radial direction, motion in axial direction is also distinct in timing belts. This motion is conditioned by the belt design and by the helicoidal coil of the drive element. During axial motion, the front surfaces of the belt and the flange come into the contact. The contact is especially strong when the belt teeth enter and exit the coupling with the belt pulley. It is then that the damage of the belt mostly occurs, especially if there are errors during manufacture or mounting of the belt pulley. In addition, the contact between the belt and the flange occurs along the envelope angle, mostly due to relative motion of the belt with respect to the belt pulley (Refs 3–7).

The influence of the axial force reflects in pressuring the belt towards the flange. Praxis has shown that the timing belts have the inclination to run into the flange or to slide off the belt pulley if there is no control. This is noticed especially in wide belts. In the case where the drives operate at high speeds or larger centre distances or if they are considerably pre-tensioned, there are larger pressures of the belts front surfaces on flanges. Friction forces arise in the contact and lead to wear of the belts endings. After several months of operation, only 80% or less of the belt total width is utilised.

FRICTION IN TIMING BELT DRIVES

The largest amount of motion and power is transferred by shape, while only a small amount is transferred by friction. The influence of friction must not, by all means, be neglected. Appearance of friction in timing belt drives and its consequences have not been thoroughly explained. In contrast to other transmissions of power and motion (gears, chain drives, cardanic transmissions, etc.) in which friction mostly occurs in the contact of the two metal surfaces, in timing belt drives, there are metal and non-metal surfaces or the two non-metal surfaces in the contact.

The basic tribomechanical systems in the timing belt drives are as follows (Fig. 5):

- belt tooth – belt pulley tooth,
- belt face – flange,
- the belt groove – apex of the belt pulley tooth.

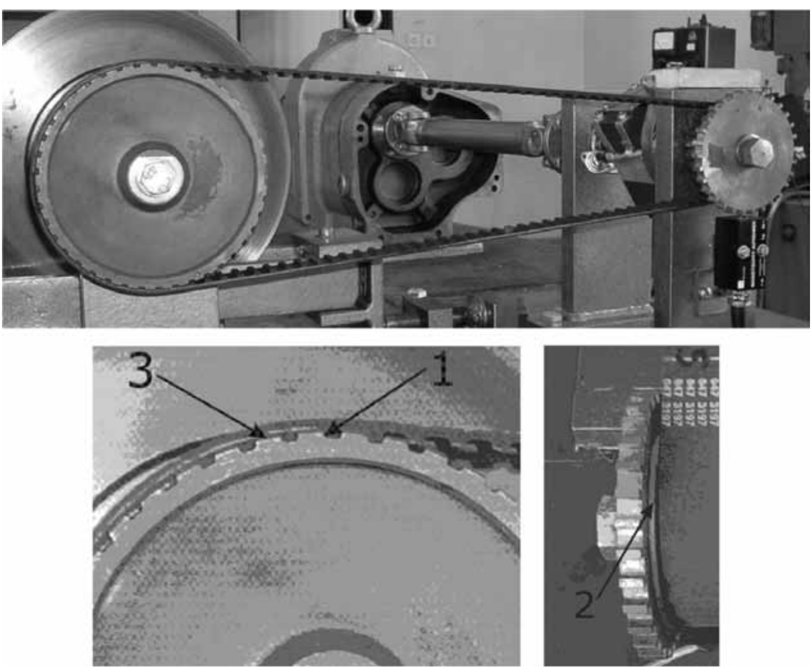


Fig. 5. Timing belt drive and basic tribomechanical systems

Types of motion that occur in these tribomechanical systems are given in Table 1.

Table 1. Tribomechanical systems and types of motion in timing belt drives (Ref. 8)

Tribomechanical system	Type of motion
Belt tooth – belt pulley tooth	impact sliding rolling
Belt face - flange	impact sliding
The belt groove – apex of the belt pulley tooth	sliding rolling

The side surfaces of the belt tooth and the belt pulley tooth are in contact during the coupling. Firstly, a line contact occurs at the point where the belt tooth enters the coupling with the belt pulley. The coupling starts with the belt tooth striking the belt pulley tooth. The belt tooth, considering its elastic properties, deforms and the contact surface increases. After the contact surface is increased and the belt and the belt pulley rotate, the belt tooth starts to slide along the side surface of the belt pulley, during which the roll friction with sliding occurs.

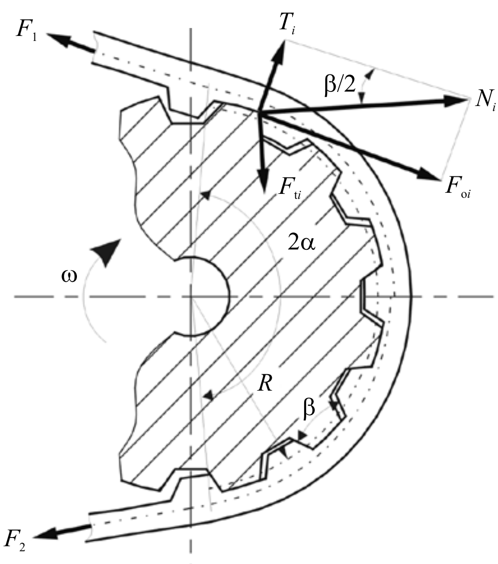


Fig. 6. Friction force at the side surface of the belt

Value of the friction force increases with the increase of the length of the sliding path and it achieves its greatest value at the root of the belt tooth (Fig. 6). At the same time, the action point of the resultant component of normal force moves from the tooth apex towards its root. The normal force changes according to parabolic law:

$$N_i = -\frac{N_{\max}}{l_t^2}\left(l - l_t\right)^2 + N_{\max} \tag{1}$$

where $N_{\max}$ is maximum value of normal force ($N_{\max} \approx 1.5F_0/z_{01}$) and l_t – the length of friction path.

The friction force occurs at the side surface of the belt tooth and its value is determined according to the following expression:

$$F_{ti} = N_i \mu = \frac{F_{oi}\,\mu}{\cos(\beta/2)} \tag{2}$$

where N_i is normal force acting on the belt tooth, μ – the friction coefficient, F_{oi} – circumferential force acting on the belt tooth and β – the angle of the belt profile.

The second tribomechanical system that is also important in analysis of friction in timing belt drives consists of face surface of the belt and the flange. The contact between the face surface of the belt and the flange frequently occurs during the entering of the tooth into the coupling with the drive belt pulley. In the case there are errors in manufacture and mounting of the drive, the impact of the belt tooth into the flange, that occurs during entering the coupling, may lead to its damage and even cracking. Besides, occasional contact between the belt face and the flange may occur along the envelope arc. During this contact, the belt slides and provokes the appearance of slide friction (Fig. 7).

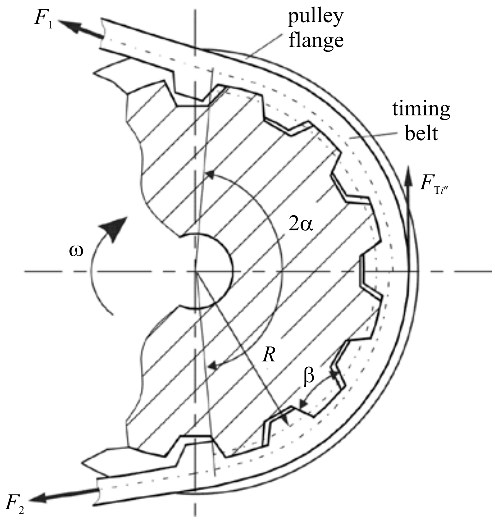


Fig. 7. Friction force between the flange and the face surface of the belt

The friction occurs along the whole envelope arc and between the belt groove and the tooth apex of the belt pulley. Relative motion of the belt along the envelope arc that arises due to deformation of the belt and the difference of loads of individual tooth, leads to appearance of the slide friction (Fig. 8). The value of this force may be determined according to expression:

$$F'_{ti} = c_K \,\Delta k \tag{3}$$

where c_K is the belt stiffness and Δk – the belt deformation along the envelope arc.

Considering that these are motions of first order, created forces are non-operational friction forces and their values are less than the values of other forces in timing belt drives. Change of direction of friction force occurs during belt motion across the envelope arc.

Variable force across the envelope arc causes the change of belt pitch. In drive belt pulleys, the belt pitch is larger than the belt pulley pitch at the loaded part.

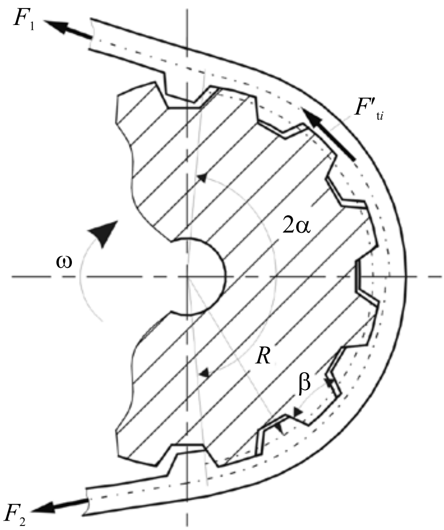


Fig. 8. Friction force between the belt groove and the apex of the belt pulley teeth

This leads to belt sliding in direction of rotation and friction force acting in direction of tension force in the tractive branch of the belt (Fig. 8). In driven belt pulleys, the belt pitch at free branch is smaller than the belt pulley pitch, while, at the tractive branch, the belt pitch is larger. These differences lead to situation in which the friction force near the tractive branch acts in opposite direction with respect to rotation direction, that is with respect to direction of the force in the free branch.

Generally, the direction of the friction force, F'_{ti}, depends on the sign of the total deformation of the belt across the envelope arc. The greatest values of the friction force arise in the case when there is a large difference in distribution of forces across the envelope arc, that is when there is a large difference between the force in tractive and free branch and the number of belt teeth in the coupling is small.

All of this leads to conclusion that direction and intensity of friction force change depending on position along the envelope arc. Change of direction of friction force always exists when there is change in belt pitch (Ref. 9). The whole explanation given is valid for the drive belt pulley, while the opposite stands for the driven belt pulley.

CONCLUSIONS

Initial contact between the belt and the belt pulley in the period of the beginning of coupling starts with the contact of the side surfaces, but also with special kind of belt tooth interference which cuts into the side surface of the belt pulley teeth. Due to the belt elasticity and the large stiffness of the belt pulley, the initial contact is followed by the belt teeth deformation. Turning of the belt pulley moves the contact surface from the tooth tip towards its root, whereat the period of entering into the coupling is followed by relative sliding between the side surfaces of the belt teeth and the belt pulley teeth, that is by occurrence of the slide friction.

The three characteristic tribomechanical systems are distinguished in the timing belt pulley. The following types of motion occur in these tribomechanical systems: impact, rolling and sliding. Analysis of these tribomechanical systems shows that the influence of the occurred friction forces is not negligible and it directly influences the transfer of power and motion and the operation life of the drive.

The values of the friction force are different in all three analysed tribomechanical systems. The friction force has the largest values at the side surface of the belt teeth and the belt pulley teeth. This force has somewhat less values between the face surfaces of the belt and the flange, while the smallest values of the friction force are between the apex of the belt pulley teeth and the belt groove. Direction and intensity of these forces are directly connected to kinematics of the coupling between the timing belt drives.

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