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NEW CONCEPTUAL SOLUTIONS FOR ELASTIC COUPLINGS WITH HIGH CAPABILITY COMPENSATION OF MISALIGNMENTS

Abstract: *The paper develops a problem of great interest in power transmissions, very widely applied in practice: the use of elastic couplings having an adequate level of torque transmission and a reasonable axial and angular misalignment capability based on elastic deformations of specific flexible elements. A characterization (discussion) of two elastic couplings characteristic for the area of compensative couplings is offered. An innovative principle of elastic coupling with reinforced flexible elements is proposed. The mechanical strength analysis for both elastic couplings (with spoked metallic membranes and reinforced elastic elements) in the case of existing axial and angular deviations is discussed also. It is revealed that the study of these couplings based on elastic deformations is of great theoretical and practical importance today.*

Key words: *elastic couplings, constructive principle, loading scheme, mechanical strength criterion.*

1. INTRODUCTION

In mechanical transmissions, couplings makes the connection, intermittent or permanent, between two shafts theoretically coaxial, in order to transmit torque and rotational movement without changing the law of motion.

If between the driving motor and the driven machine there are misalignments of shafts is necessary to use flexible couplings in order to compensate spatial elastic displacements (axial, radial and angular) and reduce torsional vibrations.

Depending on the elasticity of flexible elements in the direction of the axis' shaft, and the size of radial or angular deviations of the transmission line, these couplings have to compensate for inaccuracies due to running conditions and reduce to a minimum value the reaction forces caused by displacements from rigid connection of shafts.

For motor drive of fluid pumps, choosing of a compensatory coupling with elastic elements ensure the proper functioning of the unit in operation process, with a high degree of safety and low wear.

Endowment with parts more or less elastic between hubs allows the compensation both angular and radial deviations and a relative rotational motion of coupled shafts, under the effect of transmitted torque, because the elastic elements provide six degrees of freedom.

2. IMPORTANCE OF THE STUDY OF HIGH PERFORMANCE COMPENSATORY COUPLINGS

Couplings, as machine components located between the driving motor and the driven machine makes the torque transmission besides a multitude of functions regarding the compensation of misalignments in radial, axial and angular directions, and damping of torsional oscillations [1]. Given the multitude of types used in industry, choosing the right type of coupling can provide performance improvements of equipment, improving the quality of processed products and simplify maintenance of transmission, i.e. the kinematic chain.

2.1 Potential beneficiaries of elastic couplings

The couplings analyzed in the paper can be used in all industries, including agriculture for driving machinery requiring a complex positional compensation, small dimensions and low consumption of materials, high speeds, high reliability, and an average degree of torsional vibration damping. Potential beneficiaries are:

- cement and construction materials factories;
- chemical and petrochemical factories;
- steel foundry (the driving of raceway at rolling mills);
- construction of machine tools, agricultural, food industry.

A wide use can be estimated especially in the groups of pumping liquid and gas, driving ventilators groups, wind farms where these couplings rely on the flexure of metallic elements to accommodate misalignment and axial movement in shafts.

2.2 Constructive solutions of flexible metallic element

Couplings with flexible metallic intermediate elements are used for transmitting high torques, with small dimensions in relation to capacity. Depending on the shape of the elastic element there may be a variety of types such as:

- Circular disc, hex disc, scalloped disc, segmented disc that provides the largest degree of flexibility with lowest stresses;
- Thin flat plate (tapered contoured membrane, multiple straight membrane with spokes);
- Thin double curved element (multiple convoluted membrane);
- Bar springs, torsion bar springs, leaf springs, spiral springs, coil springs.

2.3 National state

Romanian industry does not produce membrane couplings of this type. BRAFLEX Company of Braşov produces metallic membrane couplings, but their structure differs fundamentally from coupling structure proposed in this paper.

In terms of functional performance, coupling types of this company provide torsional rigidity, but the amount of compensation in radial, axial and angular directions have lower values than that achieved by coupling type analyzed in this paper. Similar coupling types are manufactured by FLENDER Company- Germany.

2.4 International state

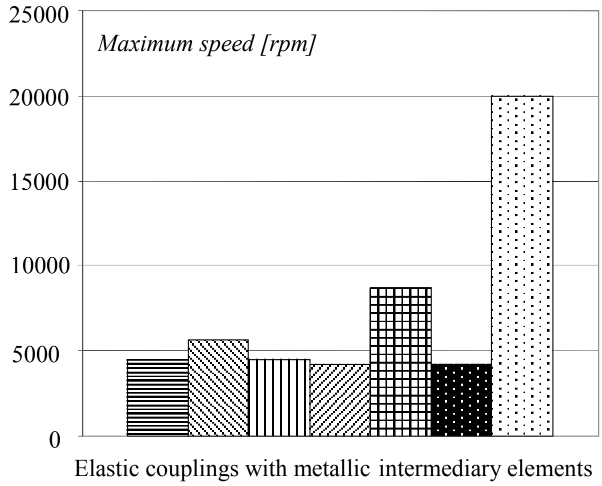
A similar type of coupling with flexible membranes is manufactured at the company Flexibox International [2] (Manchester, England), MetaStream type - simple MOS (with two sets of membranes and spacer) and double MOD (four sets of membranes with or without spacer).

Many companies specialized in the field of power transmissions produce elastic couplings with intermediate metallic elements among which:

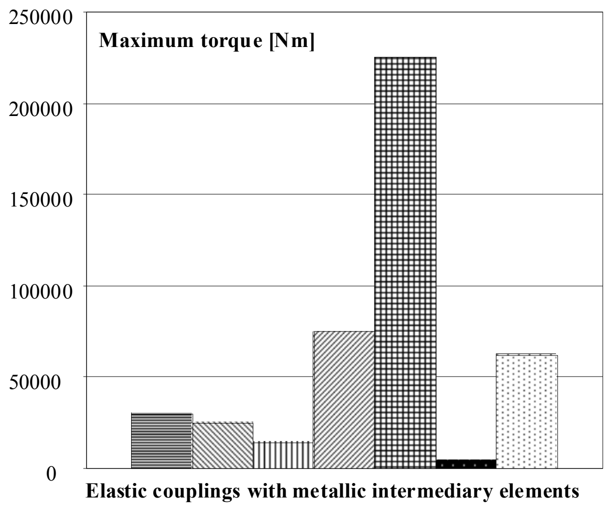
- Bar springs coupling (mounted in oblong holes) – called Forst coupling – which only compensates axial deviations of coupled shafts;
- Coupling with torsion bars, called Voith-Maurer – it can take angular deviations of up to 1.5 degrees and axial deviation of 0.6 ÷ 2 mm;
- Coupling with meandering spring – also called Bibby coupling – consists of two hubs with external teeth of special profile; in gaps between teeth is disposed a meandering spring of rectangular section. Bibby coupling allows compensating axial deviation of 4÷20 mm, radial deviation of 0.5÷3 mm and angular deviation of up to 10'÷15'. These couplings are characterized by reliability and reduced size, but require a very precise execution;
- Multiflex coupling – a variant of the Bibby coupling – has elastic element built of several clasp springs, which simplifies execution of the coupling. He has a high load capacity;
- Coupling with leaf springs – has elastic element disposed axially (Elcard type coupling) or radially. Elastic characteristic of the coupling is progressive, depending on the number of packages of springs. This coupling allows axial deviations of 5 ÷ 15 mm, radial deviations of 0.5 ÷ 2 mm and angular deviation ≤ 2.5°;
- Geislinger coupling – has a huge capacity for damping torsional vibrations. The characteristic is progressive;
- Coupling with coil springs – also called Cardeflex – limited to small and medium torques. Specialized companies (Hochreuter & Baum) performs higher dimensional variants (with eight coil springs) that can transmit torques of $M_t \leq 14700$ daNm at $n_{max} = 300$ rpm; by introducing of 12 coil springs reach a torque of 175000 daNm at $n_{max} = 330$ rpm;
- Sleeve spring coupling – has a high capacity for shock and vibration damping. By varying the radius of curvature of the recess, the number of spring packages and their diameter, and by changing the number of springs in a package, sleeve spring coupling can be adapted to transmit torque in very wide limits;
- Coupling with membranes – ensure a complex positional compensation of coupled shafts with low mass and dimension and high speeds;
- Camiro Flex coupling compensates the deviations resulted after fitting or during operation – can take 3° angular deviation, 0.5 mm radial deviation and 2 mm axial deviation. This coupling is characterized by a reinforced elastic element.

2.5 Comparative study of the performance of compensatory couplings

Data of manufacturing companies are used to draw diagrams that allow comparative analysis of possibilities to running at high speeds (fig. 1a) and transmitting torque (fig. 1b), depending on the type of coupling (fig. 2), but without taking into account the standard dimensions of analyzed coupling.



a)



b)

Fig. 1 Comparative study
a) Maximum operating speed; b) Capable torque of elastic coupling

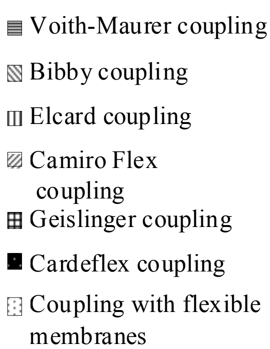


Fig. 2 Types of analyzed couplings

Of the two figures is observed high load capacity of elastic couplings with metallic intermediate elements, at small dimensions. Depending on the shape of the elastic element and the constructive solution of its mounting are obtained different performances and possibilities to compensate various misalignments of coupled shafts.

3. CONSTRUCTION STRUCTURES OF HIGH PERFORMANCE COMPENSATORY COUPLINGS

The couplings analyzed in this paper have not been addressed in mass production in the country. The novelty degree of the study, which will be the subject of this work, consists in functional optimization of membrane packets that have the ability to ensure torque transmission and to take over in the elastic deformation area of misalignments. Also, it will follow that the functional optimization to be performed in parallel with technological optimization, regarding the inner configuration of elastic components.

3.1 Flexible metallic membrane coupling

The coupling variant without spacer (fig. 3) permits the taking over of the axial and angular deviations. There is a coupling variant with intermediary spacer (fig. 4) permitting also radial deformations and the taking over of the radial deviations. In this idea, the coupling assumes significant misalignments [3].

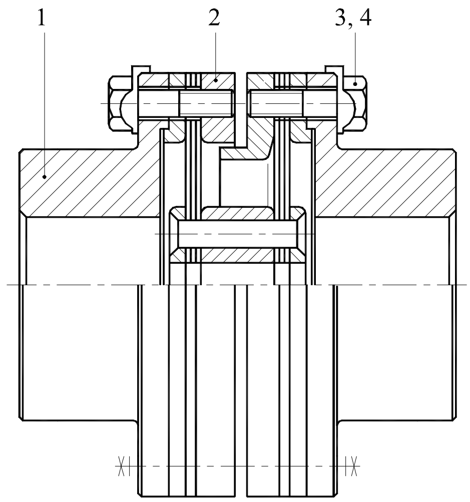


Fig. 3 Non-spacer coupling with misalignment limitation
1 – flanged hub; 2 – membrane unit; 3 – bolt; 4 –washer.

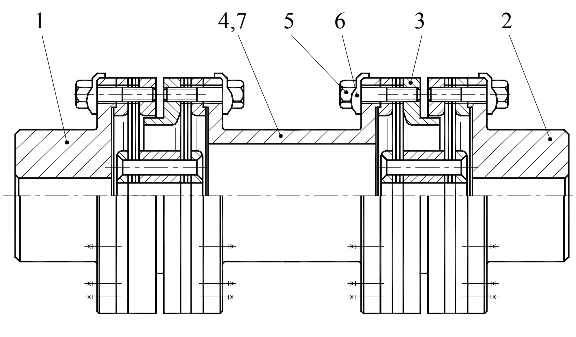


Fig. 4 Spacer coupling [1]
1, 2 – flanged hub; 3 - membrane unit; 4 - short spacer; 5 - bolt; 6 – washer; 7 – long spacer

The couplings having spoke form membranes transmit the torque from the inner diameter to the outer diameter and reciprocally, by shear loading of the membrane. Torque is transmitted by driving bolts pulling driven bolts with membrane material. More bolts provide greater torque capacity but reduce coupling flexibility [4]. The torque is transmitted through the membrane packet in tangential direction to the coupling axis and it produces a tensile stress in the membrane pack members. The coupling uses these membranes joined rigidly at their inner and outer diameters to other components. Each packet contains eight membranes.

The flexible membranes are made from spring steel and have a spoked form (fig. 5), the deformation of the spokes giving to the coupling its flexibility and thus its ability to handle installation misalignments.

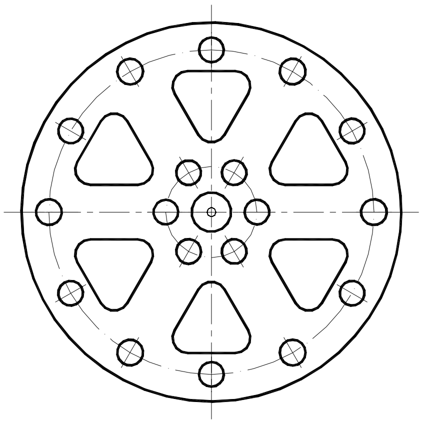


Fig. 5 Spoked form membrane

3.2 Camiro Flex coupling

Camiro Flex coupling [5] is based on Patent no. 116925, PCT recognized [6], and can be developed very well for niche of industrial areas with potentially explosive atmospheres according to proposed objectives. At this coupling is not remove any part to perform maintenance service, will not be affected the balance of subassemblies and can cover practically the entire range of flexible couplings required by the manufacturing industry by their physical and mechanical characteristics.

At Camiro Flex coupling, the flexible element is a combination of a metallic element with a non-metallic one, fact for which is called reinforced elastic element.

The coupling with adjustable flange as shown in figure 6 is part of the group of mechanical elastic couplings that can be endowed with non-metallic elements, metallic or combined, and consists of two semi-couplings 1 and 2 equipped with inner and outer axial grooves forming the space for the reinforced elastic element.

The driven semi-coupling 1 contains indexing springs 3 and bolts 4 (each mounted in blanks) and is equipped with a closure system of the reinforced elastic elements consisting of an adjustable flange 5, in that are made slots through which reinforced elastic elements (a) are inserted, some elongated holes (b) on which slides the springs and fastening screws 6 of the support ring 7. Also, the flange 5 is provided with holes (c) for indexing and the chamfers (d) for fixing the flange in the working position (closed) or in the service position (open)–fig.7.

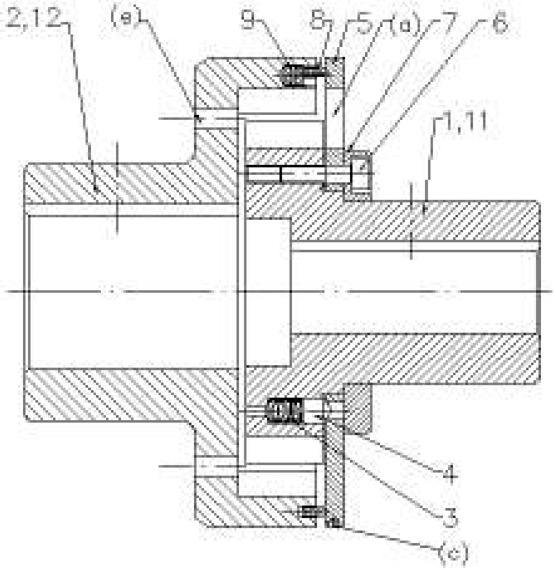


Fig. 6 Camiro Flex coupling

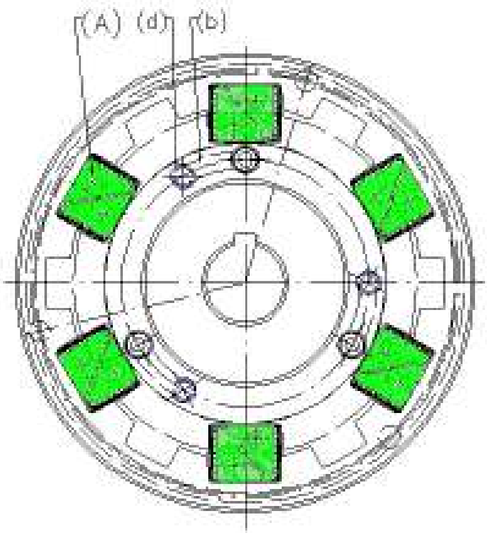


Fig. 7 Driven semi-coupling of Camiro Flex

The driving semi-coupling 2 is provided with holes (e) through which are removed, by means of a rod, the reinforced elastic elements (a) for checking or replacement. Also, this semi-coupling is provided with a circular groove and holes in which is mounted a seal ring (8) acted by springs (9).

The two semi-couplings are secured axially by means of two setscrews, 11 and 12, with self- restraint.

The elastic intermediate element "A" (fig. 8) may be non-metallic, metallic or compound. In the latter case, the non-metallic elastic element is reinforced with a metallic spring blade in the form of "Z", of spring steel, and is fitted with some active plates (3) with antifriction and soundproofing properties.

By reinforcing of the intermediate elastic element "A" with an elastic blade in the form of "Z", the solicitation is not of shear. In this case, the elastic blade is subjected to the bending and the flexible package of rubber is subjected to compression on the entire side surface of the intermediate element.

The reinforced elastic element is composed of a rubber filler formed of two triangular profiles (1) with hole, which forms a flexible zone, protected by an elastic metallic reinforcement in the form of "Z" (2), and covered on the outer active sides with teflon plates (3) with a thickness of 1...3 mm, which provides a wear protective surface with soundproofing properties. Preparation of the elastic element (A) is carried out by making a reinforced elastic plate, and then cutting to length. The phosphating process and surface treatment of elastic metallic reinforcement are made to ensure good adhesion metal-rubber and metal-teflon.

On the outer sides of the metallic reinforcement it applies an additive solution for covering with teflon plates, on the length of metallic reinforcement. After fixing of the rubber filler, the entire assembly is vulcanized in a mold provided with two tapered bolts, at a temperature of 140...180°C, for 60...110 min. Each reinforced elastic element is sorted by load capacity at a torque on a test stand.

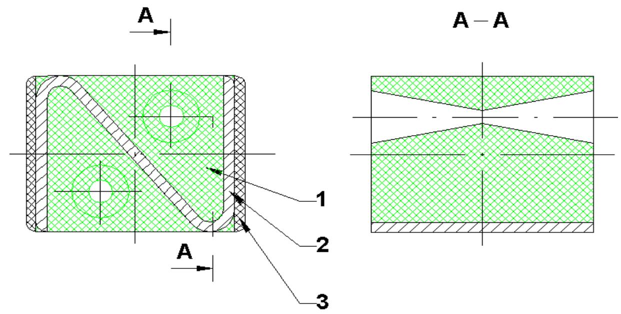


Fig. 8 Reinforced elastic element
1 - rubber; 2 – reinforcing steel; 3 – plate of duramid

4. LOADING SCHEME OF THE TWO ELASTIC COUPLINGS

4.1 Membrane stresses

The membrane stresses are more difficult to assess, as they are influenced not only by the torque and speed but by the misalignment and the method of attachment to the adjacent components. The stress state of the membrane spoke is determined by:

- Torque transmission causing shear, bending and tension, with a maximum tensile component along the line shown in fig. 9. The maximum stress, inclusive of the bending component, is adjacent to the root at the trailing edge;
- Centrifugal loading causing tension. In high speed applications this loading has a significant stiffening effect, increasing the resistance to torsional and misalignment deflections. The membrane centrifugal loading is not-important at low and medium rotational speed (under 3000-4000 rpm);
- The misalignment (angular and axial displacements) that causes bending stresses and direct tensions due to the increased distance between the inner and outer sections of the membrane assembly [1], [3].

Figure 9 shows an individual spoke of the membrane. In a coupling this spoke will be rigidly clamped at both the inner and outer diameters.

The direct tension induced can cause the bending at either end of the spoke (fig. 10) and therefore the design of the clamping support is very important. A sharp edge can cause a very small bend radius, with a correspondingly high bending stress in the membrane.

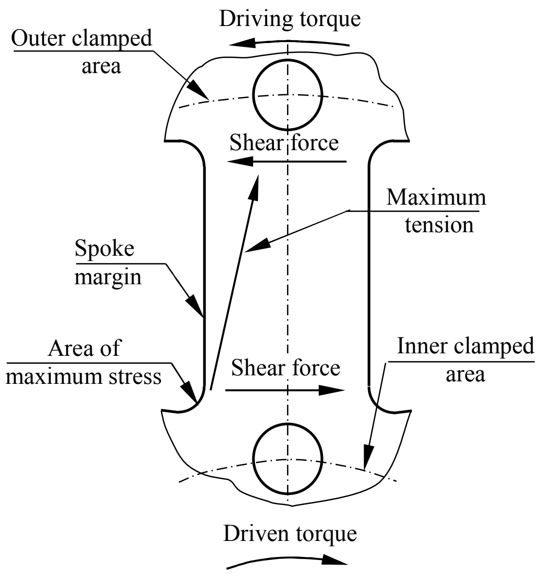


Fig. 9 Frontal loading scheme of an individual membrane spoke

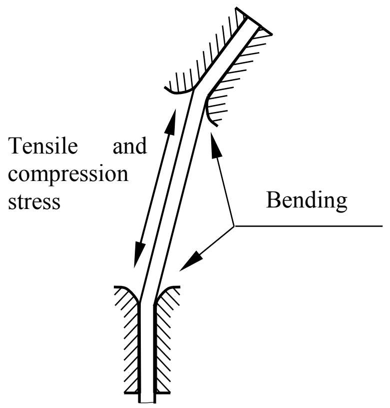


Fig. 10 Transverse loading scheme of an individual membrane spoke

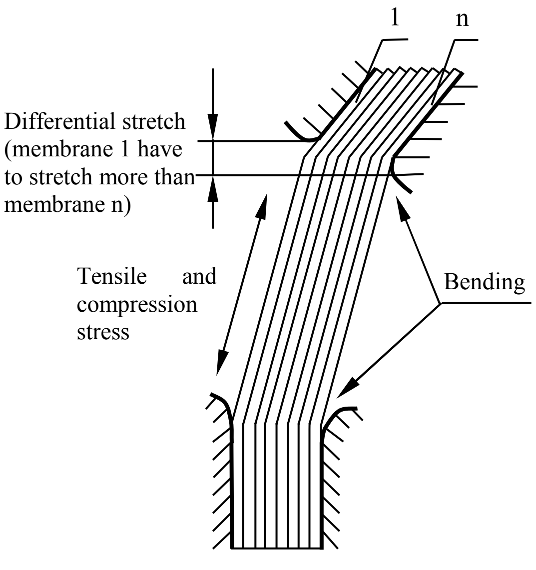


Fig. 11 Solicitation areas of membranes pack

It is very interesting to mention that the membranes on the left hand side of the packet in figure 11, have to stretch more than those on the right hand side, and therefore the induced tension will vary from membrane to membrane [2].

It is noted that the maximum stress is adjacent to the inner diameter or root of spoke, the stress due to torque transmission, speed of rotation and misalignment deflections all being a maximum at this point. A comparison of these stress levels with the fatigue properties of the membrane material will make it possible to assess a coupling's ability to resist a fatigue failure.

4.2 The simplified calculus of radial spokes of the membrane

The shear stress, in critical section placed at minimum diameter, is given by:

$$\tau_f = \frac{2 \cdot M_{tc}}{d_m \cdot l_c \cdot b \cdot n_s} \le \tau_{af} \tag{1}$$

where $d_m = D_{se} - 2 \cdot l_\alpha$ is the minimum diameter of fillet root of the membrane spokes, l_c - the thickness of membranes packet; b - width of spoke; n_s - number of spokes; l_α - the length of spoke, depending on the position of the tangent to filleted profile; D_{se} - the mounting diameter of driving bolts.

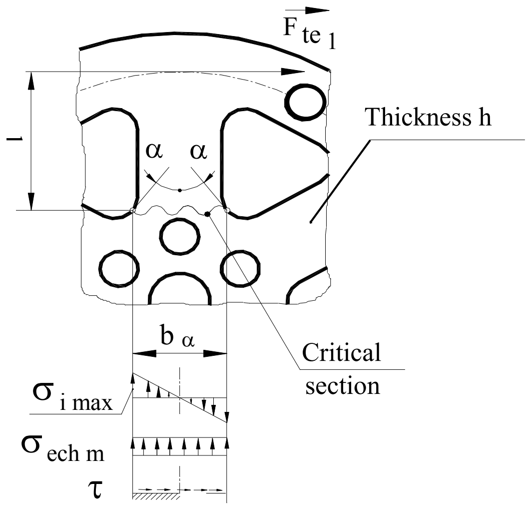


Fig. 12 Calculation scheme to the root of spoke

The calculation scheme shown in fig. 12 determines the critical section by means of lines of tangency to the root of spoke at α angles given the spoke symmetry axis. The length l measured from the point of application of force F_{te1} until the section determined by vertical lines of tangency at the profile of the attachment is determined by the expression:

$$l = \frac{D_{se}}{2} - (b + 2r)\cos 30° \tag{2}$$

Depending of the angle α, the position and dimensions of the shearing section are given by:

$$l_\alpha = l + r \sin \alpha; \quad b_\alpha = b + 2r(1 - \cos \alpha) \tag{3}$$

Substituting Eq. (3) into Eq. (1) we get the shear stress:

$$\tau_f = \frac{2 \cdot M_{tc}}{[D_{se} - 2(l + r \cdot sin\alpha)] \cdot l_c \cdot [b + 2r(1 - cos\alpha)] \cdot n_s} \le \le \tau_{af} = 0{,}7 \cdot \frac{\sigma_c}{c}. \tag{4}$$

FEA analysis (fig. 13) shows that the area of maximum equivalent stress is placed on the whole length of fillet [3].

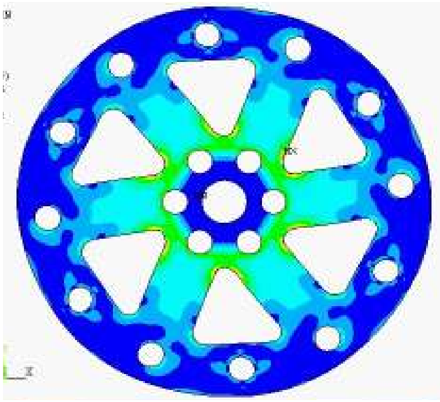


Fig. 13 Maximum equivalent (von Mises) stress [3]

4.3 Calculation model of the Camiro Flex coupling

The flexible element being stressed in elastic regime, mechanical work done by external forces it accumulates as potential energy of the deformed body.

The loading scheme shown in fig. 14 shows that the elastic element is stressed at bending [7] and accumulated energy has the expression [8]:

$$U = \int_0^l \frac{M_i^2 dx}{2EI} = \int_0^l \frac{F_1^2 \cdot x^2}{2EI} dx = \frac{F_1^2 \cdot l^3}{6EI} \tag{5}$$

where $M_i(x) = F_1 \cdot x$ is the moment produced in the section x.

The displacement in the direction of force F_1 at the point of application of this force is given by the Mohr-Maxwell formula:

$$\delta = \frac{1}{EI} \int_l M \cdot m \, dx \tag{6}$$

where:
M – the moment determined by F_1 in a current section;
m – the moment determined by the unitary force applied at the point where the displacement is calculated.

Solving of the integral (6) is done by applying the rule of Vereşceaghin:

$$\int M \cdot m \, dx = A \cdot y_G \tag{7}$$

where:
A – the total area of the M diagram;
y_G – ordinate y_G of the linear m diagram corresponding to the center of gravity of the M diagram (fig. 15).

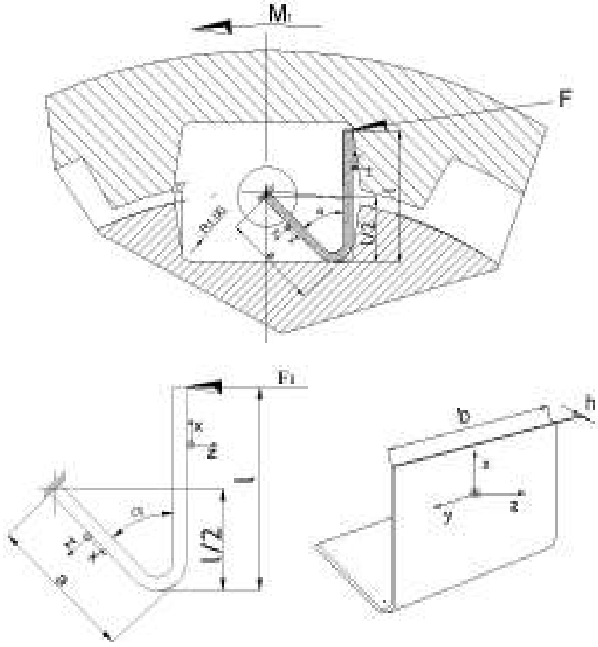


Fig. 14 Loading scheme of elastic element

Relationship (7) is applied on intervals, by adding:

$$\int M \cdot m \, dx = \sum_i A_i \cdot y_{Gi} \tag{8}$$

where i is the number of line segments that form the m diagram.

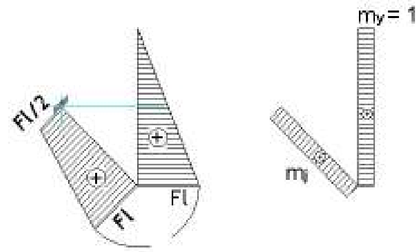


Fig. 15 M and m diagrams

The displacement has the expression:

$$\delta = \sum_i \frac{1}{EI} \cdot A_i \cdot y_{Gi} = \varphi_1 \tag{9}$$

where φ_1 is the angle at the free end of the elastic bar.

Using the fig. 15 we obtain the equation:

$$EI_y \varphi_1 = \sum_{i=1}^{2} A_i \cdot y_{Gi} = \frac{1}{2} Fl^2 + \frac{l}{2 \cdot 2\cos\alpha}\left(F_1 l + \frac{F_1 l}{2}\right) \tag{10}$$

$$EI_y \varphi_1 = \frac{F_1 l^2}{2}\left(1 + \frac{1}{2\cos\alpha} \cdot \frac{3}{2}\right) \tag{11}$$

$$EI_y\varphi_1 = \frac{F_1 l^2}{2}\left(1+\frac{3}{4\cos\alpha}\right) \Rightarrow$$
$$\varphi_1 = \frac{F_1 l^2}{2EI_y}\cdot\left(1+\frac{3}{4\cos\alpha}\right) \quad (12)$$

We have that:

$$F_1 = \frac{M_{te}}{z(R+l)} \quad (13)$$

By substitution we get:

$$\varphi_1 = \frac{M_{te}\cdot l^2}{2EI_y z(R+l)}\left(1+\frac{3}{4\cos\alpha}\right)[rad] \quad (14)$$

where:

$$E = 2.1\cdot 10^5\left[{N}/{m^2}\right];\ I_y = \frac{bh^3}{12}\left[mm^4\right],\ z{=}6 \quad (15)$$

5. ADVANTAGES IN USE OF ANALYZED COUPLINGS

Elastic couplings with reinforced elastic elements - Camiro Flex - and with flexible membranes are able to work in potentially explosive areas located in:

- platforms for storing and conveying petroleum products and natural gas;
- offshore platforms for drilling and commissioning of deposits in the Black Sea;
- jackets to extract oil and gas from the continental shelf of the Black Sea;
- platforms for storing, conveying, handling and processing of grain products (silos, grinding mills);
- platforms for processing and storage timber (lumber mills and furniture);
- commercial ships.

In coupling applications situated in flame-proof areas, to ensure that no sparks or other causes of ignition shall occur, the materials can be substituted in the construction of the membrane units by monel.

The couplings with membranes are configured with two flexing elements, each consisting of two membrane units that are used in pairs. This innovative design of membrane coupling can compensate for many operational variables, such as parallel offset and angular misalignment present anytime between two attached shafts.

All flexing occurs within the membranes with a complete absence of wearing parts and therefore no necessity for lubrication, adjustment or any other form of maintenance.

Under conditions of extreme overload, because of pump seizure or other causes of failure in the transmission line, the coupling will shear its membrane unit and the drive will immediately cease to be transmitted, thus obviating the possibility of serious damage to the machinery. The membrane unit can be replaced quickly and cheaply and the expensive repair or replacement of shafts or wrecked pumps is avoided and production time lost is reduced to a minimum.

The membrane coupling permits axial movement between the half couplings, completely independent of the torque applied, and thus end thrust is not transferred from one machine to the other.

This coupling has the mass symmetrically and evenly distributed about the centre line, resulting in a natural and permanent degree of dynamic balance. Another benefit is improved life of machinery bearings because of low resisting forces under misaligned running conditions.

The Camiro Flex coupling (fig. 16) provides the following advantages:

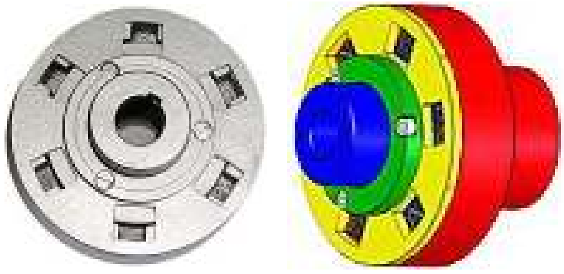


Fig. 16 Physical and virtual prototype of Camiro Flex coupling

- Ultra ergonomic service by eliminating many intermediary operations – the elastic elements are easy to extract without dismantling any component and without modifying the centering; Simply rotation of the adjustable flange in service position allows verifying any elastic element and replaced if necessary (fig. 17);
- Optimal operation of bearings - new family of flexible couplings with reinforced elastic elements eliminate any axial component that could be brought in the elastic joint by the ends of the two shafts, and any radial component will be diminished by 30-90%;

a)

b)

Fig. 17 Mounting of Camiro Flex coupling

- The new family of flexible couplings is more compact and robust caused by an efficient use of materials;
- High resistance to wear of the new elastic intermediate elements by eliminating shear loading and by compression stress on a larger surface, adopting an elastic spring steel blade and/or semi-rigid protective plaques of polyamide, with antifriction and soundproofing properties;
- Efficient torque carrying capacity, depending on the loads to be undertaken by the choice of intermediate element (metallic, non-metallic or compound), by its shape, and by choosing the appropriate thickness of reinforcement (mono-lamellar or multi-lamellar);
- By choice of elastic intermediate elements materials, can take families couplings with heavy load and special elastic features, providing effective shock damping (by adopting an optimal hysteresis), reduction of torsional oscillations, elastic compensation of misalignments and low noise;
- The two half couplings work independently from each other and allow independent rotation of the engine or driven unit by extracting elastic elements. This advantage is exploited particularly in the case of engine testing or repair is necessary without loading;
- In the case of elastic couplings without metallic reinforcement, there are no metal to metal contacts, avoiding any possibility of initiation of an explosion from a spark;
- Coupling balance is easily executed and can be checked anytime by extracting elastic elements.

6. CONCLUSIONS

The reliability and efficiency is main problem that supports renovations of the high power rotating systems.

The flexible metallic couplings are systems used in power transmissions for several specific main advantages: great flexibility to assume the possible different misalignments and high-power transmitted. These couplings are designed to satisfy the power rating plus a margin of safety sufficient to ensure that the couplings will not fail under a temporary overload of reasonable magnitude.

The design and the innovations introduced by the coupling family with special elastic intermediate elements has a great potential of development and will produce a revolution in both the improvement of existing couplings, and the elimination of bad clutches.

Installing or removing the elastic elements is performed without moving the motor or driven unit. This advantage allows inspection of elastic elements or very quick and easy replacement of worn reinforced elastic elements without changing the centering of subassemblies in the transmission line.

It's important to mention that a correct coupling alignment improves the membrane or reinforced elastic element life. By choosing an appropriate elastomer it can provide a lifetime of over 25,000 hours under normal working conditions. Camiro Flex coupling represents a new branch in the domain of elastic couplings.

The couplings analyzed in this paper can compete with every coupling produced by great firms [9] such as: Vulkan, Ortlinghaus, Suco, Stromag, Enemac, Samiflex, Voith Turbo, Gerwah, Marzorati and Desch.

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