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Jaroslav HOMIŠIN[1]

CONTRIBUTION AND PERSPECTIVES OF NEW FLEXIBLE SHAFT COUPLING TYPES – PNEUMATIC COUPLINGS

Summary. The contribution briefly approaches the author's profile in the field of scientific research during his work at TU in Košice. More precisely, it presents a selected, specific area of torsional oscillation of mechanical systems concerning the characteristics, research and application of new elements, i.e., so-called pneumatic tuners of torsional oscillation (pneumatic couplings), a field that the author has long been devoted to. In the process, the article informs the reader about the development of new types of flexible shaft couplings, i.e., tangential and differential pneumatic couplings (also with autoregulation), presents the results of static and dynamic measurements made on certain couplings with the interconnection of pneumatic flexible elements and draws attention to the conditions involved in the application of these coupling types in torsionally oscillating mechanical systems.

Keywords: torsionally oscillating mechanical systems; pneumatic flexible shaft couplings – characteristic

[1] Faculty of Mechanical Engineering, Technical University of Košice, Letná 9, 042 00 Košice, Slovakia. Email: Jaroslav.Homisin@tuke.sk.

1. INTRODUCTION

Since my arrival at the Department of Machine Parts and Mechanisms, Faculty of Mechanical Engineering of Technical University of Košice (1981) (then known as VŠT), my scientific research was focused upon the clarification of the problematic regulation of dangerous torsional oscillations in mechanical systems, especially in torsionally oscillating mechanical systems (TOMS). As it was proven that dangerous torsional oscillations can be regulated via the application of suitable flexible elements, via the concrete application of pneumatic flexible shaft couplings, I increasingly devoted my attention to these issues and to the development of and research into new types of flexible shaft couplings. Indeed, theoretical and practical analysis (development of and research into coupling prototypes) was at the core of my dissertation, entitled *The Impact of Pneumatic Flexible Shaft Couplings upon the Torsional Oscillations of Mechanical Systems* [1].

In the following period, I focused my attention on the narrower specification and concretization of the issue concerning the functioning of pneumatic flexible shaft couplings in TOMS. The obtained results in this area were summarized in my habilitation thesis, *Application of Pneumatic Couplings in Modelled Torsionally Oscillating Mechanical Systems* [2].

Further, I was dealing with the issue of tuning TOMS during steady-state operations, i.e., in states of continuous tuning, as one of the methods of TOMS tuning, which resulted in successfully completing a grant-funded project called “Research of Torsional Oscillations of Mechanical Systems with Regard to Possibilities of Their Regulation” (2000-2002). The results of this project pointed to five modes of so-called continuous tuning - tuning during the operation of TOMS, as follows:

a) Tuning via a regulatory system for securing continual change in the characteristic of pneumatic couplings [11]
b) Tuning via a regulatory system for the realization of the continuous tuning of mechanical systems [4]
c) Tuning via the application of pneumatic coupling with an added regulatory system [12]
d) Tuning via static optimization on the basis of an extremal regulation method [3,4]
e) Tuning via the application of pneumatic coupling with autoregulation [9,10]

Each of the suggested methods for the continuous tuning of TOMS (a, b, c, d, e) is presently a topic of interest in postgraduate studies. The proposed method for the continuous tuning of TOMS (c) is currently a part of the FENA Katowice Company’s offer.

Optimizing TOMS via a new method for the regulation of dangerous torsional oscillations is narrowly interconnected with the diagnostics of given systems. For this reason, I consider it necessary in future to focus upon the total diagnostics of TOMS from the aspect of the size of torsional oscillations and mechanical oscillations caused by them.

With the aim of preparing a general and up-to-date characterization of my scientific research over the last four decades at TU in Kosice, I can say that it was mainly focused on reduction issues, especially the regulation of dangerous torsional oscillations in mechanical systems. In the sense of a time sequence, as I was progressing my research, it is possible to select and specify the following thematic areas:

- Development of and research into new flexible shaft coupling types
- Development of and research into the regulation of dangerous torsional oscillations
- Application of pneumatic flexible shaft couplings in TOMS via suggested five methods of continuous tuning

- Optimizing TOMS with an emphasis upon the regulation of dangerous torsional oscillation size
- Diagnostics of TOMS from the aspect of the size of torsional oscillations and mechanical oscillations caused by them

The research results, which I obtained for each of stated areas, were subsequently published in domestic and foreign professional papers, presented at scientific conferences and summarized in a monograph and textbooks. In the process of researching these issues, a total of 52 patents was granted.

Regarding the restricted size of the paper, but primarily due to the extent of my research results in the individual thematic areas, it is impossible to present a more detailed analysis in any of stated issues (each would deserve it). However, I will try to focus my attention on one of the selected areas of my research work, which I consider essential and which is serving as a basis for the development of others. I will concentrate on a brief presentation about new types of flexible shaft couplings - tangential and differential pneumatic flexible shaft couplings (also with autoregulation). At the same time, I will present some results of realized laboratory measurements and define the conditions for the application of certain types of couplings in TOMS.

2. BRIEF CHARACTERISTICS OF FLEXIBLE SHAFT COUPLINGS

Based on the general characteristics of flexible shaft couplings, it is valid to state that, besides adjusting the axial, radial and angle misalignment of shafts, these devices serve as a very efficient tools for restricting the occurrence of resonance in a range of operating speeds in TOMS. In other words, suitably selected flexible shaft couplings, as described by several researchers [5,6,7,8], represent simple and relatively cheap devices for restricting the occurrence of resonance in the operating speed range and reducing the dynamic torsional load of all elements in the system. Usually, this involves shifting the natural frequency of torsional oscillations of the system and, consequently, critical revolutions, from individual harmonic components of torque load into the area of lower-frequency revolutions. As a result, during speedy acceleration or braking, unacceptable torsional accelerations will not occur, as coupling will be able to absorb them.

In the case of mechanical systems offering a broad range of operating speed, the regulation of dangerous torsional oscillations is a very demanding task [12]. The difficulty is caused by the need for a coupling that is able to withstand all demands in terms of dynamic load during the whole operating range (minimal - manoeuvring, maximal - full load) of revolutions, but also under the demanding conditions of starting, stopping and reversing the system. The requirement of the secure functioning of the system across the whole operating range is achieved via the use of flexible coupling with non-linear progressive characteristics.

Consequently, it is the aim of every designer, firstly, to suitably adjust the dynamic properties of flexible coupling to the dynamic properties of the mechanical system, to the maximum degree, in order to control the dangerous torsional oscillations found in TOMS.

The long-lasting operation, which causes wear and fatigue in the material, especially in flexible shaft couplings, as well as accidental occurrences mainly caused by a change in the properties of a driving or driven piston device, negatively impacts the smooth operation of a mechanical system from the aspect of dangerous torsional oscillations [5].

As a result of these negative circumstances, the preliminary tuned mechanical system becomes mistuned. In turn, its tuning element - a flexible shaft coupling - is not able to reduce, or completely eliminate, growing dangerous torsional oscillations in the system.

With the aim to reduce these dangerous torsional oscillations and therefore secure the tuning of TOMS, it is appropriate to apply newly developed pneumatic flexible shaft couplings, i.e., pneumatic tuners of torsional oscillations, whose characteristics I will discuss in the following section of this paper.

3. TANGENTIAL PNEUMATIC FLEXIBLE SHAFT COUPLINGS

Tangential pneumatic flexible shaft couplings (Fig. 1) consist of driving (1) and driven (2) parts, with a compression space inserted in-between.

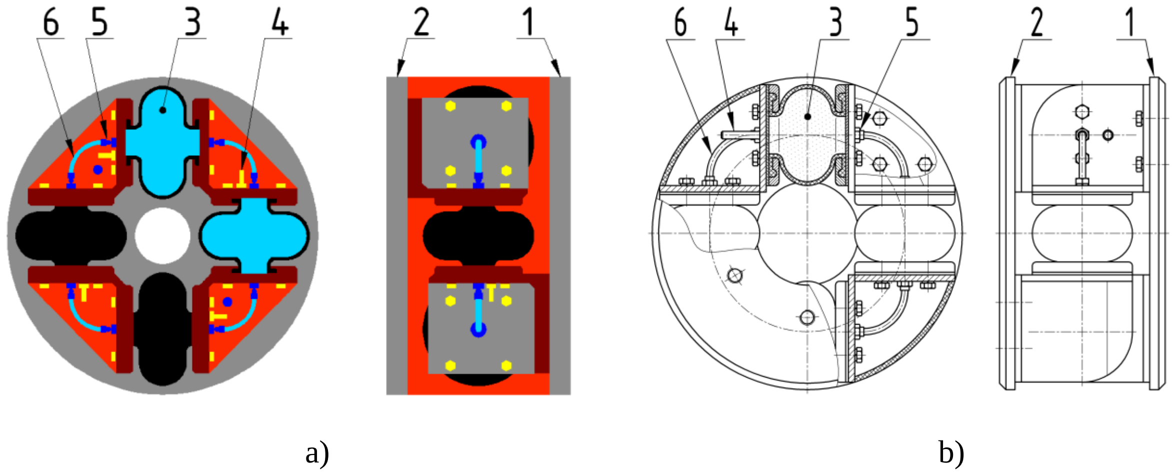

Fig. 1. Tangential pneumatic flexible shaft coupling with the complete mutual interconnection of pneumatic flexible elements: a) graphic representation, b) design solution

A compression space is created by four pneumatic flexible elements, positioned along the circumference (tangentially) in one row (3), with a diameter of 130 mm, marked 4-1/130-T. A pneumatic flexible element consists of bellow-shaped rubber cord material filled with a gaseous medium (in our case, air). During the transmission of torque, the two pneumatic flexible elements are pressed and, at the same time, two other elements are pulled. In this way, the construction of two-sided coupling is secured and a valve (4) filling the compression space of coupling with a gaseous medium is executed. The design solution for pneumatic coupling enables the mutual interconnection of individual pneumatic flexible elements with the help of interchangeable throttling nozzles (5) and hoses (6). In turn, three basic pneumatic coupling option are created:

- Pneumatic coupling without the mutual interconnection of pneumatic flexible elements (4-1/130-T-A) when the carrying units of a compression space of tangential pneumatic coupling are not mutually interconnected
- Pneumatic coupling with the mutual interconnection of pneumatic flexible elements (4-1/130-T-B) when a compression space of tangential pneumatic coupling consists of two independent flexible units,

- Pneumatic coupling with the full mutual interconnection of pneumatic flexible elements (4-1/130-T-C; see Fig. 1) when a compression space of tangential pneumatic coupling consists of two mutually interconnected flexible units

In my research, the tangential pneumatic coupling underwent static and dynamic measurements [1,2,7]. For illustration purposes, the results gained by measuring pneumatic coupling with the complete interconnection of pneumatic flexible elements (4-1/130-T-C) are presented.

3.1. Results of static measurements executed on tangential pneumatic coupling with the complete interconnection of pneumatic flexible elements

The gained results indicated that, due to a change in the pressure of the gaseous medium, pneumatic coupling is able to operate with variable characteristics (Fig. 2), that is, it is able to operate with various properties (torsional stiffness and damping coefficient).

Based on Fig. 2, it is possible to state that the static characteristics of pneumatic coupling are moderately non-linear. Their courses can be expressed by the following simple equation:

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

where the constants a_0 and a_3 are determined from the measured curves via the least squares method.

From Eq. (1), using the method of equivalent linearization, the equivalent static torsional stiffness k_{est} is determined (2). For the static characteristics of coupling (Fig. 2), in terms of pressure (p_S=0÷700 kPa), based on Eq. (2) the values of k_{est} are computed. Fig. 3 shows which courses depend on pressure:

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

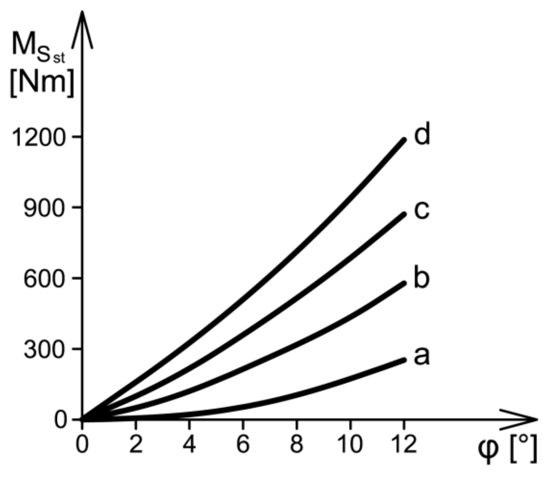

Fig. 2. The courses of static characteristics of tangential pneumatic coupling: Courses a, b, c, d respond to pressures of gaseous medium p_S=100, 300, 500 and 700 kPa

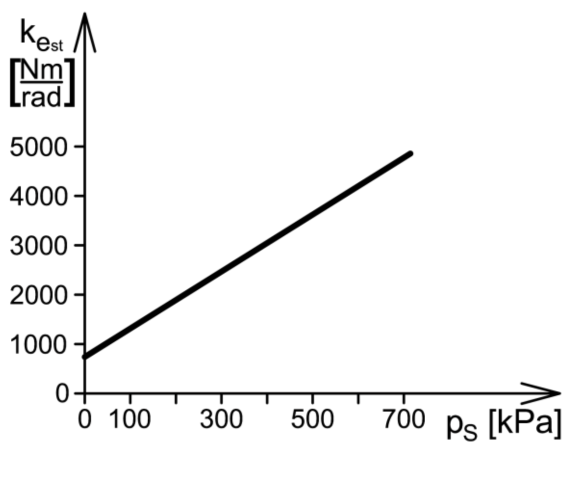

Fig. 3. The course of dependence of the equivalent static torsional stiffness k_{est} on the pressure of gaseous medium p_S in pneumatic coupling

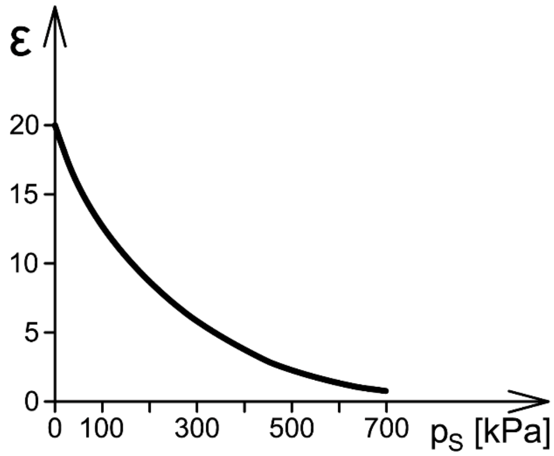

Fig. 4. The dependence of the coefficient of non-linearity ε from the pressure of gaseous medium p_S in a pneumatic coupling

By changing the gaseous medium in the pneumatic coupling, the values of its static torsional stiffness (Fig. 3) are also changed; at the same time, to a considerable degree, the size of its non-linearity $\varepsilon = a_3/a_0$ is influenced. On the basis of the calculation, it is possible to state that, during the increase in pressure from 100 kPa to 700 kPa, the coefficient of non-linearity decreases in the range $\varepsilon = 15 \div 1.2$ (Fig. 4). The results point to the conclusion that, in the range of the gaseous medium $p_S = 200 \div 700$ kPa, pneumatic coupling can be defined as linear. This statement is supported by research reports [5,6], which confirm that, in the case of $\varepsilon < 10$, flexible coupling is considered to be linear.

3.2. Results of dynamic measurements realized from tangential pneumatic coupling Type 4-1/130-T-C

To determine the dynamic properties of pneumatic coupling, in our research, a dynamic method of free oscillations with the preload was applied. On the basis of the recorded free oscillations, the resulting dynamic characteristics were determined (Fig. 5) [1], which are expressed by Eq. (3).

$$M_{Sd} = k_0.\varphi + k_3.\varphi^3. \tag{3}$$

On the basis of Eq. (2), equivalent values of dynamic torsional stiffness k_{ed} of pneumatic coupling for various pressures of the gaseous medium were established (Fig. 6). The research reports [5,6] indicate that, due to the ratio between dynamic and static torsional stiffness, the growth in flexible torque, which is dependent on the coupling oscillations' frequency, is respected. In our case, it is possible to agree with this argument almost entirely.

This leads to the conclusion that, given the relation of dynamic and static torsional stiffness (Fig. 7), a growth in the flexible element of pneumatic coupling is respected, which is similar to the construction according to the equation below:

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

Through the further elaboration of free oscillations records, the values of pneumatic coupling, with an equivalent damping coefficient b^* under various pressures, were defined [1]. The results of our measurements confirm the claim [5,6] that the values of the damping coefficient of flexible couplings depend on the preload, amplitude and temperature to smaller degree, while they depend upon the frequency of oscillations ω to a greater degree. Based on this conclusion, the impact of the frequency upon the damping coefficient can be expressed by Eq. (5), when the coefficient of absorption constant b^* [1] (Fig. 8) refers to the given preload, amplitude and temperature, which are approximately constant, that is:

$$b_e = b^* / \omega. \tag{5}$$

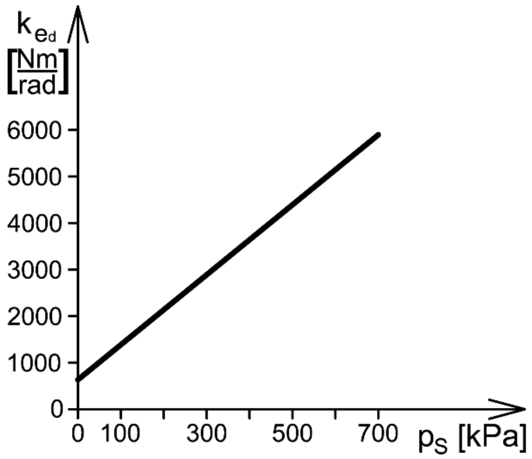

Fig. 5. The courses of the dynamic characteristics of tangential pneumatic coupling; courses a, b, c, d correspond to the pressures of gaseous medium p_S=100, 300, 500 and 700 kPa

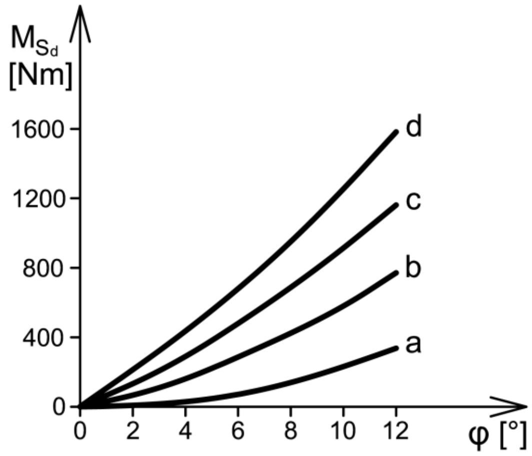

Fig. 6. The course of dependency of the equivalent dynamic torsional stiffness k_{ed} on the pressure of gaseous medium p_S in tangential pneumatic coupling

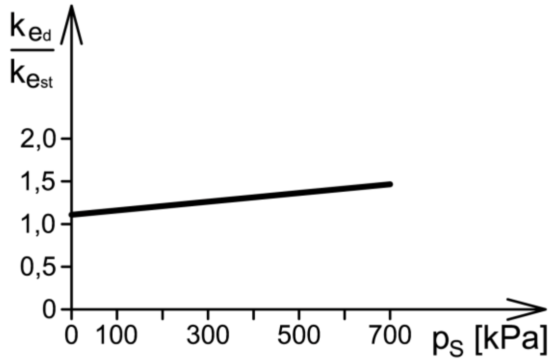

Fig. 7. The course of dependence of the ratio of equivalent dynamic torsional stiffness k_{ed} to equivalent static torsional stiffness k_{est} on the pressure of gaseous medium p_S in tangential pneumatic coupling

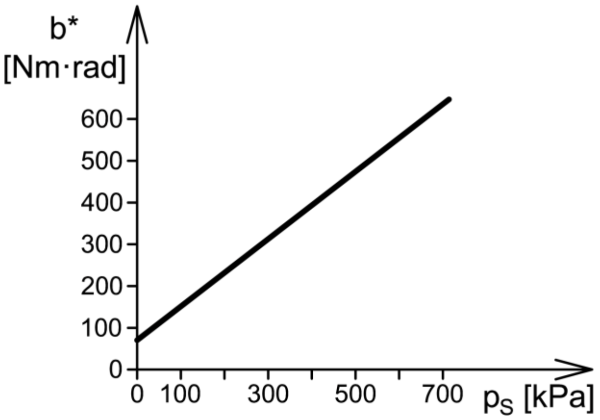

Fig. 8. The course of dependence of the absorption constant coefficient b^* on the pressure of gaseous medium p_S in tangential pneumatic coupling

4. DIFFERENTIAL PNEUMATIC FLEXIBLE SHAFT COUPLINGS

In the sphere of development of and research into differential pneumatic couplings in our department, attention has been given to:

- Differential pneumatic flexible shaft couplings of Type 3-1/130-D (Fig. 9)
- Differential pneumatic shaft couplings with autoregulation of Type 3-1/130-D/A (Fig. 10)

A differential pneumatic coupling (Fig. 9) consists of a driving part (1), a driven part (2) and a compression space filled with a gaseous medium (in our case, air) in-between. A compression space is created by three interconnected differential elements, marked 3-1/130-D, positioned along the circumference. Each differential element consists of a pressed (3) and a pulled pneumatic flexible element (4) with an outside diameter of 130 mm. The mutual interconnection of differential elements is secured by interconnecting hoses (5), while a valve (6) fills the compression space of a coupling, which affects a change in the pressure of the gaseous medium inside it.

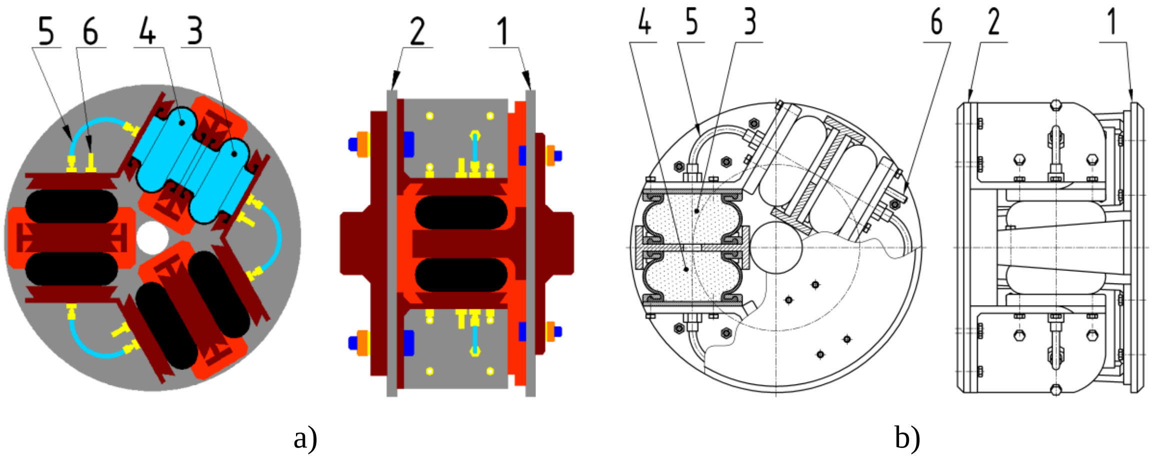

Fig. 9. Differential pneumatic flexible shaft coupling Type 3-1/130-D: a) graphic representation, b) design solution

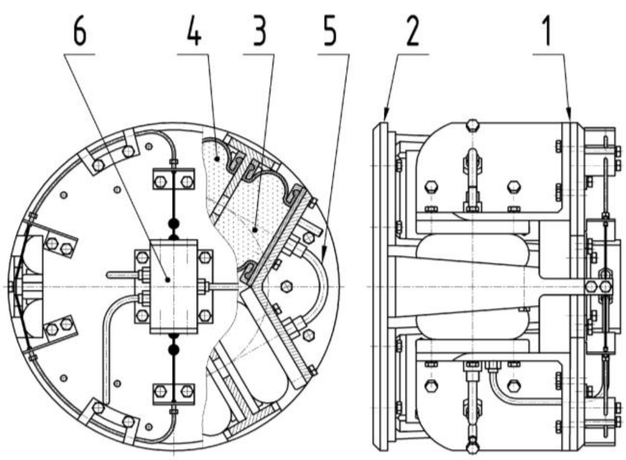

Fig. 10. A differential pneumatic flexible shaft coupling with the auto-regulation of Type 3-1/130-D/A

A differential pneumatic flexible shaft coupling with autoregulation (Fig. 10), of which the basic principle is elaborated in granted patent claims [9,10], has, compared with differential pneumatic coupling, a common construction base. The main difference is the absence of a valve and the insertion of a regulator (6), which maintains the constant twist angle of the coupling. The basic characteristic of coupling is the ability to autoregulate the twist angle change caused by an actual change in load torque to the preliminary set constant twist angle value φ_k. In this way, autoregulation of the gaseous medium pressure value in the pneumatic coupling compression space in relation to the actual value of load torque will be secured.

4.1. The results of laboratory measurements realized for differential pneumatic flexible shaft coupling and differential pneumatic flexible shaft coupling with autoregulation

In the frame of laboratory tests, measurements on a differential pneumatic coupling were realized. The following results were obtained (Figs. 11-13).

The values of the dynamic torsional stiffness of pneumatic coupling (Fig. 11, Course b) were determined via Eq. (4) on the basis of static values, according to Fig. 11, Course a. Fig. 11 shows that the courses of torsional stiffness in pneumatic coupling increase the dependence on gaseous medium pressure.

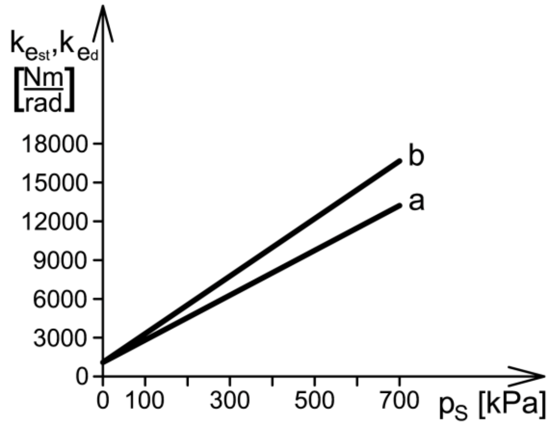

Fig. 11. The courses of dependence of static torsional stiffness k_{est} (Course a) and dynamic torsional stiffness k_{ed} (Course b) on the pressure of gaseous medium p_S in differential pneumatic coupling

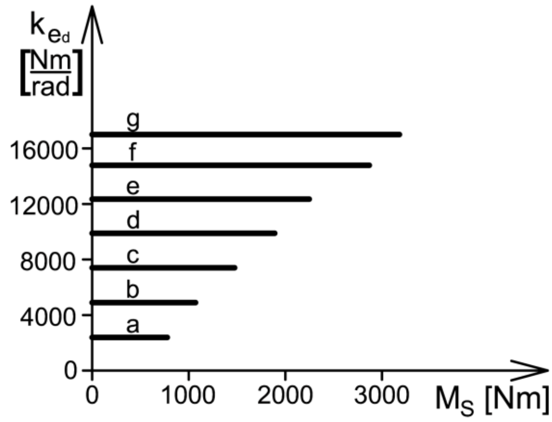

Fig. 12. The courses of dependence of dynamic torsional stiffness k_{ed} in pneumatic coupling on the load torque M_S, when Courses a, b, c, d, e, f, g correspond to the pressure of the gaseous medium in the range from p_s=100÷700 kPa to 100 kPa

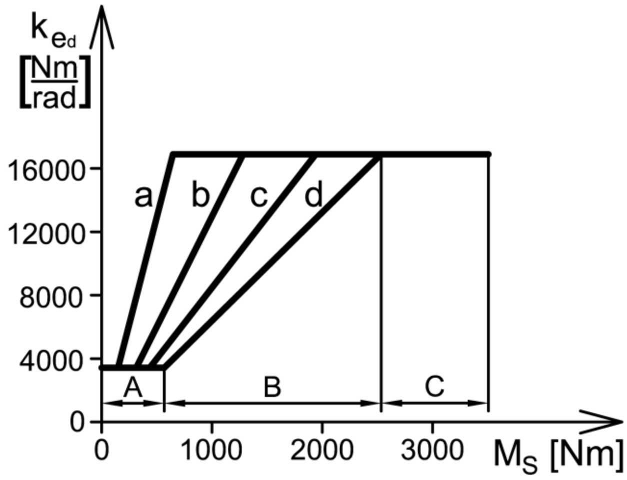

Fig. 13. The courses of dynamic stiffness k_{ed} in differential pneumatic coupling with autoregulation in the dependence on the load torque M_S

The courses of dynamic torsional stiffness in the dependence on load torque (Fig. 12a-g) are constant.

Fig. 12 provides information about the range of dynamic torsional stiffness in differential pneumatic coupling, while, at the same time, providing information about the suitability of the given coupling to operate in a particular mechanical system.

Autoregulation of the gaseous medium pressure value and the preliminary set value of the constant twist angle influence the dynamic properties of pneumatic flexible shaft coupling with autoregulation to a considerable degree. Fig. 13 illustrates the courses of coupling dynamic torsional stiffness in the dependence on the load torque. One course of torsional stiffness marked as a, b, c, d corresponds to each constant twist angle φ_k=2°, 4°, 6° and 8°.

The stated courses are limited by the minimal and maximal value of torsional stiffness, which corresponds to the pressure of the gaseous medium in the range of p_S=100÷700 kPa. At the same time, the courses are shown by a broken line consisting of pre-regulatory (A), regulatory (B) and above-regulatory (C) zones. As shown on the scheme, via a change in φ_k, the length of the pre-regulatory and regulatory zones, and primarily the value of torsional stiffness, are impacted. This means that pneumatic coupling with an increased constant twist angle and the same mean load torque will operate with decreased torsional stiffness. In this way, via a change in the constant twist angle with a value of φ_k=8°, relatively stiff coupling, for example, when φ_k=2°, operating with maximal torsional stiffness (k_{ed}=17000N.m.rad^{-1}), will result in highly flexible coupling due to load torque M_S=592N.m, which will reach the maximal value of dynamic torsional stiffness (k_{ed}=17000N.m.rad^{-1}), but only when torque M_S=2375N.m.

5. REQUIREMENTS PLACED ON PNEUMATIC COUPLINGS FOR THEIR APPLICATION IN TORSIONALLY OSCILLATION MECHANICAL SYSTEMS

Pneumatic tuners of torsional oscillations in TOMS must fulfil the following conditions:

- ❖ Alignment of axial, radial and angular misalignments of shafts caused by manufacturing imperfections.
  - ➢ During the transfer of load torque, the alignment of axial, radial and angular misalignments between driving and driven shafts is secured by a flexible compression space.
- ❖ The securing of stable dynamic properties and stable flexible transmission of load torque during the lifespan of mechanical system.
  - ➢ The twisting of pneumatic coupling enables the compression of a gaseous medium in its compression space, which is adequate for the load; and, in this way, the flexible transmission of load torque in TOMS is realized. The stable flexible transmission is secured by the use of flexible material in a coupling, which is a gaseous medium (in our case, air). Air has a dominant impact upon the basic properties of pneumatic tuner [11] and, during its whole operation, it is resistant to wear and tear. As a consequence, the pneumatic coupling does not lose its original characteristic properties and it is stabile during whole lifespan of TOMS.
- ❖ The capacity to suitably tune TOMS, that is, the ability of tuning to adjust its dynamic properties to the dynamics of the systems.
  - ➢ On the basis of a gaseous medium pressure p_S change in the compression space of pneumatic coupling, the dynamic torsional stiffness k_{ed} of the coupling is tuned. This has a decisive influence on the natural frequency Ω_O of the system, when I_{red} is the reduced mass moment of inertia of the system.

$$\Omega_O = \sqrt{k_{ed} / I_{red}}\,. \tag{6}$$

- Thus, the principle of the suitable tuning of TOMS via pneumatic couplings, as explained above, is based on the adjustment of the natural frequency of the system Ω_O to the exciting frequency ω in a manner preventing the state of resonance in the operating range of the system ($\Omega_{O=}\omega$). Consequently, this results in the prevention of dangerous torsional oscillations.

6. CONCLUSION

The control of dangerous torsional oscillations in mechanical systems is currently resolved by the use of highly flexible couplings with suitably selected courses of linear or non-linear characteristics. Only certain types of flexible couplings are able to fulfil this need, because not all types of couplings are capable of achieving satisfactorily low torsional stiffness and, at the same time, satisfactory strength. The torsional stiffness and strength are dependent upon the shape of the flexible element and the material used for manufacturing the flexible element. It is also appropriate to mention that each linear or non-linear flexible coupling presently used is defined only by one characteristic. To change the characteristics of the flexible coupling, in order to suitably adjustment its dynamic properties to the dynamic of the system, it is necessary to use a different element of flexible coupling, or to use a different flexible shaft coupling. In addition, it is unacceptable to overlook the fatigue and wear of flexible materials, which, in the end, impact the original dynamic properties. The instability of dynamic properties of flexible couplings caused by the wear and fatigue of these flexible elements, together with the frequent malfunction of other parts of the system, results in the mistuning of preliminary TOMS. In this case, the tuning part, i.e., the flexible shaft coupling, has no capacity to remove or reduce increasing dangerous torsional oscillations.

By taking these facts into consideration with the aim of tuning up or tuning TOMS and limiting the dangerous torsional oscillations, a proposal was made to apply the newly developed flexible shaft couplings as so-called pneumatic tuners of torsional oscillations. These pneumatic couplings have, at their disposal, a whole array of characteristics (not just one) and, at the same time, a range of characteristic properties. The properties of these couplings are influenced by changes in gaseous medium pressure, namely, in differential pneumatic flexible shaft couplings, and the selection of constant twist angles of couplings with a parallel change in gaseous medium pressure, namely, in differential pneumatic flexible shaft couplings with autoregulation.

Based on the results of experimental measurements performed on newly developed pneumatic couplings, we can say that, due to a gaseous medium pressure change in a compression spaces, the dynamic torsional stiffness of a coupling is also changed (tuned), which has a decisive impact upon the natural frequency of the system. Thus, the basis of the principle of tuning TOMS via pneumatic tuners is the adjustment of the natural frequency of mechanical system to the existing frequency in a manner whereby a state of resonance and, consequently, dangerous torsional oscillations in the operating range are prevented.

In the context of dangerous torsional oscillations of mechanical systems, the development of and research into various types of flexible couplings are highly topical and, from the aspect of limiting dangerous torsional oscillations, unquestionably necessary. It has been shown that one of the types of shaft couplings, which are exceptionally suitable for the fulfilment of this aim, are pneumatic shaft couplings, as they function as pneumatic tuners of torsional oscillations.

In summarizing my results to date in the area of the torsional oscillation of mechanical systems research, it is possible to state that this work has made a contribution by broadening and enriching knowledge in this field. This scientific contribution can be evaluated primarily from the two perspectives:

- Elaboration of new elements - pneumatic couplings, tuners of torsional oscillations
- Implementation of new control methods for torsional oscillations via several innovative approaches

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