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PNEUMATIC FLEXIBLE SHAFT COUPLINGS

Summary. Main effort of every design engineer is reduction of torsional oscillation in any mechanical system. At present this problem can be solved by means of a suitable modification of dynamic properties of flexible shaft couplings according to dynamics in the given systems. But the dynamic properties of nowadays-applied flexible couplings are not unchangeable because of aging and fatigue processes occurring in flexible coupling elements. Result of this fact causes detuning of mechanical system. Taking into consideration the above-mentioned situation, we suggest for mechanical systems application of a newly developed pneumatic couplings that have constant characteristic features during the whole current operation and thus they have a positive influence on the system running.

ELASTYCZNE SPRZĘGŁO PNEUMATYCZNE

Streszczenie. Głównym zadaniem inżyniera konstruktora układów napędowych jest takie zaprojektowanie tego układu, aby poziom drań skrętnych generowany przez zmienny moment obrotowy był jak najmniejszy. Problem ten może być rozwiązany przez zastosowanie sprzęgła podatnego o odpowiednich własnościach sprężysto-tłumiących, umożliwiających redukcję drgań skrętnych układu napędowego. Obecnie stosowane sprzęgła podatne posiadają niezmienne charakterystyki, które nie umożliwiają dostosowania się do danego układu napędowego. W artykule przedstawiono budowę i badania sprzęgła pneumatycznego, umożliwiającego dostosowanie charakterystyki do pracy układu napędowego.

1. INTRODUCTION

A long-time operation of mechanical system causes aging and fatigue of currently used flexible shaft couplings, as well as it causes accidental effects due to changes of mechanical properties of driving and driven piston machinery, that are able to cause dangerous torsional oscillation in the given mechanical system.

For this reason a system, which was tuned originally, is being de-tuned. In such case the tuning component in the system, i.e. the flexible shaft coupling, is not able to reduce further or to eliminate dangerous torsional oscillation in the system.

Our suggestion is for us to apply developed pneumatic flexible shaft couplings, i.e. pneumatic tuners of torsional oscillations with the aim to reduce dangerous torsional oscillation and in this way to ensure a suitable tuning of torsional oscillating mechanical systems (TOMS).

The main purpose of this article is to present to the technical community up-to date knowledge from the area of research and development of new kinds of flexible shaft couplings, namely pneumatic flexible shaft couplings that are developed by our research team.

2. PNEUMATIC FLEXIBLE DIFFERENTIAL SHAFT COUPLINGS

In the research and development area concerning pneumatic couplings there are two main domains of attention:

- pneumatic flexible differential shaft couplings with type designation 3-1/130-D (Fig.1) and
- pneumatic flexible differential shaft couplings with autoregulation, type designation 3-1/130-D/A (Fig. 2).

2.1. Pneumatic flexible differential shaft coupling

The pneumatic differential coupling (Fig.1) consists of a driving part (1) and a driven part (2). Between these two parts is situated a compression space filled with gaseous medium (in our case it is the air).

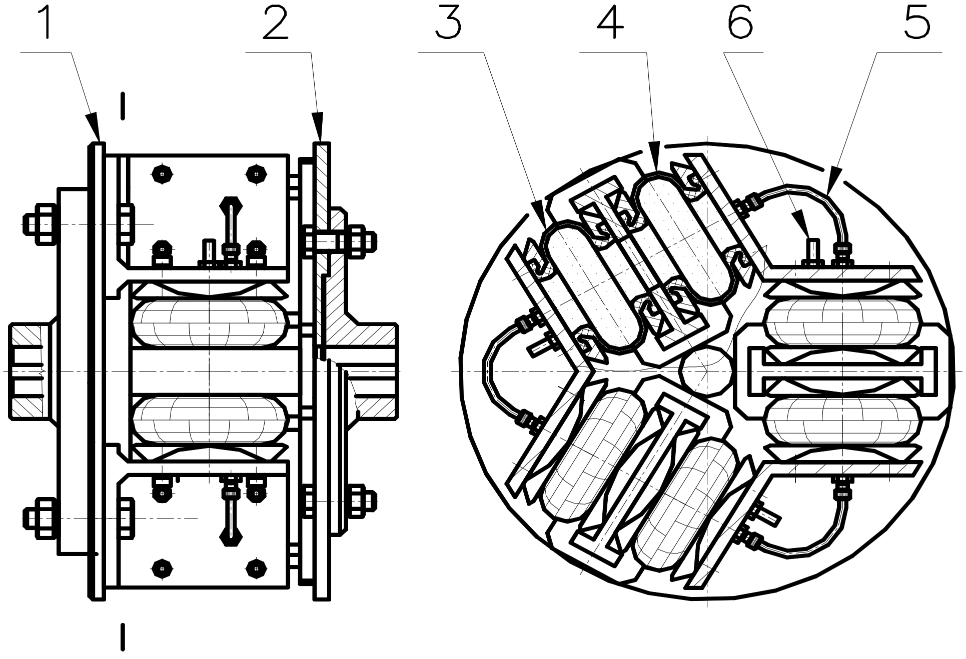

Fig. 1. Pneumatic flexible differential shaft coupling, type 3-1/130-D
Rys. 1. Elastyczne pneumatycznie połączenie współpracujących wałów typu 3-1/130-D

Compression space is created by three differential components, which are in-circuit arranged and interconnected to each other. Each of differential components has a pressed (3) and a pulled pneumatic-flexible element (4) with the external diameter *130 mm*. Interconnection between the differential components is ensured with a connecting hosepipe (5). Infilling of compression space is possible through a valve (6). In this way there is changed pressure of gaseous medium in the compression area.

2.2. Pneumatic flexible differential shaft coupling with autoregulation

The pneumatic flexible differential shaft coupling with autoregulation (Fig. 2 and 3) has its design-base common with the pneumatic differential coupling. Principle of autoregulation is under the patent protection [21], [23]**.** The main difference represents a regulator (*6*) instead of valve. The regulator ensures a constant twisting angle of coupling. The basic principle of this coupling is ability of self-regulation of angular torsion caused by loading torque change and in this way to keep the twisting angle value φ_k constant. So, this coupling is able to self-regulate pressure of gaseous medium in the compression space according to momentary level of loading torque.

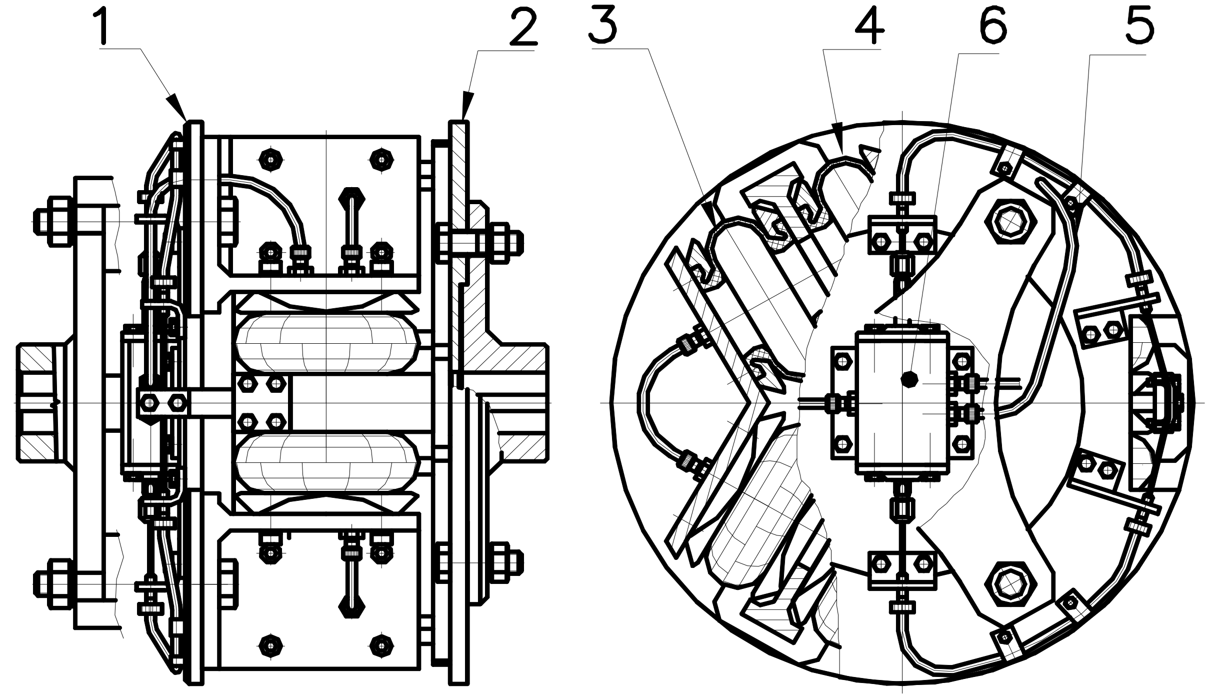

Fig. 2. Pneumatic flexible differential shaft coupling with autoregulation, type 3-1/130-D/A
Rys. 2. Elastyczne pneumatycznie połączenie współpracujących wałów z regulacją typu 3-1/130-D

2.3. Results of measurements performed at pneumatic couplings

There were performed series of static and dynamic measurements of pneumatic couplings [10], [15]. For illustration and for information about the basic characteristic features of pneumatic couplings we present only some of results from the measurements.

According to the obtained results of static and dynamic measurements it is evident, that with changing pressure of gaseous medium is the pneumatic coupling able to operate with always other characteristics (Fig. 4 and 5), i.e. to operate with always other characteristic properties (torsional rigidity and damping coefficient).

With regard to the Fig. 4 and Fig. 5 it is possible to say that static characteristics of pneumatic couplings are slightly non-linear. They are described with equation (1):

$$M_{Sst} = a_0 . \varphi + a_3 . \varphi^3 . \tag{1}$$

From the formula (*1*) it is possible to determine values of equivalent static and dynamic torsional rigidity k_{est} and k_d by means of equivalent linearization method, using relation (2):

$$k_{est,d} = a_0 + \frac{3}{4} a_3 . \varphi^2 . \tag{2}$$

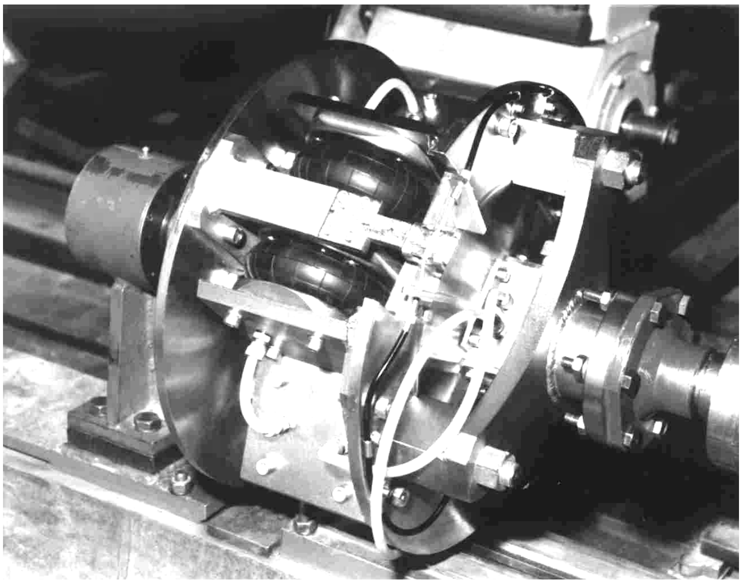

Fig. 3. Photo of the pneumatic flexible differential shaft coupling with autoregulation
Rys. 3. Zdjęcie połączenia elastyczno-pneumatycznie współpracujących wałów z regulacją

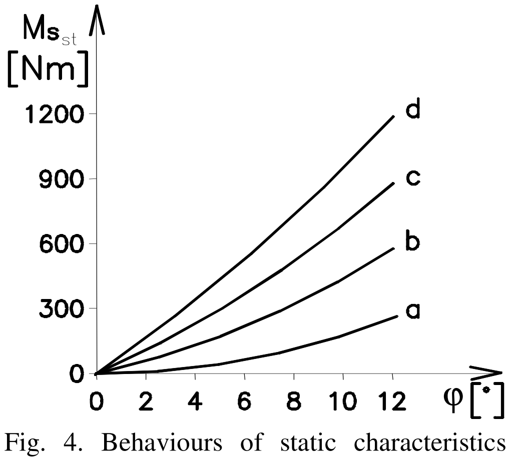

Fig. 4. Behaviours of static characteristics of pneumatic coupling; curves *a, b, c, d* are valid for gaseous medium pressure values p_S = *100, 300, 500* and *700 kPa*

Rys. 4. Zależności dla statycznych charakterystyk sprzęgieł pneumatycznych; wykresy *a, b, c, d* podane dla średniego ciśnienia gazu p_S = *100, 300, 500* i *700 kPa*

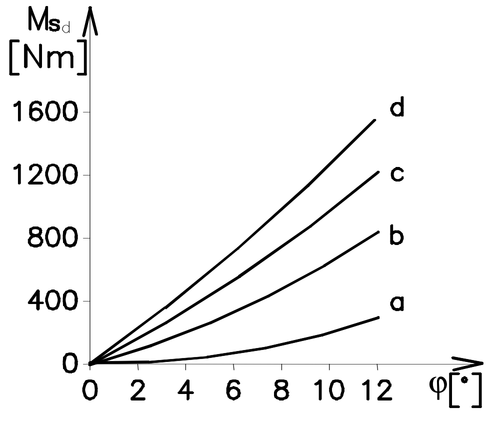

Fig. 5. Behaviours of dynamic characteristics of pneumatic coupling; curves *a, b, c, d* are valid for gaseous medium pressure values p_S = *100, 300, 500* and *700 kPa*

Rys. 5. Zależności dla dynamicznych charakterystyk sprzęgieł pneumatycznych; wykresy *a, b, c, d* podane dla średniego ciśnienia gazu p_S = *100, 300, 500* i *700 kPa*

Behaviour of dependence between ratio of equivalent dynamic torsional rigidity to equivalent static torsional rigidity and gaseous medium pressure is illustrated on the Fig. 6 and it is described with relation (*3*):

$$\frac{k_{ed}}{k_{est}} = 1{,}05 + 4{,}14.10^{-4}.p_S . \tag{3}$$

Together with the change of gaseous medium in pneumatic coupling there are also changing values of its static and dynamic torsional rigidity, as well as value of non-linearity $\varepsilon = a_3 / a_0$ in the coupling. According to calculation it is possible to state, that after pressure increase from *100 kPa* to *700 kPa*, coefficient of non-linearity descends in interval $\varepsilon = 15 \div 1{,}2$ (Fig. 7). With regard to the above-mentioned results it can be defined, that in the interval of gaseous medium pressure $p_S = 200 \div 700\ kPa$ the pneumatic coupling behaves like a linear coupling[1].

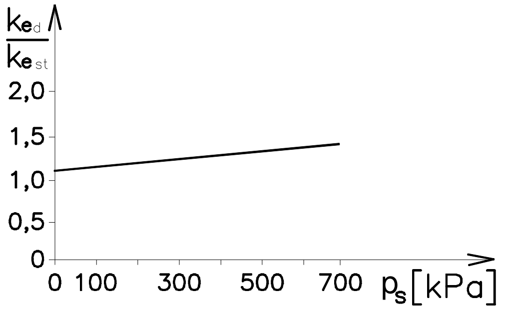

Fig. 6. Dependence between ratio of equivalent dynamic torsional rigidity k_{ed} to equivalent static torsional rigidity k_{est} and gaseous medium pressure p_S in pneumatic coupling

Rys. 6. Zależność między stosunkiem redukowanej dynamicznej sztywności na skręcanie k_{ed} do redukowanej statycznej sztywności na skręcanie k_{est} i średnim ciśnieniem gazu p_S w sprzęgłach pneumatycznych

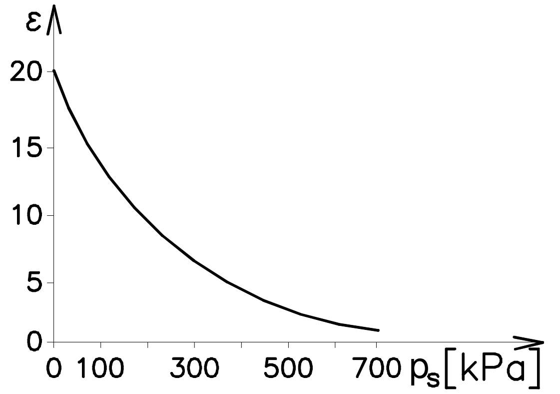

Fig. 7. Dependence between coefficient of non-linearity ε and gaseous medium pressure p_S in pneumatic coupling

Rys. 7. Zależność między koeficjentem nieliniowości ε i średnim ciśnieniem gazu p_S w sprzęgłach pneumatycznych

Next step in elaboration process of measurement results was determination of equivalent coefficient of damping b_e in the pneumatic coupling for individual pressure levels[2].

Results of our measurements confirm the fact that values of coefficient of damping in flexible couplings do not depend so strongly on pre-stress, amplitude and temperature, but they depend on frequency of oscillation ω predominately. With regard to this knowledge it is possible to formulate influence of frequency on the coefficient of damping by means of relation (*4*), whereas the coefficient of damping constant b^{*}[3] (Fig. 8) is invariable for given pre-stress, amplitude and temperature, approximately, i.e.:

$$b_e = b^{*} / \omega. \tag{4}$$

Behaviours of dynamic torsional rigidity in dependence on loading torque for pneumatic differential coupling are illustrated on the Fig. 9 *a*, *b*, *c*, *d*, *e*, *f*, *g*.

By means of self-regulation of gaseous medium pressure and by means of pre-configured value of constant twisting angle it is possible to influence dynamic properties of pneumatic coupling with autoregulation. On the Fig. 10 are presented behaviours of dynamic torsional rigidity in given coupling in dependence on loading torque. For each of presented constant twisting angle $\varphi_k = 2°, 4°, 6°$ and $8°$ is assigned one behaviour of torsional rigidity with designation *a*, *b*, *c*, *d*.

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[1] This argument is supported also by research reports [6], [7], [8], [9]. Authors of these reports mention, that in the case of $\varepsilon < 10$, the flexible coupling is like a linear coupling.

[2] Measurement for determination of equivalent coefficient of damping b_e and coefficient of damping constant b^{*} are described in author's dissertation thesis [4].

[3] By reason that values of coefficient of damping in flexible couplings do not depend so strongly on pre-stress, amplitude and temperature, but they depend on frequency of oscillation ω predominately, author Ing. V. Zoul, CSc. implements a new value – coefficient of damping constant b^{*} [7], [8], [9].

Given behaviours are limited with minimum and maximum value of torsional rigidity, according to gaseous medium pressures from the range $p_S = 100 \div 700\ kPa$. There are also illustrated behaviours with a broken line, which consists of pre-regulation area – *A*, regulation area – *B* and over-regulation area – *C*. From the picture it can be seen, that with the change of φ_k it has changed the length of pre-regulation area as well as regulation area, but mainly the value of torsional rigidity in coupling in the framework of system operational area. It means, that the pneumatic coupling with a higher constant twisting angle operates at certain loading torque level with a lower torsional rigidity. So, for example, by means of change of constant twisting angle from $\varphi_k = 2°$ up to the value $\varphi_k = 8°$, it becomes from a relatively hard coupling a "new" high flexible coupling, which will operate at maximum value of dynamic torsional rigidity ($k_{ed} = 17000\ N.m.rad^{-1}$) as late as from the loading torque value $M_S = 2375\ N.m$, while before it was already from $M_S = 592\ N.m$ for $\varphi_k = 2°$.

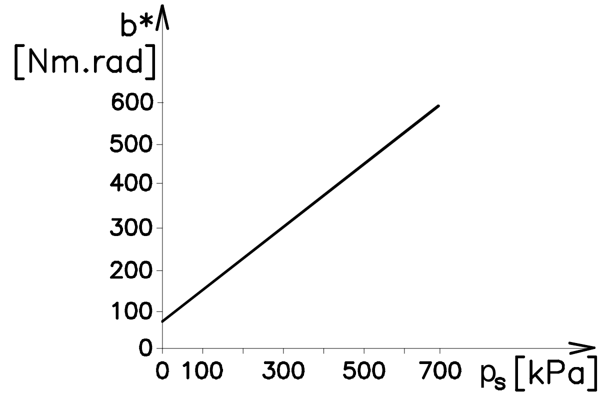

Fig. 8. Behaviour of dependence between coefficient of damping constant b^* and gaseous medium pressure p_S in pneumatic coupling

Rys. 8. Zależność między współczynnikiem tłumienia b* a ciśnieniem p_s w układzie sprzęgła pneumatycznego

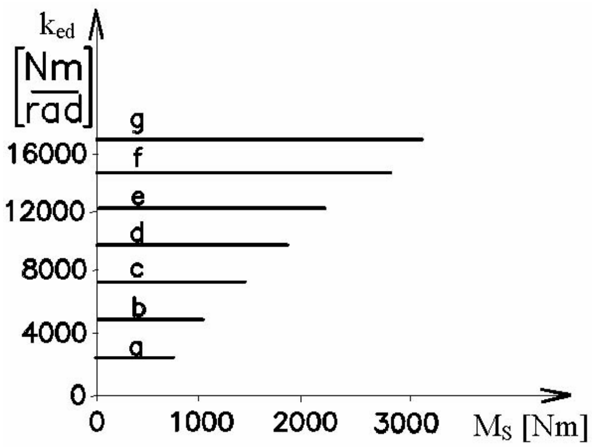

Fig. 9. Behaviours of dependence between dynamic torsional rigidity k_{ed} in pneumatic differential coupling and loading torque M_S

Rys. 9. Zależność między współczynnikiem sztywności k_{ed} przy danym poziomie ciśnienia w układzie sprzęgła a przenoszonym momentem M_s

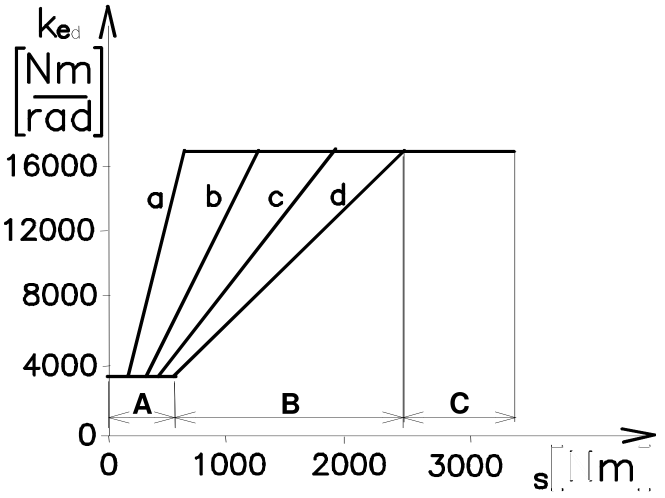

Fig. 10. Behaviours of dynamic torsional rigidity k_{ed} in pneumatic differential coupling with autoregulation in dependence on loading torque M_S

Rys. 10. Zależność między współczynnikiem sztywności k_{ed} przy danym poziomie ciśnienia w układzie sprzęgła z regulacją a przenoszonym momentem M_s

3. CONDITIONS IMPOSED ON PNEUMATIC COUPLINGS FOR APPLICATION IN TORSIONAL OSCILLATING MECHANICAL SYSTEMS

Pneumatic couplings have to fulfil the following conditions in TOMS:

v ***to equalize axial, radial and angular misalignments of shafts caused by production inaccuracies***

Equalizing of axial, radial and angular misalignments of shafts during torque transmission is ensured with flexible compression space in coupling.

v ***to ensure stable dynamic properties and stable flexible transmission of loading torque during service life of mechanical system***

Due to angular torsion of pneumatic coupling the gaseous medium is compressed in the compression space according to the loading, what is a basic principle of loading torque transmission in TOMS. A stable flexible transmission is ensured by application of gaseous medium (in our case it is air), which fulfils the function of flexible material in coupling. The gaseous medium has a dominant influence on the basic characteristic properties of pneumatic coupling and what is important; this medium is not subject to growing old and fatigue [10], [11]. From this reason the pneumatic coupling keeps always its original characteristic properties during the whole operating life of TOMS.

The main and the most important part of presented pneumatic couplings is the compression area, which consists of the pressed and the pulled pneumatic-flexible elements (rubber-cord coat) filled with gaseous medium. In such cases the characteristic features of pneumatic coupling is depending on a rubber-cord coat influence and on gaseous medium – like its filling.

Here arises the question, what has a dominant influence on the basic characteristics of pneumatic couplings – gaseous medium or rubber-cord coat?

During the research process, concerning influence of both components on the change of characteristic features of pneumatic coupling, it can be stated, that increasing tendency of influence of gaseous medium is in the interval QV = 66,22% ÷ 89,83 % (behaviour - a), while the decreasing tendency of influence of rubber-cord coat is from the range QG = 33,78% ÷ 10,17% (behaviour – b), in relation to gaseous medium pressure pS in pneumatic coupling. With regard to given facts it is possible to say, that already at the beginning, i.e. when pS =100kPa, the influence of gaseous medium is two-time greater than influence of rubber-cord coat and at the end, i.e. when pS = 700 kPa, this influence is nine-times greater.

The final result sounds explicitly, that the gaseous medium has a dominant influence on the characteristic properties in pneumatic couplings.

v ***to be able to tune properly torsional oscillating mechanical systems, i.e. to modify its dynamic properties according to system dynamics***

By means of change of gaseous medium pressure p_S in the compression space of pneumatic coupling it is currently changed, i.e. it has tuned also its dynamic torsional rigidity k_{ed}. Torsional rigidity is decisive for natural frequency Ω_O of the system. Value I_{red} is a reduced mass moment of inertia for given system:

$$\Omega_O = \sqrt{k_{ed} / I_{red}} \, . \qquad (5)$$

From the above-mentioned facts follows **principle of a suitable tuning of TOMS by means of pneumatic couplings.** The basic idea is **adjustment of natural angular frequency Ω_O of system to actuating angular frequency ω, so that to avoid a resonance state ($\Omega_O = \omega$), i.e. to eliminate dangerous torsional oscillation of mechanical system in operational mode.**

4. CONCLUSION

Taking into consideration the above-mentioned facts, like aging and fatigue of currently used flexible elements in given couplings, we suggest to apply our developed pneumatic flexible shaft couplings with a view to reduce dangerous torsional oscillation. Pneumatic couplings have not only one, but they have a wide range of characteristics and characteristic features in the framework of the whole interval of gaseous medium pressure in compression space. Mechanical properties of these couplings are influenced by the change of gaseous medium pressure – especially in the case of pneumatic flexible differential coupling, as well as there is another influence - influence of constant twisting angle together with pressure change of gaseous medium – in the case of pneumatic flexible differential shaft coupling with autoregulation.

According to results of experimental verification it is possible to say that by means of change of gaseous medium pressure in compression area of pneumatic tuner, it is tuned dynamic torsional rigidity of coupling with impact on natural frequency of mechanical system. The basic principle of TOMS tuning by means of pneumatic tuner is adjustment of natural angular system frequency to actuating frequency so that to avoid a resonance state, i.e. to eliminate dangerous torsional oscillation of mechanical system in operational mode.

Pneumatic flexible differential shaft couplings are suitable for mechanical systems with constant speed and pneumatic flexible differential shaft couplings with autoregulation are desirable for mechanical systems operating with a range of speed.

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