BRANIMIR PAVIĆ, D.Sc.
Fakultet strojarstva i brodogradnje
Zagreb, I. Lučića 5
JERKO RADOŠ, D.Sc.
SILVESTAR PERŠE, D.Sc.
Fakultet prometnih znanosti
Zagreb, Vukelićeva 4

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INFLUENCE OF AXIAL FORCE IN THE INTERMEDIATE SHAFT ON THE LOAD CAPACITY OF THE PAIRED CARDAN MECHANISM

ABSTRACT

The design of intermediate shaft with axially movable splined joint must be adapted to the variable position of the shaft axis, i.e. to the change of the joint angle during operation. This design is also used for the reduction of axial forces which are caused by inaccuracy in the production and assembling of Cardan mechanisms. The axial force which is generated by friction of contact surfaces in the splined joint is the function of the magnitude of the transferred torsion moments, splined dimensions, lubrication conditions, and materials used for contact surfaces. It will cause additional bearing loads at cross journals and in the shaft supports, as well as unallowed vibrations and noise during operation, thus affecting the safety and lifetime of the Cardan mechanism. The theoretical and empirical analysis of Cardan mechanisms, which have been studied with and without axial forces in the splined joint and its effect on durability of mechanism elements have been presented.

KEY WORDS

cardan mechanism, splined shaft

1. INTRODUCTION

In many machines (cars, agricultural machinery, rolling mills) the joint angles change during the operation of the Cardan mechanism. The change in length, i.e. axial shift of the shaft is necessary both in the application with the variable joint angle, and during mounting and dismounting. The additional change of the shaft length is planned with the aim of compensating for the inaccuracy of its manufacture, mounting and temperature oscillations. Splined joints or other ways of axial compensation have to insure the given length variations. Axial friction force which occurs in the splined intermediate shaft is the result of the acting of the torsion load and inter-shifting of the splined elements. Axial forces occur when the shaft of constant length serves as the suspension element or when Cardan mechanisms with fixed centres and movable splined joints are used on the shaft of constant length. When the end of the shaft moves due to the action of high torsion loads, the resulting axial friction force in the splined joint becomes excessive and thus undesirable. Excessive axial forces can be dangerous not only for the shaft, but also for the support bearings and other elements of the Cardan mechanism.

Figure 1 shows a paired synchronous Cardan mechanism with one movable support [1]. In this case the spacing between the Cardan joint centres O_1O_2 changes during operation, and in order to insure proper operation of the mechanism, a movable pair needs to be added on the joining shaft, which will at the same time transmit the torsion moment. Such a movable pair is most often designed as a splined joint.

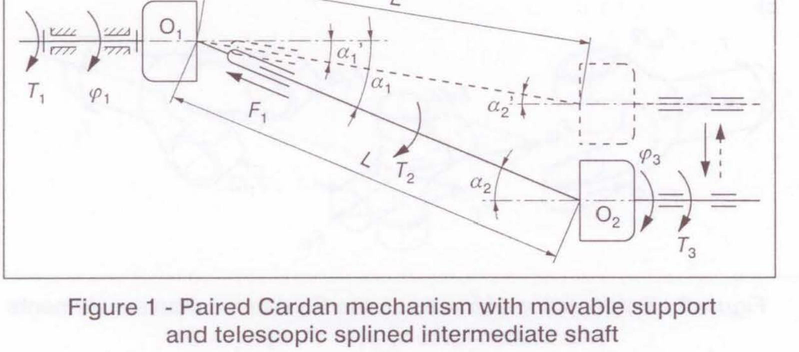


Figure 1 - Paired Cardan mechanism with movable support and telescopic splined intermediate shaft

2. ANALYSIS OF THE INFLUENCE OF AXIAL FORCE ON THE CARDAN MECHANISM ELEMENTS

The friction force in the splined joint of the intermediate shaft [3], which occurs by the transmission of torsion moment, and acts on the Cardan mechanism is determined from:

$$F_T = \pm\mu \frac{2T_2}{d_{sr}} = \pm\frac{2\mu}{d_{sr}} \cdot T_1 \cdot \frac{1-\sin^2\alpha\cdot\cos^2\varphi_1}{\cos\alpha} \quad (2\text{-}1)$$

where:

μ – is the friction coefficient in the splined joint

d_{sr} (m) – is the mean diameter of the splined pair

T_2 (Nm) – is the torsion moment on the intermediate shaft

The friction force F_T creates additional load on the shaft supports and journal bearings of the Cardan mechanism. If we transfer the friction force to point O_1 of the Cardan mechanism and disassemble it into components, an overview of loads on Cardan mechanism elements for various angles of rotation φ_1 of the driveshaft according to Figure 2 is obtained.

The components of the friction force are determined from Figure 2:

– axial component of the friction force acting on the bearings in driveshaft supports

$$F_{Ta} = F_T \cdot \cos\alpha = \frac{2\mu}{d_{sr}} \cdot T_1 \cdot (1-\sin^2\alpha\cdot\cos\varphi_1) \quad (2\text{-}2)$$

– radial component of the friction force acting on the bearings at cross journals

$$F_{Tr} = F_T \cdot \sin\alpha = \frac{2\mu}{d_{sr}} \cdot T_1 \cdot \tan\alpha \cdot (1-\sin^2\alpha\cdot\cos\varphi_1) \quad (2\text{-}3)$$

From the expressions (2-1), (2-2) and (2-3) the magnitudes of loads on the Cardan mechanism elements in Figure 2 can be determined for certain rotation angles φ_1 of the driveshaft according to the equations:

Friction force F_T

for $\varphi_1 = 0°$

$$F_T = \frac{2\mu}{d_{sr}} \cdot T_1 \cdot \frac{1-\sin^2\alpha}{\cos\alpha} = \frac{2\mu}{d_{sr}} \cdot T_1 \cdot \cos\alpha \quad \text{(minimal)}$$

for $\varphi_1 = 90°$ $$F_T = \frac{2\mu}{d_{sr}} \cdot \frac{T_1}{\cos\alpha} \quad \text{(maximal)}$$

(2-4)

– axial component of the friction force F_{Ta}

for $\varphi_1 = 0°$ $$F_{Ta} = \frac{2\mu}{d_{sr}} \cdot T_1 \cdot \cos^2\alpha \quad \text{(minimal)}$$

for $\varphi_1 = 90°$ $$F_{Ta} = \frac{2\mu}{d_{sr}} \cdot T_1 \quad \text{(maximal)}$$

(2-5)

The projection of the radial friction force component F_{Tr} in the direction of the cross journal axis forms axial load on the bearings at Cardan forks V_1 and V_2:

– on the drive-fork V_1:

$$F'_{Tr} = F_{Tr} \cdot \cos\varphi_1 = $$
$$= \frac{2\mu}{d_{sr}} \cdot T_1 \cdot \tan\alpha \cdot (1-\sin^2\alpha\cdot\cos^2\alpha)\cdot\cos\varphi_1 \quad (2\text{-}6)$$

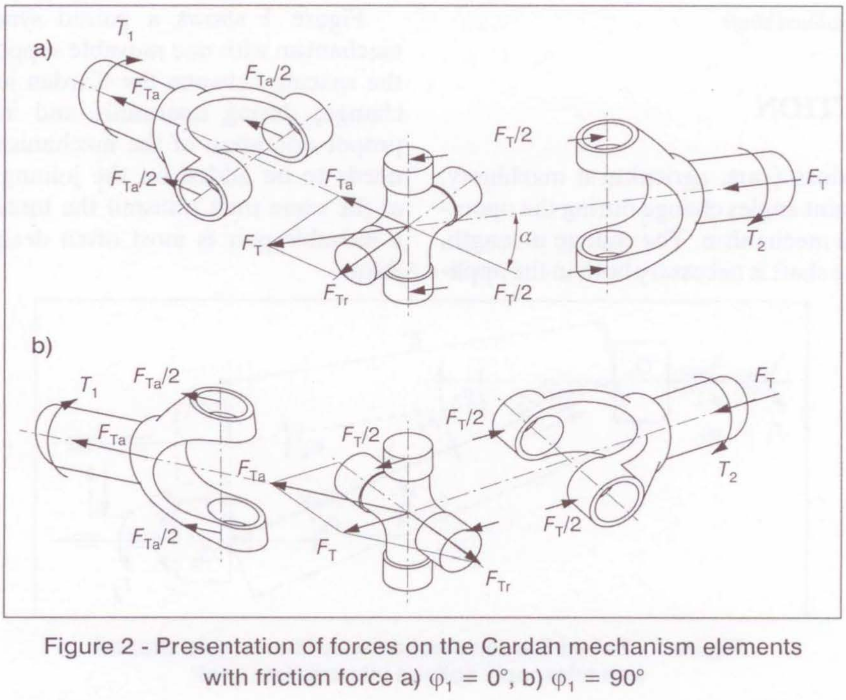


Figure 2 - Presentation of forces on the Cardan mechanism elements with friction force a) $\varphi_1 = 0°$, b) $\varphi_1 = 90°$

for $\varphi_1 = 0°$ $\quad F'_{Tr} = \frac{2\mu}{d_{sr}} \cdot T_1 \cdot \sin\alpha \cdot \cos\alpha$

for $\varphi_1 = 90°$ $\quad F'_{Tr} = 0$

– on the driven fork V_2:

$$F'_{Tr} = F_{Tr} \cdot \sin\varphi_1 =$$

$$= \frac{2\mu}{d_{sr}} \cdot T_1 \cdot \tan\alpha \cdot (1 - \sin^2\alpha \cdot \cos^2\alpha) \cdot \sin\varphi_1 \qquad (2\text{-}7)$$

for $\varphi_1 = 0°$ $\quad F'_{Tr} = 0$

for $\varphi_1 = 90°$ $\quad F'_{Tr} = \frac{2\mu}{d_{sr}} \cdot T_1 \cdot \tan\alpha$

3. STUDY OF INFLUENCE OF AXIAL FORCE ON THE CARDAN MECHANISM ELEMENTS

The magnitude of the axial force used for loading of Cardan joints at the testing device, was determined on the basis of the theoretical expressions and tests done for the test design of the joining intermediate shaft. The appropriate magnitude of the friction force in the splined joint which appears in operation at a changeable joint angle gradient, was achieved by additional design presented in Figure 3.

In Figure 3 certain positions indicate:

1 – tested Cardan joints
2 – telescopic pipe with inner rectangular grooves
3 – threaded joining element
4 – counter-nut for insuring the given magnitudes of force
5 – nut
6 – ring
7 – spring
8 – shaft with outer rectangular grooves
9 – ring

The axial force F_{Tisp} between the contact surfaces of the splined joint is achieved by suitable compression of spring 7, which acts over the supports 6 and 9 on the telescopis pipe 2 and shaft 8. The appropriate magnitude of axial force is obtained by regulating the spring deflection by means of twisting the nut 5 and tightening the counter-nut. Setting the magnitude of the necessary spring deflection, i.e. achieved axial force, depended on the value of the torsion moment in certain testing conditions. The magnitude of the necessary axial force achieved by the spring is obtained from the expression (2-1) for the desired testing torsion moments.

The tested splined joint has been designed with rectangular profile of grooves and insured good lubrication of the sliding surfaces. In this way, the magnitude of axial force acting on the tested Cardan joints was brought close to the values in actual loading conditions during exploitation. The actual magnitude of axial force can be obtained only by tests in exploitation, taking into consideration the actual volume and rate of the change of the joint angle gradient for certain operation conditions in using the Cardan mechanism. Such tests are applied in determining the durability and hardness of the splined joints. In order to prove the influence of the axial friction force in the splined telescopic shaft on the Cardan joint, comparison tests are carried out using the device presented in Figure 4. Such a device is considered to be the most economical for determining and assessing the characteristics of the Cardan joint, since four specimens, operating in a closed cycle under the same conditions, can be tested simultaneously. The closed cycle of the preloading device has been developed with two parallel Cardan shafts and two pairs of gears at each end of the device. The transmission ratio of gearboxes equals one. One gear pair has been set on a base so that it can be moved in accordance with the necessary length of the shaft and joint gradient angle, and fixed in the desired position afterwards.

The positions in Figure 4 indicate:

1 – electrical motor
2 – fixed gearbox
3 – movable gearbox
4, 5, 6, and 7 – tested specimens of Cardan joints
8, 9 – telescopic splined shafts
10 – coupling which allows for obtaining the desired static torsion moment on the considered Cardan joints
11 – measuring shaft which allows that the magnitude of the torsion moment is read at the measuring bridge
12 – bearings

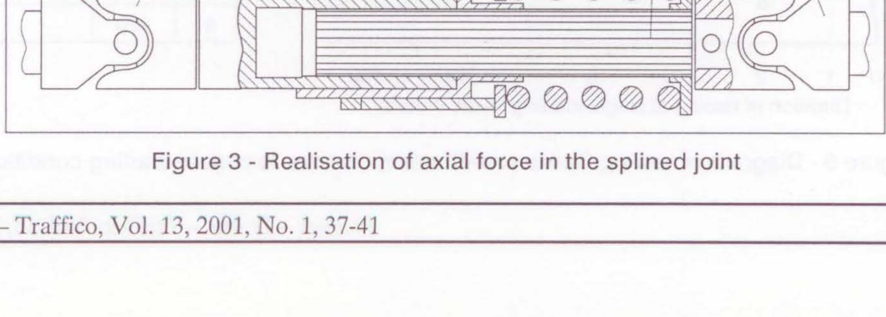


Figure 3 - Realisation of axial force in the splined joint

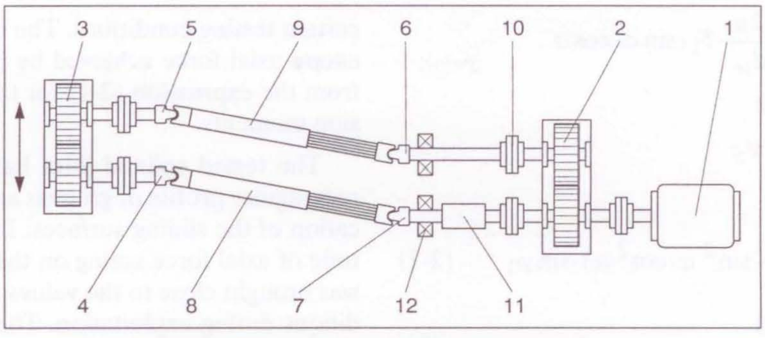


Figure 4 - The preloading device scheme

4. TEST RESULTS

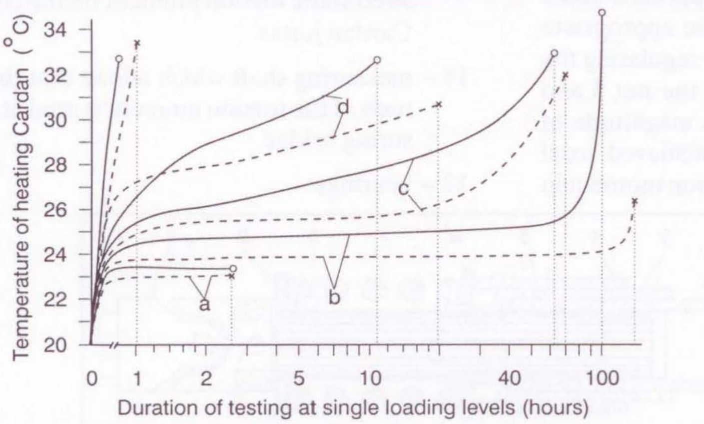
The basic hypothesis in this work was that the axial force formed in the splined joint of the intermediate shaft will significantly influence the overall durability of the whole Cardan mechanism due to the change of joint gradient angle during operation or due to inaccuracies in manufacture and mounting. Since this tests were aimed at studying the influence of axial force on Cardan joints, the applied loading and selection of axial force magnitudes have given sufficiently valid results.

The test results obtained with and without axial forces acting on the Cardan mechanism are presented in comparison in the diagram (example in Figure 5) depending on the operating conditions given in Tables next to the diagrams. Curves in diagrams presented by full line represent tests with axial forces acting, whereas broken line represents functional dependence of the temperature of the joint cross journal and the test duration in certain testing conditions, but with no axial force acting in the splined joint. During operation of the Cardan joint, friction forces occur at the contact surfaces of the cross journal, needles and bushing, which are the greater, the greater contact stresses and friction coefficient. Acting of friction forces at contact surfaces causes their heating, which is transmitted to other parts of the Cardan joint and the environment. Heating causes thermal load that influences strength. Besides, heating of contact surfaces influences also the lubricant properties, which becomes less viscous at higher temperatures. In case of high contact stresses, lubricant can easily be displaced from the contact surfaces. The changed magnitude of the friction coefficient and greater friction forces, with certain constant parameters of the joint load (torque, rotation speed, and Cardan joint shaft gradient angle), cause greater heating of the contact surfaces. Therefore, determining the temperature of the joint is important because of the already mentioned impact of temperature on the mechanical properties of the joint elements, as well as due to the impact on the lubrication quality. Heating of Cardan joint elements subjected to friction is the greater, the greater the friction and the lower the heat conductivity of the joint elements.

Testing was interrupted when heating of the joint was excessive and when additional vibration appeared in the whole Cardan mechanism, which is indicated in the diagrams as sudden increase in temperature.

5. CONCLUSION

Testing of influence of axial force in the splined joint of the intermediate shaft indicated its significance in the loading capacity and durability of the



	T	n	α^{o}
	Nm	rev/min	
a	20		
b	60		
c	80	710	3
d	100		
e	120		

Figure 5 - Diagram of testing Cardan mechanism crosses in certain loading conditions

Cardan mechanism. Using the method of determining maximal loading capacity of the Cardan joints in certain loading conditions based on monitoring the temperature change during heating of joint elements provided reliable orientation magnitudes of the loading level. The selected method and the axial force in the splined joint in order to prove its influence on the Cardan mechanism, as well as carried out tests of its magnitude in certain operating conditions, give sufficiently accurate data compared to the actual magnitudes in exploitation conditions. Comparison analysis of the results obtained by testing the Cardan mechanisms with and without axial force in the splined joint of the intermediate shaft indicated that tested specimens subjected to axial forces show greater increase in joint temperature, and the testing in the same operating conditions had to be interrupted earlier. It may be generally concluded that there is a greater increase in temperature at the beginning of testing, up to the limit of temperature proportionality, and the temperature continues to increase more mildly further on. Only in cases of higher loads, the intensity of temperature rise did not decrease.

SAŽETAK

UTJECAJ AKSIJALNE SILE U MEĐUVRATILU NA OPTERETIVOST UDVOJENOG KARDANSKOG MEHANIZMA

Konstrukcija međuvratila kardanskog mehanizma s mogućnošću aksijalnog pomicanja ižljebljenog spoja, prilagođena je promjeni položaja osi vratila, odnosno promjeni veličine kuta zgloba u toku rada. Ujedno se takva konstrukcija koristi i za smanjenje aksijalnih sila, koje se prijavljuju uslijed netočnosti u izradi i montaži kardanskih mehanizama. Aksijalna sila koja se stvara trenjem dodirnih površina užlijebljenom spoju, funkcija je veličine prenašanog torzijskog momenta, dimenzija užljebljenja, uvjeta podmazivanja i primijenjenih materijala dodirnih površina. Ona će utjecati na pojavu dodatnog opterećenja ležajeva na rukavcima križa i u osloncima vratila, te nedopuštenih vibracija i šumova u radu, čime utječe na sigurnost i vijek trajanja kardanskog mehanizma. Teorijskom i eksperimentalnom analizom kardanskih mehanizama, koji su promatrani sa i bez djelovanja aksijalne sile u ižljebljenom spoju pokazan je njen utjecaj na trajnost elemenata mehanizma.

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