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NEW DESIGNS OF VARIABLE STIFFNESS COUPLINGS

Summary. Flexible couplings are widely used in mechanical drives of transport and other machines. A fundamental function of flexible shaft couplings regarding torsional vibration is the optimum tuning of torsional oscillating mechanical systems. At the authors' workplace, the focus is on the research and design of pneumatic couplings, where the torque is transmitted mainly by compressed gas (air) in their pneumatic flexible elements. The primary advantage of these couplings is that their mechanical properties can be quickly and effectively adjusted, especially the dynamic torsional stiffness, by air pressure change directly while the mechanical system is running. This allows us "to tune" the properties of the pneumatic coupling according to the current parameters of the machine drive to avoid resonance and minimize torsional vibration. Therefore, we tend to refer to them as "pneumatic tuners of torsional vibration". This paper aims to present two new types of these "pneumatic tuners" that were recently granted patent protections, namely "Pneumatic flexible shaft coupling with hose flexible element" and "Drum pneumatic flexible shaft coupling". Because these pneumatic tuners are not in practical use yet, this paper describes only their design and supposed benefits.

Keywords: variable stiffness couplings, pneumatic torsional vibration tuners, design, patents, properties

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1. INTRODUCTION

Nowadays, the vibration and noise of machines, especially transport machines, are coming to the fore, especially regarding the health and comfort of humans and also the fatigue and durability of machines [1, 5, 14, 23]. Therefore, several novel methods have been developed to improve mechanical drives to solve these issues. Engines with internal combustion underwent major modifications for dynamics, efficiency and emissions, for example, [3, 17]. For torque transmission between rotating shafts, flexible shaft couplings are commonly used [1, 4, 6, 12, 16, 25, 28]. Each drive needs a careful selection of flexible coupling based on detailed torsional analysis, otherwise excessive torsional vibration may appear [1, 5, 7, 16]. The selected coupling should have appropriate mechanical properties. The primary parameter affecting the size of torsional vibration is dynamic torsional stiffness.

Various materials (metals, rubber and plastic) are currently used for manufacturing shaft coupling flexible elements. These materials of flexible elements are exposed to cyclic loading, which is then manifested by subsequent fatigue and wear of flexible elements. Consequently, the shaft coupling loses its initial (nominal) mechanical properties. As such, it cannot fulfil its tasks, the most important being “tuning of the mechanical system”, which entails minimizing torsional vibration.

The tuning of modern mechanical drives working in a wide range of working speeds and uneven cylinder operation (uneven fuel supply or deactivated cylinders) due to efforts to increase efficiency and reduce emissions is even more problematic. It is hard to select proper flexible shaft coupling (as a passive vibroisolation element using no additional energy) capable of providing optimum tuning for such a wide range of operating parameters. To overcome these problems, there are developed passive tuners with load characteristics or torsional stiffness adapted to the specific device to which they are applied. Therefore, flexible couplings with variable stiffness (as a semi-active vibroisolation element capable of changing its mechanical properties during operation) are currently being developed.

The change of torsional stiffness is currently possible by some of the existing variable stiffness couplings, for example, pneumatic flexible shaft couplings [5, 27] and magnetic shaft couplings [15, 24]. Some authors proposed the use of variable stiffness coupling using magnetorheological elastomers [11, 18] or leaf springs with variable active length [9]. Elements with variable torsional stiffness (referred to as “variable stiffness joints” and “variable stiffness actuators”) are developed in robotics too [26]. They are used mainly for robots working in environments where the possibility of collision with surrounding objects or humans cannot be completely avoided; however, it is also possible to use their working principles for shaft couplings in the field of mechanical drives. These designs use various types of flexible elements, such as leaf springs with variable active length [2], magnets, cable mechanisms with preloaded springs [13] and cam mechanisms with preloaded springs [29]. Variable stiffness vibroisolation elements are also used for damping rectilinear vibration [10, 23].

At our workplace, we research and develop pneumatic flexible shaft couplings. For this type of shaft coupling, the torque transmission is provided by compressed air, which is not subject to fatigue and ageing. A great advantage of these flexible shaft coupling types, a few of them for which patents were granted can be found in [19 – 22], is the ability to adjust their torsional stiffness depending on the air pressure in pneumatic flexible elements. This ensures that the dynamic torsional stiffness of a pneumatic coupling can be adapted to the mechanical system’s current operating conditions.

We focused specifically on tuning mechanical systems (regarding torsional vibration) during operation, with the application of “pneumatic tuners of torsional oscillation” as devices for semi-active tuning of torsional vibration. For this purpose, we have developed our own electronic control systems. This paper presents two patented types of “pneumatic tuners”:

1. Pneumatic flexible shaft coupling with hose flexible element [19],
2. Drum pneumatic flexible shaft coupling [21].

Because the presented “pneumatic tuners” are not manufactured yet, the paper describes only their working principles and expected advantages. In our future research, we plan to manufacture and test the prototypes of these couplings.

2. NEW FLEXIBLE SHAFT COUPLINGS

2.1. Pneumatic flexible shaft coupling with hose flexible element

This coupling design, as described in the patent [19], uses a novel type of pneumatic flexible element. It is a hose-shaped flexible element winding between the supporting surfaces of the coupling’s hubs (
Fig. 1). Proposed pneumatic shaft coupling with hose flexible element (
Fig. 1
Fig. 2) consist of two hubs *(1, 2)* connected flexibly via hose pneumatic flexible element *(3)*.The hose flexible element winds between the support surfaces of the driving *(4)* and driven *(5)* hub.

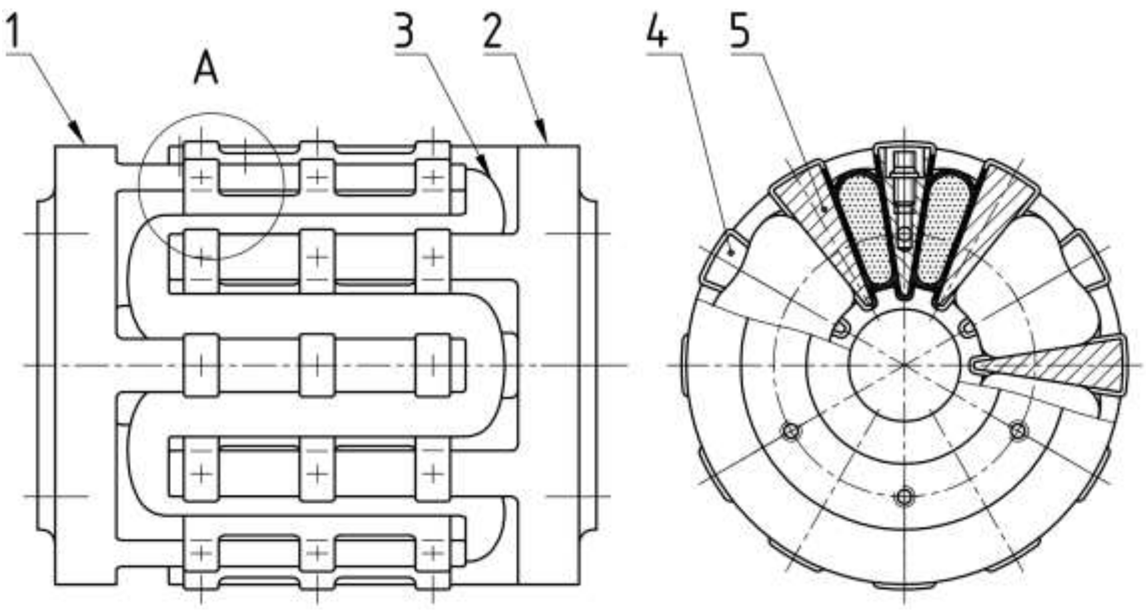

Fig. 1. Pneumatic flexible shaft coupling with hose flexible element [19]

Compressed gaseous medium is filled into the compression volume of the coupling through a pneumatic plug *(6)* which is secured in the opening of the support surface by an adjusting screw *(7)*. The sealing of the pneumatic plug is solved by sealing rings *(8)*. Compressed gaseous medium is filled into the coupling's compression volume via a filling valve *(9)*. The pneumatic hose element is fixed to the support surfaces with screws *(10)* and washers *(11)*.

Due to the relative rotation of the hubs from the neutral position, the compression volume of the hose flexible element is compressed, thereby ensuring a flexible torque transmission between the two hubs. The advantage of this hose flexible element is that the compression volume of the entire pneumatic coupling has to be sealed only at the location of the pneumatic plug and the filling valve ensuring the supply of the compressed gaseous medium. Furthermore, the design of the hose flexible element allows for quick and easy assembly and dismantling, if necessary.

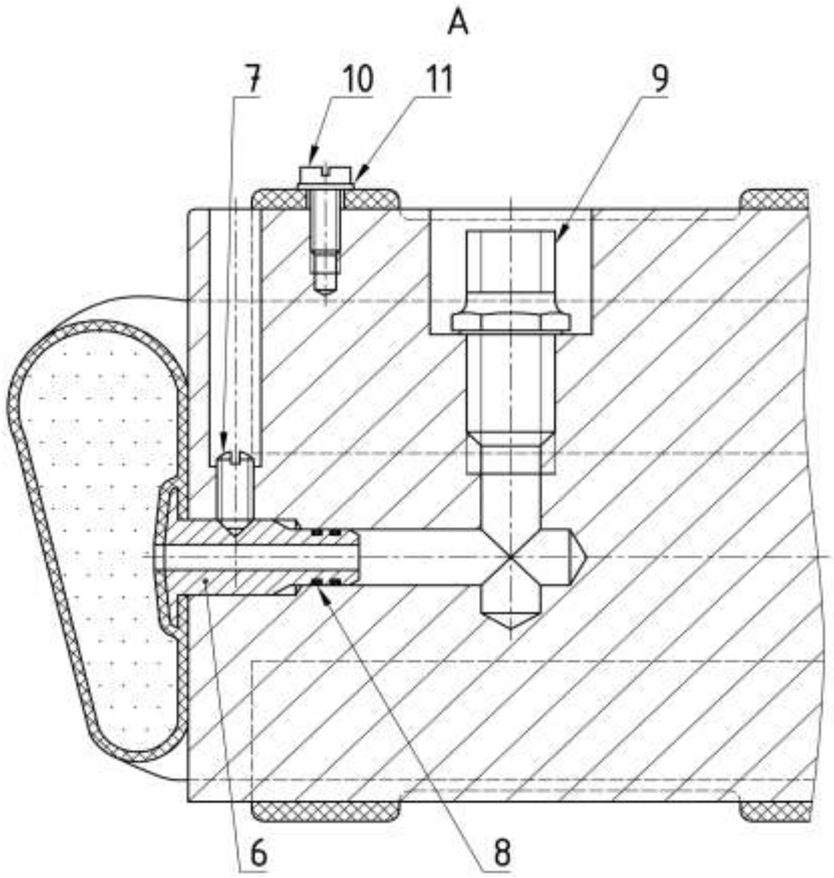

Fig. 2. Pneumatic flexible shaft coupling with hose flexible element – Detail of the pneumatic plug connection [19]

2.2. Drum pneumatic flexible shaft coupling

The proposed "Drum pneumatic flexible shaft coupling" (Fig. 3 Fig. **4**) is made up of the driving parts – a driving drum and a driven part. Between the driving and driven parts, the coupling's compression volume is situated. The driving drum is made up of a driving flange (1), segments (2) and a support disc (3). The driven part is made up of a driven disc body (5), a support disc (4), deformational rollers (6), which are rotatably mounted on pins (7), rotatably mounted small rollers (8) and rotatably mounted guiding small rollers (9).

Flexible torque transmission from the driving drum to the coupling's driven part is ensured by the coupling's compression volume, which is made up of flexible hollow bodies (10), which are, together with shaped rigid bodies (11), fastened to the segments (2) of the driving drum. Each shaped rigid body (11) is undismountably joined with a flexible hollow body (10). Through a valve (12), which is part of one of the distributing bodies (13), the gaseous medium can stream in the compression volume of the coupling. By the distributing bodies (13) and connecting hoses (14), the mutual interconnection of the flexible hollow bodies (10) is ensured. The distributing bodies (13) are fastened to the shaped rigid bodies (11). Intake ducts (15) are created in the shaped rigid bodies (11).

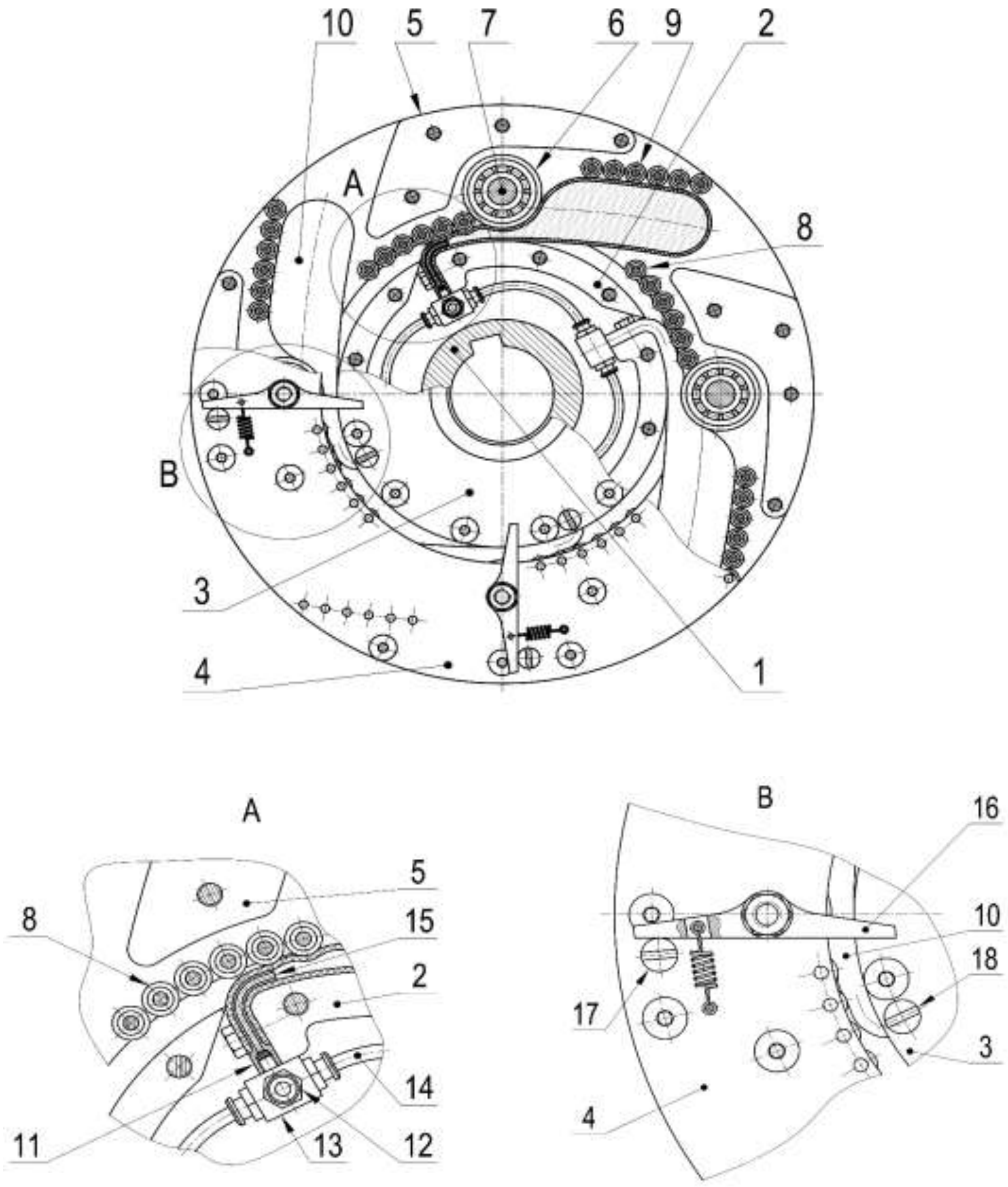

Fig. 3. Drum pneumatic flexible shaft coupling in a partially loaded state – main view with details

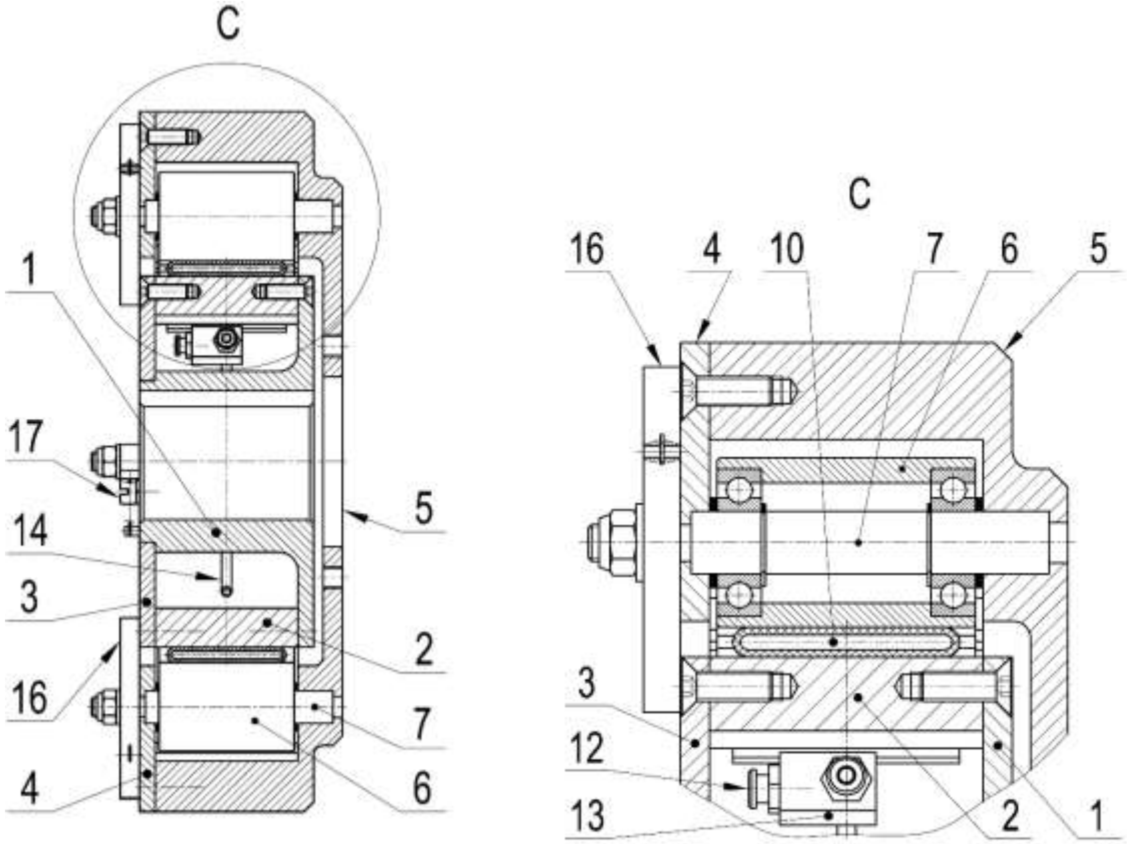

Fig. 4. Drum pneumatic flexible shaft coupling in a partially loaded state – side view with detail

If the flexible hollow bodies (10) of the unloaded shaft coupling are filled through the valve (12), distributing bodies (13), connecting hoses (14) and intake ducts (15) with gaseous medium (which suitable overpressure value was set in advance), sprung levers (16), which are rotatably mounted on pins (7), lean on stoppers (17) and (18). So, the driving drum acquires its basic position towards the driven part of the coupling. A load torque causes an angular deflection of the driving drum towards the driven part of the coupling (Fig. 3) and, consequently, a deformation of the hollow bodies (10) (coupling's pneumatic flexible elements). The deformation is caused by deformational rollers (6). The deformed pneumatic flexible elements (10) are wrapped around the driving drum. The gaseous medium compression in the compression volume is related to the load; therefore, a flexible transmission of a load torque occurs in the mechanical system.

The rotatably mounted small rollers (8) ensure that the deformed pneumatic flexible elements (10) stay in the deformed shape (

Fig. **5**) when the coupling is twisted. Rotatably mounted guiding small rollers (9) guide the pneumatic elements (10) during rotation of the coupling when a centrifugal force acts on the elements.

The coupling transmits a load torque flexibly in one direction only. The sprung levers (16) block the twisting of the coupling in the opposite direction. Because an over-twisting of the coupling is enabled at an overload, given that the coupling also acts as a safety coupling in mechanical systems.

We can see that the coupling is designed so that it is possible to achieve a high value of the maximum twist angle α (

Fig. **5**). This fact is fundamental to creating a high-flexible coupling.

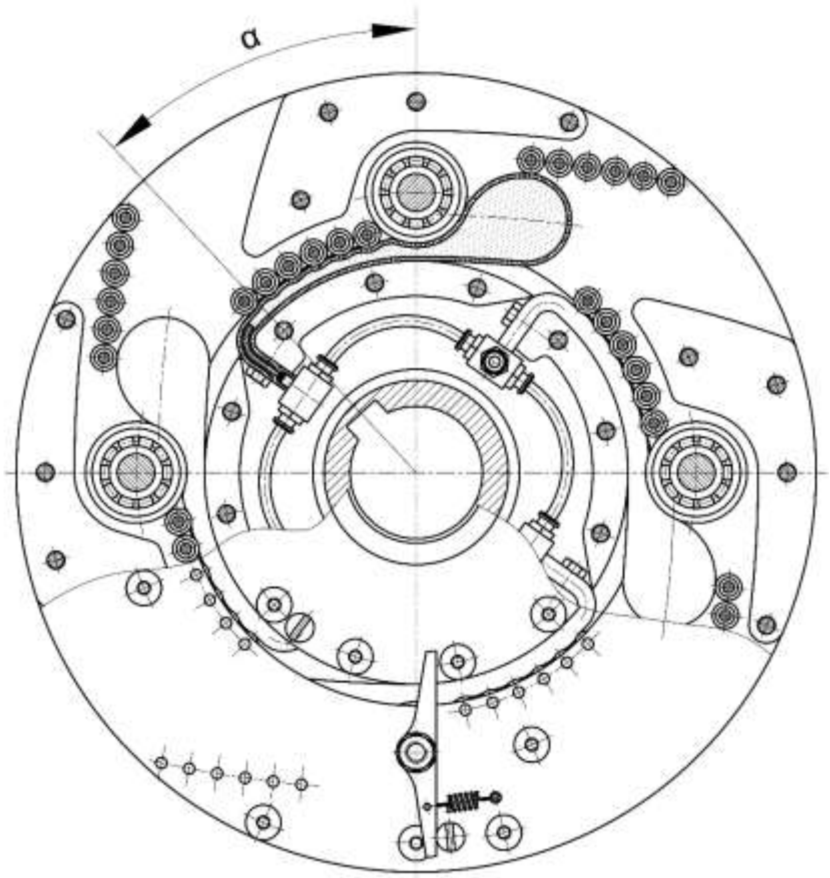

Fig. 5. The drum pneumatic flexible shaft coupling at maximum twist angle α (fully loaded state)

Flexible coupling with very low relative torsional stiffness k_0 can be considered a high-flexible coupling. The k_0 can be expressed as follows:

$$k_0 = \frac{k_{DN}}{M_N}\left[rad^{-1}\right]. \quad (1)$$

From equation (1), we can see that the k_0 is expressed as the ratio of the k_{DN} (nominal dynamic torsional stiffness of the coupling) to the M_N (nominal torque of the coupling), whereas the k_{DN} value is considered at M_N. The k_0 range of commonly used flexible couplings is $10 \div 30$ rad^{-1}, whereas the k_0 value of a high-flexible coupling is lower than 10 rad^{-1}.

If a high-flexible coupling (*coupling 2* in

Fig. **6**) is applied in a torsional oscillating mechanical system (TOMS), we can avoid the resonances in the operating speed range (OSR) of the system and move them to the low speed range far enough below idle speed n_V, for example [1, 5, 23]. It is possible to get over this low speed range at the start-up of the TOMS (

Fig. **6**). In the interference diagram of a mechanical system (

Fig. **6**), the torsional vibration excitation harmonic component order is marked as i .

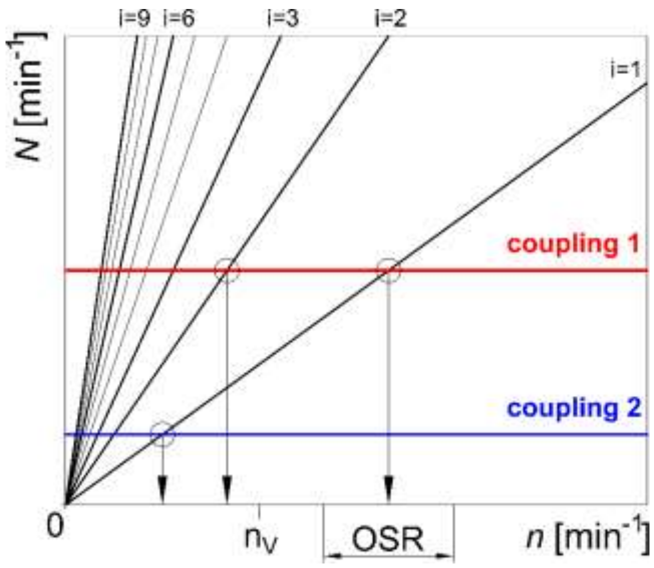

Fig. 6. General interference diagram

If the drum pneumatic coupling is applied in a mechanical drive system, flexible torque transmission is possible. Because its torsional stiffness can be changed, the tuning of TOMS is also possible in diverse operating conditions.

The primary goal of the design of drum pneumatic coupling is the creation of a high-flexible coupling.

3. CONCLUSION

“Pneumatic flexible shaft coupling with hose flexible element” and “Drum pneumatic flexible shaft coupling” can be used in mechanical drive systems. Due to their adjustable torsional stiffness, they provide flexible torque transfer and guarantee system adjustment under various operating modes.

The principal benefit of “Pneumatic flexible shaft coupling with hose flexible element” is that the compression volume of the entire coupling is sealed only at the location of the pneumatic plug and the filling valve ensuring the supply of compressed gaseous medium. Furthermore, the design of the hose flexible element allows for quick and easy assembly and dismantling, if necessary.

Considering the “Drum pneumatic flexible shaft coupling”, the purpose of the design is to achieve high flexibility, which corresponds to a very low relative torsional stiffness. A gaseous media in the compression volume of a pneumatic coupling does not suffer from ageing; therefore, the initial positive dynamic properties of a pneumatic coupling are well preserved. For example, nowadays, in the automotive industry, high-flexible couplings are commonly used as dual mass flywheels. Therefore, it is possible to assume that the combination of the benefits of a pneumatic coupling and a high-flexible coupling will result in the creation of usable machine parts.

We believe that the two pneumatic couplings described can raise the technological capability and reliability of the machine where they could be used for the abovementioned reasons.

Therefore, as part of the objectives of our subsequent grant project, we will build and test the prototypes of the specified pneumatic couplings.

Accordingly, we plan to focus our future study on the following issues:

- Using the ideas of the given patents to design and produce unique pneumatic coupling prototypes centred on transport machine drives,
- Experimentally determining the static and dynamic operational parameters of the couplings,
- Formulating the math-physical models of the couplings,
- Implementing the new couplings into experimental mechanical devices to test mainly continuous tuning for torsional dynamics. The couplings will be used for semi-active torsional vibration tuning operated by our advanced electronic control systems,
- Developing and formulating mathematical models of the examined experimental devices,
- Comparing the measured data with the results of the mathematical simulation,
- If necessary, further improve the mentioned mathematical and physical models.

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References

1. Dmitrieva Valeriya Valer'evna, Pavel Yevgen'evich Sizin, Aleksey Andreevich Sobyanin. 2021. „Application of the soft starter for the asynchronous motor of the belt conveyor”. *IOP Conference Series: Earth and Environmental Science* 942(1): 012003. DOI: 10.1088/1755-1315/942/1/012003.
2. Fang, Lijin, Yan Wang. 2017. „Stiffness Analysis of a Variable Stiffness Joint Using a Leaf Spring”. In: *10th International Conference on Intelligent Robotics and Applications, ICIRA 2017*: 225-237. Huazhong Univ Sci & Technol. 16-18 August 2017, Wuhan, China. DOI: 10.1007/978-3-319-65292-4_20.
3. Galdo María Isabel Lamas. 2021. „Marine Engines Performance and Emissions”. *Journal of Marine Science and Engineering* 9(3): 280. DOI: 10.3390/jmse9030280.
4. Gierz Łukasz, Łukasz Warguła, Mateusz Kukla, Krzysztof Koszela, Tomasz Szymon Zwiachel. 2020. „Computer aided modeling of wood chips transport by means of a belt conveyor with use of discrete element method”. *Applied Sciences* 10(24): 9091. DOI: 10.3390/app10249091.
5. Homišin Jaroslav. 2016. „Characteristics of pneumatic tuners of torsional oscillation as a result of patent activity”. *Acta Mechanica et Automatica* 10(4): 316-323. ISSN: 1898-4088. DOI: 10.1515/ama-2016-0050.
6. Hrabovský Leopold, Jiří Fries. 2021. „Transport Performance of a Steeply Situated Belt Conveyor”. *Energies* 14(23): 7984. DOI: 10.3390/ en14237984.
7. Chaban Andriy, Tomasz Perzyński, Andrzej Popenda, Radosław Figura, Vitaliy Levoniuk. 2022. „Mathematical Modeling of Transient Processes in the Susceptible Motion Transmission in a Ship Propulsion System Containing a Shaft Synchronous Generator”. *Energies* 15(9): 3266. DOI: 10.3390/en15093266.
8. Kinnunen Kalle, Sampo Laine, Tuomas Tiainen, Raine Viitala. 2022. „Method for Adjusting Torsional Natural Frequencies of Powertrains with Novel Coupling Design”. *Machines* 10(3): 162. DOI: 10.3390/machines10030162.

9. Kołodziej Paweł, Marek Boryga. 2014. „Frequency analysis of coupling with adjustable torsional flexibility". *Eksploatacja i Niezawodnosc – Maintenance and reliability* 16(2): 325-329. ISSN: 1507-2711.
10. Ledezma-Ramirez Diego Francisco, Neil Ferguson, Michael Brennan. 2011. „Shock isolation using an isolator with switchable stiffness". *Journal of Sound and Vibration* 330(5): 868-882. DOI: 10.1016/j.jsv.2010.09.016.
11. Lee Kang-Hyun, Jae-Eun Park, Young-Keun Kim. 2019. „Design of a stiffness variable flexible coupling using magnetorheological elastomer for torsional vibration reduction". *Journal of Intelligent Material Systems and Structures* 30(15): 2212-2221. DOI: 10.1177/1045389X19862378.
12. Li Xiangong, Yu Li, Yuzhi Zhang, Feng Liu, Yu Fang. 2020. „Fault Diagnosis of Belt Conveyor Based on Support Vector Machine and Grey Wolf Optimization". *Mathematical Problems in Engineering* 2020: 1367078. DOI: 10.1155/2020/1367078.
13. Li Zhongyi, Weihai Chen, Jianbin Zhang, Qihang Li, Jianhua Wang, Zaojun Fang, Guilin Yang. 2022. „A novel cable-driven antagonistic joint designed with variable stiffness mechanisms". *Mechanism and Machine Theory* 171: 104716. DOI: 10.1016/j.mechmachtheory.2021.104716.
14. Liptai Pavol, Marek Moravec, Ervin Lumnitzer, Marcela Gergeľová. 2017. „Proposal of the sound insulating measures for a vibrational sorter and verification of the measured effectiveness". *Advances in Science and Technology-Research Journal* 11(3): 196-203. ISSN: 2299-8624. DOI: 10.12913/22998624/76068.
15. Lubin Thierry, Alexandre Colle. 2020 „Simulation analysis and experimental evaluation of the transient behaviour of a reluctance magnetic coupling". *IET Electric Power Applications* 14(3): 391-397. DOI: 10.1049/iet-epa.2019.0678.
16. Maláková, Silvia. 2017. „Analysis of gear wheel body influence on gearing stiffness". *Acta Mechanica Slovaca* 21(3): 34-39. ISSN: 1335-2393.
17. Puškár Michal, Melichar Kopas. 2018. „System based on thermal control of the HCCI technology developed for reduction of the vehicle NOX emissions in order to fulfil the future standard Euro 7". *Science of the Total Environment* 643: 674-680. ISSN: 0048-9697. DOI: 10.1016/j.scitotenv.2018.06.082.
18. Syam Thaer, Ahmed Hegazi, Asan Muthalif, Yousif Badri. 2021. „Magnetorheological elastomer-based variable stiffness flexible coupling for vibration isolation". *Transactions of the Canadian Society for Mechanical Engineering* 46(1): 1-10. DOI: 10.1139/tcsme-2021-0007.
19. SK 288800 B6. *Pneumatická pružná hriadeľová spojka s hadicovým pružným elementom.* Technická univerzita v Košiciach, Košice, SK. 02.06.2021. [In Slovak: SK 288800 B6. *Pneumatic Flexible Shaft Coupling with Hose Flexible Element.* Technical University of Košice, Košice, SK. 02.06.2021.]
20. SK 288875 B6. *Pneumatická pružná hriadeľová tangenciálna spojka s osovo deformovanými elementmi.* Technická univerzita v Košiciach, Košice, SK. 14.07.2021. [In Slovak: SK 288875 B6. *Tangential pneumatic flexible shaft coupling with axially deformed flexible elements.* Technical University of Košice, Košice, SK. 17.07.2021.]
21. SK 288878 B6. *Pneumatická pružná hriadeľová bubnová spojka.* Technická univerzita v Košiciach, Košice, SK. 09.06.2021. [In Slovak: SK 288878 B6. *Drum pneumatic flexible shaft coupling.* Technical University of Košice, Košice, SK. 09.06.2021.]
22. SK 288879 B6, *Pneumatická pružná reťazcová hriadeľová spojka.* Technická univerzita v Košiciach, Košice, SK. 09.06.2021. [In Slovak: SK 288879 B6. *Tangential pneumatic*

flexible shaft coupling with serial arranged flexible elements. Technical University of Košice, Košice, SK. 09.06.2021.]

23. Sturm Martin, Lubomír Pešík. 2017. „Determination of a Vibrating Bowl Feeder Dynamic Model and Mechanical Parameters". *Acta Mechanica et Automatica* 11(3): 243-246. ISSN: 1898-4088. DOI: 10.1515/ama-2017-0038.
24. Sudano, Angelo, Dino Accoto, Loredana Zollo, Eugenio Guglielmelli. 2013. „Design, development and scaling analysis of a variable stiffness magnetic torsion spring". *International Journal of Advanced Robotic Systems* 10(10): 372. DOI: 10.5772/57300.
25. Szántó Attila, János Kiss, Tamás Mankovits, Gusztáv Áron Szíki. 2021. „ Dynamic Test Measurements and Simulation on a Series Wound DC Motor". *Applied Sciences* 11(10): 4542. DOI: 10.3390/app11104542.
26. Vanderborght Bram et al. 2013 „Variable impedance actuators: A review". *Robotics and Autonomous Systems* 61(12): 1601-1614. DOI: 10.1016/j.robot.2013.06.009.
27. Vinogradov B. V., Khristenko A. V., 2016. „Flexible couplings with rubber-cord shells in dual pinion mill drives". *Naukovyi visnyk Natsionalnoho Hirnychoho Universytetu* 2016(1): 42-46. ISSN: 2071-2227.
28. Xu Shichang, Gang Cheng, Yusong Pang, Zujin Jin, Bin Kang. 2021. „Identifying and Characterizing Conveyor Belt Longitudinal Rip by 3D Point Cloud Processing". *Sensors* 21(19): 6650. DOI: 10.3390/s21196650.
29. Zhu Hongxi, Ulrike Thomas. 2019. „A new design of a variable stiffness joint". In: *IEEE/ASME International Conference on Advanced Intelligent Mechatronics*: 223-228. IEEE, IES, ASME, Hong Kong, China. DOI: 10.1109/AIM.2019.8868648.

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