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NEW METHODS FOR TUNING OF MECHANICAL SYSTEMS DURING OPERATION IN STEADY STATE

Summary. The main purpose of this paper is to inform the technical community about new tuning methods of torsional oscillating mechanical systems (TOMS) during operation in a steady state by means of application of pneumatic flexible shaft couplings.

It is possible to change the torsional stiffness of pneumatic couplings by means of a change of gaseous medium pressure either out of operation or during operation. There are two possibilities how to tune the torsional oscillating mechanical systems:

- tuning of torsion oscillating mechanical systems out of operation, what fulfils condition of given system tuning,
- tuning of torsion oscillating mechanical systems during operation in a steady state, what fulfils condition of given system continual tuning.

The basic principle of TOMS tuning during operation in the steady state consists in an adjustment of basic dynamical properties of pneumatic coupling according to the system dynamics. This adjustment can be made by means of a regulation system working in regulation circuit arrangement with a feedback. In this way it is possible to change dynamical properties of pneumatic coupling continuously with regard to dynamic of mechanical system, so that it can be eliminated dangerous torsional oscillation of given system in the working mode.

Keywords: dangerous torsional oscillation, new tuning methods, tuning of mechanical system, pneumatic couplings

NOWE SPOSOBY DOSTRAJANIA MECHANICZNYCH UKŁADÓW NAPĘDOWYCH PODCZAS ICH EKSPLOATACJI

Streszczenie. Celem niniejszego artykułu jest przedstawienie informacji o nowych sposobach dostrajania drgających skrętnie mechanicznych układów napędowych (DSMUN) pracujących w stanie ustalonym. Sposoby te polegają na zastosowaniu podatnych sprzęgieł pneumatycznych. Zmiana sztywności skrętnej sprzęgła pneumatycznego może być realizowana przez zmianę ciśnienia medium gazowego, i to zarówno w stanie niepracującym, jak i podczas pracy układu napędowego. Z tego wynikają dwa proponowane sposoby dostrajania drgających skrętnie układów mechanicznych:

- dostrajanie DSMUN w stanie niepracującym w celu spełnienia warunków tak zwanego strojenia parametrów danego układu,

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- dostrajanie DSUMN podczas ich eksploatacji w stanie ustalonym w celu spełnienia warunków tak zwanego płynnego dostrajania parametrów danego układu.

Charakter dostrajania DSMUN podczas eksploatacji w ustalonym stanie pracy wynika z odpowiedniej adaptacji podstawowej charakterystyki dynamicznej sprzęgła pneumatycznego do dynamiki układu. Adaptacja jest realizowana przez system regulacyjny, który tworzy zamkniętą pętlę sterowania ze sprzężeniem zwrotnym. Pozwala to na ciągłe zmiany, czyli dostosowanie charakterystyki dynamicznej sprzęgła pneumatycznego do układu mechanicznego w taki sposób, aby w trakcie działania systemu nie wystąpiły niebezpieczne drgania skrętne.

Słowa kluczowe: niebezpieczne drgania skrętne, nowe sposoby dostrajania, regulowanie mechanicznego układu, sprzęgła pneumatyczne

1. INTRODUCTION

In mechanical systems with piston engines such as propulsion of ships, locomotives and heavy vehicles, as well as systems with electric driven fans and compressors applies a growing need to control their dangerous torsional vibration. It was confirmed that vibration can be reduced to an acceptable level by tuning and continuous tuning of the system during steady state operation by application of pneumatic couplings proposed by us.

The essence of the proposed continuous tuning and tuning of mechanical systems results from a suitable adaptation of the basic dynamic characteristics of pneumatic couplings. Given adaptation can be provided out of operation or during operation at steady state.

Based on the above it can be concluded that application of new methods of continuous tuning or tuning the mechanical systems creates new ways to control dangerous torsional vibration.

Therefore presented contribution aims to inform the technical public with the results of application of new ways of continuous tuning and tuning of torsionally oscillating mechanical systems (TOMS) developed by us with use of pneumatic couplings.

2. PROPOSED METHOD TO CONTROL TORSIONAL VIBRATION OF MECHANICAL SYSTEMS

Change of torsional stiffness of pneumatic couplings can be realized by changing the pressure of gaseous medium, out of operation or during operation of mechanical systems. This leads to two proposed ways of tuning torsionally oscillating mechanical systems:

- Tuning torsionally oscillating mechanical systems out of operation, ensuring the condition of tuning the system:
- Tuning torsionally oscillating mechanical systems during operation in steady state, ensuring the continuous tuning of the system.

In the present paper we will pay attention to TOMS tuning during operation in steady state, ie. continuous tuning, which basic principle is:
„The essence of tuning TOMS during operation in steady-state results from the proper adaptation of fundamental dynamic properties (dynamic torsional stiffness and damping coefficient) of pneumatic coupling to the system dynamics. Adaptation is possible to ensure by the control system that creates closed-loop feedback. This allows us continuously change, or adapt the dynamic properties of pneumatic coupling to the dynamics of the mechanical

system so that during operating mode of the system do not occur dangerous torsional vibration“.

3. RESULTS OF APPLICATION OF PROPOSED TUNING METHOD OF TORSIONAL OSCILLATING MECHANICAL SYSTEM

Controlling dangerous torsional vibration of any TOMS, as mentioned earlier, is largely determined by the appropriate tuning.

In the present chapter is our primary goal to present the tuning of modeled and realized TOMS, we have made, based on theoretically provided results characterizing the size of the torsional vibration:

- Tuning torsionally oscillating mechanical systems during operation in steady state:
  - ➢ applying pneumatic couplings with autoregulation [4], [5], [3].

3.1. Results of tuning torsional oscillating mechanical system during steady state operation

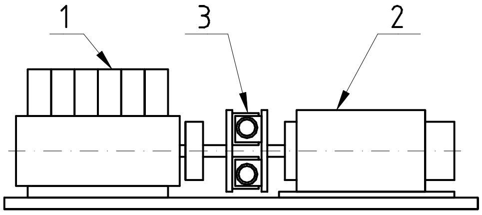

Fig. 1. Modeled torsional oscillating mechanical system
Rys. 1. Układy mechaniczne drgające skrętnie

The results of tuning were obtained on modeled TOMS (*Fig.1*), composed of driving part (*1*), driven part (*2*) and pneumatic coupling (*3*). The driving part, formed by six-cylinder four stroke diesel engine 6S 160 PN, driven part consists of DC-generator type DN 1144-4.

Size of torsional vibration of modeled TOMS will be investigated under these conditions:

- balanced excitation of engine cylinders,
- unbalanced excitation of engine cylinders,
- one cylinder out of operation

and presented by course of dynamic torque amplitudes *(1)* introducing torsional vibration to the pneumatic coupling, depending on the speed.

$$M_d = \sum_{i=1}^{n} M_i . \frac{I_2}{I_1 + I_2} . \frac{\sqrt{1 + \left(\frac{i.\omega}{\Omega_0}\right)^2 . \left(\frac{2\chi}{\Omega_0}\right)^2}}{\sqrt{\left[1 - \left(\frac{i.\omega}{\Omega_0}\right)^2\right]^2 + \left(\frac{i.\omega}{\Omega_0}\right)^2 . \left(\frac{2\chi}{\Omega_0}\right)^2}} . \tag{1}$$

3.1.1. Application of differential pneumatic coupling with autoregulation

The tuning of modeled system by pneumatic flexible shaft coupling with autoregulation (*Fig. 2*) is presented by Campbell diagram (*Fig. 3*).

Differential pneumatic flexible shaft coupling with autoregulation [4][1], [5][2] consists of driving part (*1*), driven part (*2*), between them is the compression space filled with a gaseous medium (air in our case). Compression space consists of three interconnected differential members uniformly spaced around the perimeter. Each differential member consists of the compressed (*3*) and expanded pneumatic flexible element (*4*). Interconnection of differential members is provided by connecting hoses (*5*). Pneumatic coupling contains regulator (*6*) to ensure its constant twist angle. The fundamental nature of the coupling is the ability to autoregulate twist angle caused by actual change of load torque at a predetermined constant angular value φ_k. This ensures the autoregulation of gaseous medium pressure in the compression space, thus its adaptation to the actual size of load torque.

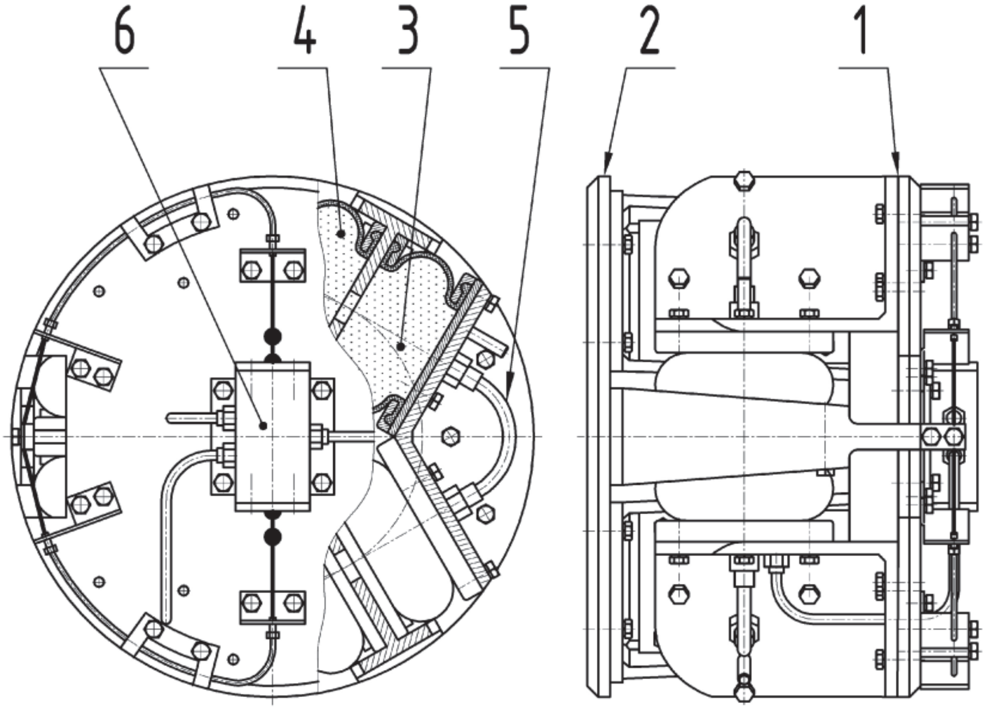

Fig. 2. Differential pneumatic flexible shaft coupling with autoregulation type 3–1/130–D/A
Rys. 2. Elastyczne sprzęgło pneumatyczne z autoregulacją o typowym oznaczeniu 3–1/130–D/A

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[1] Patent: *„HOMIŠIN, J.: Pneumatic flexible shaft coupling with the ability to autoregulation. Pat. 278025/95", which was awarded to author relates to:" Pneumatic coupling, which is designed to provide a flexible transmission of mechanical energy in TOMS with autoregulation of its basic dynamic properties using the regulator to ensure a constant twist angle of the coupling."*

[2] Patent: *„HOMIŠIN, J.: Pneumatic coupling with an additional regulator of constant twist angle. Patent No. 278272/96", which was awarded to author relates to:" Regulator for ensuring constant coupling twist angle. By controlling the regulator we ensure the delivery of gaseous medium in flexible hollow bodies or its discharge from flexible hollow bodies, thus addressing the issue of control the required dynamic characteristics of pneumatic coupling".*

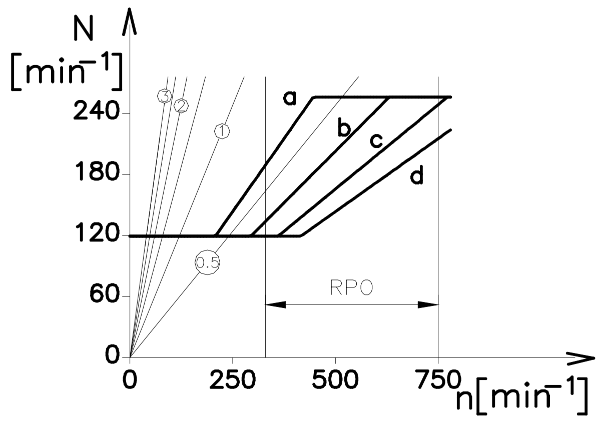


Fig. 3. The Campbell diagram of modeled TOMS using differential pneumatic flexible shaft coupling with autoregulation

Rys. 3. Diagram Campbella analizowanego UMDS, w którym zastosowano różnicowe elastyczne sprzęgła pneumatyczne z autoregulacją

Campbell diagram on *fig.3* shows four courses of natural frequencies *a*, *b*, *c*, *d*, corresponding to constant twist angles of pneumatic coupling $\varphi_K = 2°,4°,6°$and $8°$.

Based on the Campbell diagram, it can be concluded that the couplings constant twist angle $\varphi_K = 2°$ is not suitable for the modeled system.

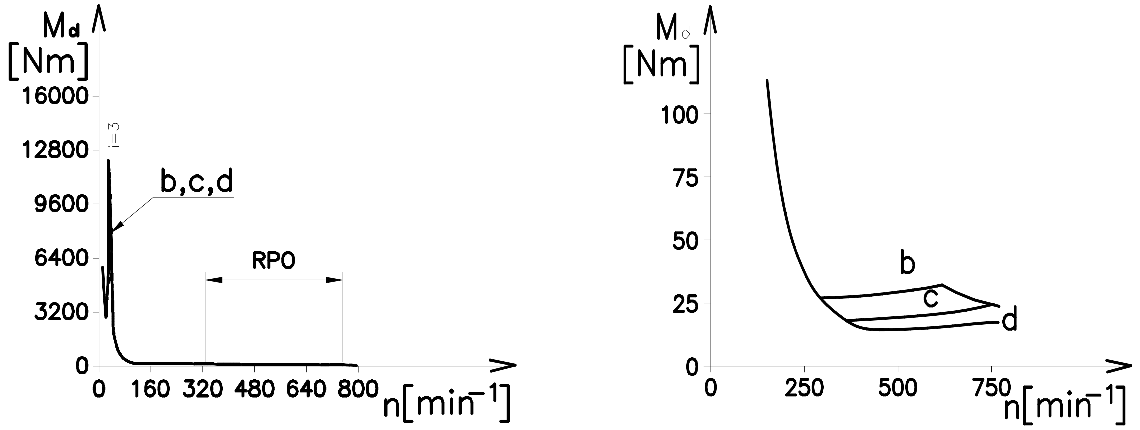
By using pneumatic coupling with twist angles $\varphi_K = 4°$, $6°$ a $8°$ does not occur resonance from any of load torque harmonic components. Therefore, further we will examine the tuning of system at those constant twist angles.

Tuning of modeled system by use of pneumatic coupling with autoregulation by mentioned constant twist angles is characterized by *fig.4.a*, *b* and *fig.5.a*, *b*.

For the above figures it can be concluded that the highest values of dynamic torque and of dynamic twist angle is achieved at the speed $n = 630\ min^{-1}$ with constant twist angle of coupling $\varphi_K = 4°$.

Specific parameters M_d characterizing the size of the torsional vibration acquire in the examined cases, these values:

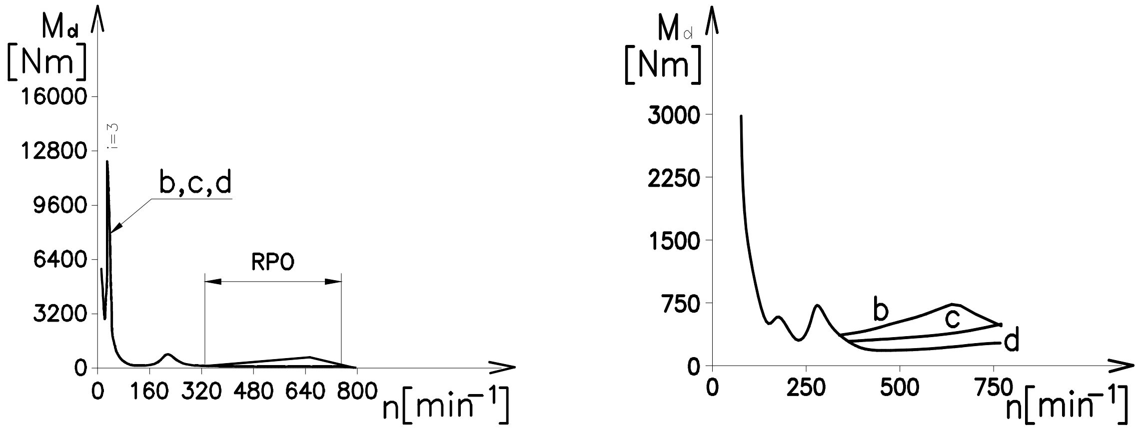
- *balanced excitation of engine cylinders* $M_d = 33{,}3\ N.m$,
- *unbalanced excitation of engine cylinders* $M_d = 83{,}3\ N.m$,
- *one cylinder out of operation* $M_d = 700\ N.m$.



a) **b)**

Fig. 4. Courses of dynamic torque amplitudes M_d depending on the speed *n* in the case of Engine cylinders balanced excitation

Rys. 4. Przebiegi amplitud momentu obciążającego M_d w funkcji prędkości obrotowej *n* w przypadku równoczesnego zapłonu cylindrów



a) b)

Fig. 5. Courses of dynamic torque amplitudes M_d depending on the speed n in the case of one cylinder out of operation

Rys. 5. Przebiegi amplitud momentu dynamicznego M_d w funkcji prędkości obrotowej n w przypadku wyłączenia jednego z cylindrów

It is caused by frequency ratio for the speed of half-harmonic component which reaches a relatively low value, equal to *1,23*.

Frequency ratio by $n = 630\ min^{-1}$ for $i = 0,5$ by constant coupling twist angle $\varphi_K = 8°$ reaches relatively higher value $\eta = 1,75$. Therefore, dynamic torque and dynamic twist angle acquire in given location relatively low values. Specifically, for referred order of work conditions of piston device, the values of dynamic parameters are following:

▪ *balanced excitation of engine cylinders*	$M_d = 15,8\ N.m$,
▪ *unbalanced excitation of engine cylinders*	$M_d = 30,0\ N.m$,
▪ *one cylinder out of operation*	$M_d = 200\ N.m$.

The above analysis shows that the lowest dynamic parameters are obtained at a constant twist angle of pneumatic coupling with autoregulation $\varphi_K = 8°$. This means that for this angle of twist the coupling can be provided the most quiet system operation in terms of torsional vibration. Based on the results it is possible to say that $\varphi_K = 8°$ is the most appropriate constant twist angle of pneumatic coupling with autoregulation for the modeled system.

From the results of analysis it can be concluded that differential pneumatic flexible shaft coupling with autoregulation with an appropriate constant twist angle can be used in TOMS with a wide range of operating speed.

4. CONCLUSION

Reduction of dangerous torsional vibration mechanical systems is currently dealt with by using highly flexible couplings with suitably adapted characteristics, particularly with customized course of torsional stiffness. This requirement are able to meet only some types of flexible couplings. The reason for this that not all types of couplings are possible to achieve a sufficiently low torsional stiffness at the same time having enough suitable strength properties. It should also be noted that any linear or non-linear flexible shaft coupling has only one characteristic. The result of this is only one course of natural speed frequencies in the Campbell diagram. Unlike the above, the pneumatic differential flexible couplings developed by us have not one, but a range of characteristics, therefore, a range of their characteristic propertiesespecially dynamic torsional stiffness

Change of pneumatic couplings torsional stiffness can be realized by changing the pressure of gaseous medium, namely out or during the operation of mechanical systems.

The essence of tuning TOMS during operation in steady state results from an appropriate adjustment of basic dynamic characteristics of pneumatic coupling to systems dynamics.

In the case of application of pneumatic coupling with autoregulation can be concluded that the characteristics (particularly dynamic torsional stiffness) of the coupling are affected both by selecting appropriate constant twisted angle φ_K and the continuously variable overpressure of gaseous medium in its compression chamber. This means that using a pneumatic couplings with autoregulation in any TOMS the Campbell diagram will contain a number of speed frequencies linked to a specific, pre-set value of constant twist angle.

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