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# FUNCTIONAL PROTOTYPE OF PNEUMATIC FLEXIBLE SHAFT COUPLING WITH MECHANICAL CONSTANT TWIST ANGLE REGULATOR

**Summary.** Pneumatic couplings with constant twist angle control are suitable for tuning mechanical systems where the load torque is proportional to the square of shaft speed. This is typical mostly for drives of ships used in water transportation. In given conditions, the coupling maintains the ratio of natural torsional frequency to rotational speed of the mechanical system at a constant value. With proper setting of constant twist angle, resonance with harmonic excitation components in a specific range of operating speed can be avoided.

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The goal of this article is to present a design of a newly built prototype of coupling with mechanical constant twist angle regulator. During further research, it is planned to be tested in laboratory conditions.

**Keywords:** pneumatic shaft coupling, constant twist angle control, mechanical regulator, pneumatic spring, variable stiffness, fan characteristics, semi-active vibroisolation

## 1. INTRODUCTION

Pneumatic shaft couplings, as elements of transport machine drives, are a relatively new devices suitable for providing semi-active torsional vibration control. The torsional stiffness of these couplings can be changed during operation by adjusting the air pressure in their pneumatic elements. Pneumatic elements have been commonly used for tuning rectilinear vibration for a long time [10]. In the area of torsional vibration, several tuning methods have been elaborated for utilization of pneumatic shaft couplings [4]. One of them, the constant twist angle control method, or sometimes called also as autoregulation, is designed especially for mechanical systems where the load torque is proportional to the square of shaft rotational speed, which we can encounter in marine and fan drives. With proper setting of constant twist angle, resonance with harmonic excitation components in specific range of operating speed can be avoided [4]. As this article focuses on description of coupling prototype design we will not go into details any further, an interested reader can find detailed description of constant twist angle control in works [4, 5, 8, 9]. A common solution to problems associated with torsional oscillation is a selection of proper torsional flexible coupling. A coupling with suitable torsional stiffness ensures that the natural torsional frequency of the mechanical system is far enough away from the excitation frequency of any load torque harmonic component. But as marine drives are working usually in a wide range of operating speeds, avoiding resonance in full range of operating speed can be problematic [3, 11, 13]. One solution is to use highly flexible couplings with low torsional stiffness, ensuring that the natural frequency is always lower than the excitation frequencies; thus, the system is running in supercritical area [4]. Another solution is to use flexible couplings with non-linear progressive load characteristics, where the torsional stiffness is dependent on load torque. Proper non-linear load characteristics can provide avoidance of resonance in a wide range of speed [3, 4]. On the contrary, improper non-linear load characteristic causes that system remains in resonance area in wider range of operating speed [11]. Another problem with classic flexible couplings using rubber flexible elements is that their torsional stiffness depends on temperature, loading frequency, number of completed work cycles and age of rubber [7]. So then during operation the mechanical system can be out of tune. Because of that, some authors recommend to use high safety factors for such flexible shaft couplings [3]. Pneumatic flexible shaft coupling's properties are much less sensitive to such influences [4]. We also want to mention that there are flexible couplings with adjustable stiffness based on other than pneumatic principles too [6, 12].

The main goal of this article is to present a prototype of pneumatic flexible shaft coupling with mechanical constant twist angle regulator produced for the purpose of subsequent laboratory testing.

## 2. DESCRIPTION OF PNEUMATIC COUPLING PROTOTYPE

The presented coupling was designed with focus to make a system with as simple as possible with a fully mechanical constant twist angle regulator without any electronic components. We also wanted to use, if possible, only standard pneumatic elements available on the market. In one of previously published works [5] the authors presented an electronic constant twist angle control system.

In Fig. 1 the main view and in Fig. 2 the partial side view of coupling are shown.

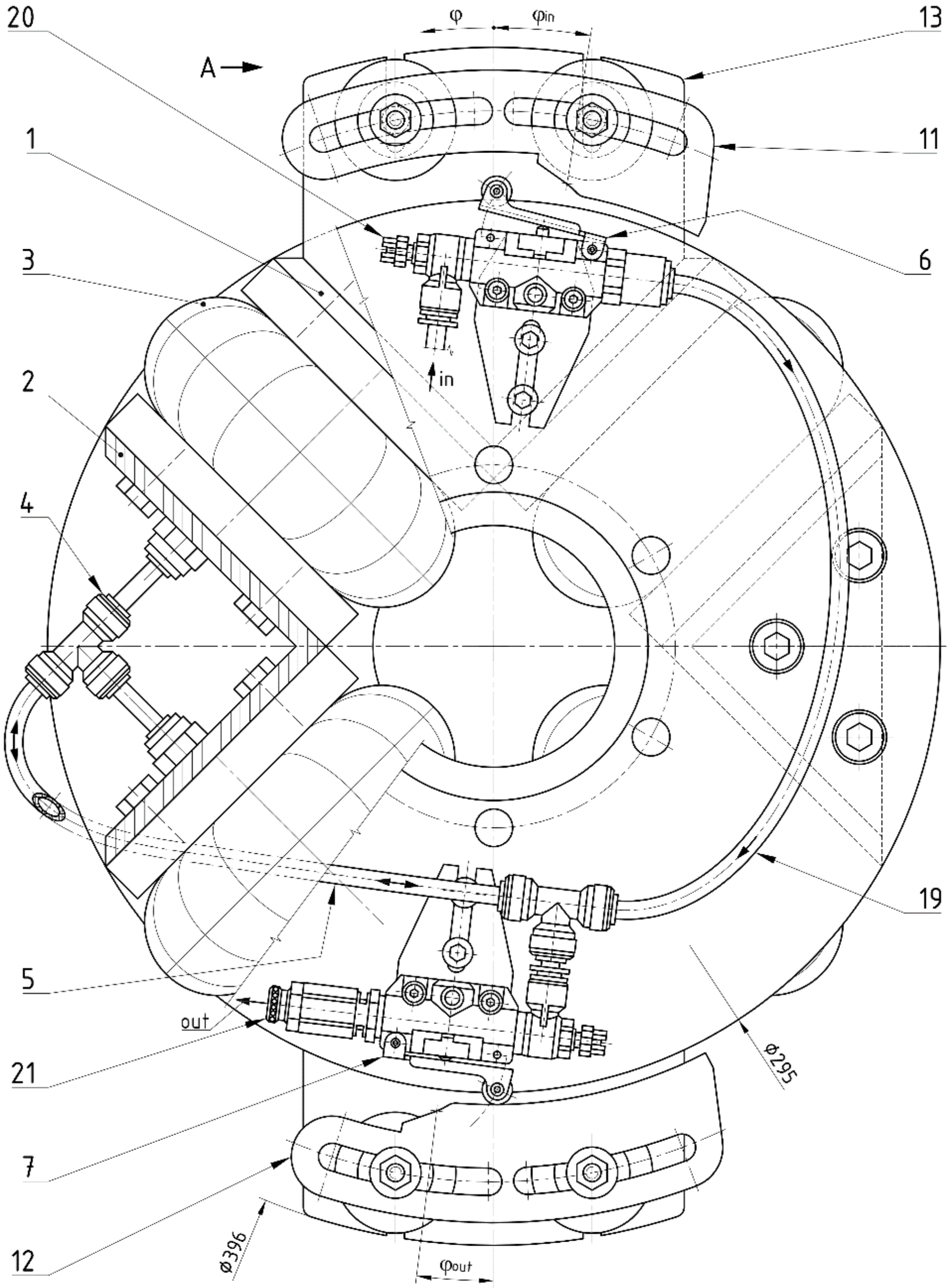

Fig. 1. Pneumatic flexible shaft coupling with mechanical constant twist angle regulator

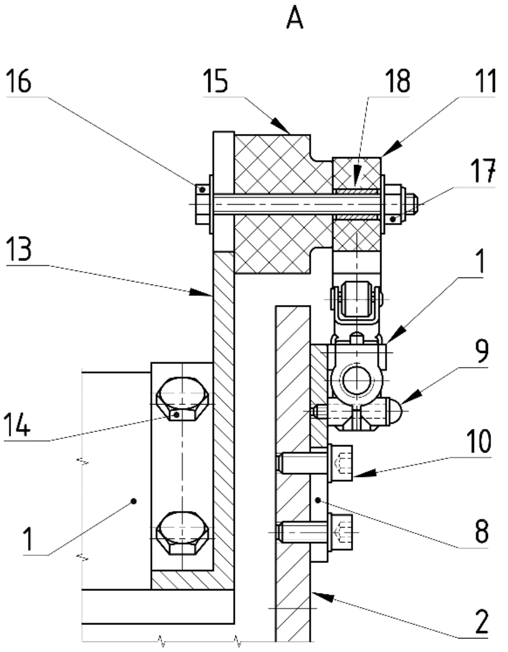

Fig. 2. Pneumatic flexible shaft coupling with mechanical constant twist angle regulator, detail of cam and roller valve connection

At first, we will describe only the mechanical composition of coupling the assembly and the function of the regulator will be described afterwards.

The coupling consists of a driving body which main part is a driving disc *(1)* and a driven body which main part is a driven disc *(2)*, the driving and driven bodies are connected with pneumatic springs *(3)* ensuring the possibility to accommodate radial, angular and axial misalignments of connected shafts and, last but not least, flexible torque transmission. The internal volumes of the springs are interconnected via pneumatic tubes and fittings. The filling and discharge of compressed air into the coupling's compression space are realized with Push-In T/connector *(4)* and a pneumatic tube *(5)*. In figure (Fig. 1), the direction of air flow in the pneumatic tubes is shown by arrows. The filling and discharging of compressed air into the coupling are controlled by a system of roller lever valves mounted on the driven disc and cams located on the driving disc.

The inlet roller valve *(6)* and outlet roller valve *(7)* are the part of the driven body. They are located on holding plates *(8)* attached to driven disc *(2)*. The roller valves are fixed to the holding plates with screws *(9)*. The holding plates themselves are attached to the driven body through straight slots with screws *(10)*, this ensures the possibility to adjust their radial position to the coupling's axis.

The inlet cam *(11)* and outlet cam *(12)*, controlling the respective inlet and outlet roller valves, are part of the driving body. For manufacturing the cams, the 3D printing method has been used which is a very modern approach in the field of rapid prototyping [1, 3]. The cams are mounted on plates *(13)* attached to the driving disc with screws *(14)*. The proper axial position of the cams is ensured by spacer rings *(15)*.

The connection of the cams to the plates is realized with bolts *(16)*, nuts *(17)*, the previously mentioned spacer rings and cylindrical cases *(18)*. The radial position of the cams, similarly to the roller valves, can be properly adjusted as the bolts are located in straight slots of plates. The tangential position of the cams, is adjustable too, as they are mounted through circular arc slots. The tangential position of the cams determines the values of inlet angle $\varphi_{in}$ and outlet angle $\varphi_{out}$ when the corresponding valves are just opened (or closed).

The compressed air is fed into the coupling trough inlet (in Fig. 1 marked with an arrow labeled as *in*). The inlet and outlet valve are connected with a pneumatic tube *(19)*. Both the inlet and outlet valve have an adjustable throttle valve *(20)* on the input that we can adjust the airflow rate if needed. The discharge of compressed air from the coupling is solved with an adjustable safety valve *(21)*, so the operating pressure cannot drop under the selected minimum value.

The pneumatic coupling, as shown in Fig. 1, is in a neutral position at zero twist angle. For the presented prototype design, we consider only one direction of rotation. The direction of twisting of the driving disc (cams) to driven discs (roller valves) is marked with arrow labelled as $\varphi$. By disassembling the cams and flipping them around, the opposite direction of twisting can be obtained.

A photo of a manufactured coupling prototype is shown in Fig. 3.

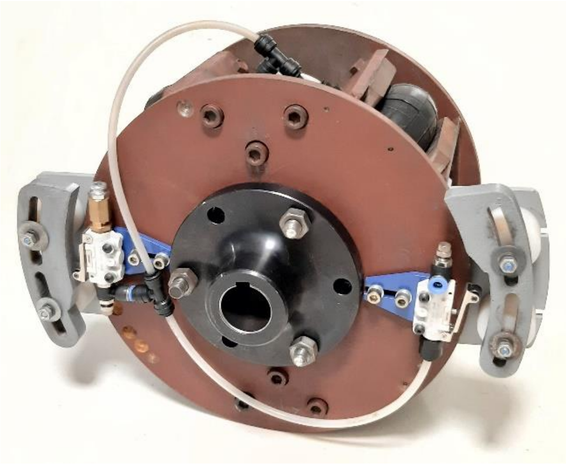

Fig. 3. Photo of a manufactured pneumatic coupling prototype

The ideal function of coupling when loaded with slowly increasing torque $T$ from zero to maximum and then decreasing it back to zero can be described according to illustrative figure Fig. 4.a). This cycle is shown with a wide continuous line. In neutral position at zero twist angle $\varphi = 0$, when the coupling is unloaded, the outlet roller valve is opened as the outlet roller valve is activated with outlet cam and the inlet valve is closed (see Fig. 1 too). The compressed air in the coupling can flow out until it reaches the minimum value $p_{min}$ set by the safety valve. After we start increasing the load torque, the twist angle starts to increase. Now the coupling works on the load characteristics corresponding to minimum pressure $p_{min}$. Load characteristics at different pressures ($p_{min} < p_1 \dots < p_3 < p_{max}$) are shown in Fig. 4.a). The pressure in coupling remains on minimum value until the twist angle reaches the outlet angle $\varphi_{out}$, then the outlet valve is closed. Now both valves are closed, and no air flows into or out the coupling. After reaching the inlet angle $\varphi_{in}$, the inlet roller valve starts releasing compressed air from the inlet tube to the coupling and tries to hold the twist angle on this value ($\varphi_{in}$) until the load torque reaches the value corresponding to maximum pressure $p_{max}$. From this point, the load characteristics of coupling are corresponding to load characteristics at maximum pressure. When decreasing the load torque, at first, the coupling works at maximum pressure. Then, after reaching the inlet angle, both valves are closed until we reach the outlet angle. Now the control mechanism tries to maintain the twist angle at this value ($\varphi_{out}$) until we reach the minimum pressure, and after this, the coupling works at minimum pressure. The inlet angle and outlet angle can be independently set to desired values by changing the tangential positions of the respective cam. If, in the described process, we insert an in-between cycle (illustrated with semi-bold dashed lines) when increasing the torque at inlet angle we reach pressure $p_3$ so that now we slowly decrease the torque, the pressure remains on value $p_3$ until we reach the outlet angle the control system opens the outlet valve and tries to maintain this deflection. Let say, now we decrease the torque until pressure $p_1$ is reached, and again we start slowly increase the torque. Between the inlet and outlet angle when both valves are closed, the coupling works at characteristics with pressure $p_1$. We can say that the range between the inlet and outlet angles is the deadband of the regulator, where the valves remain closed and the coupling works at constant pressure.

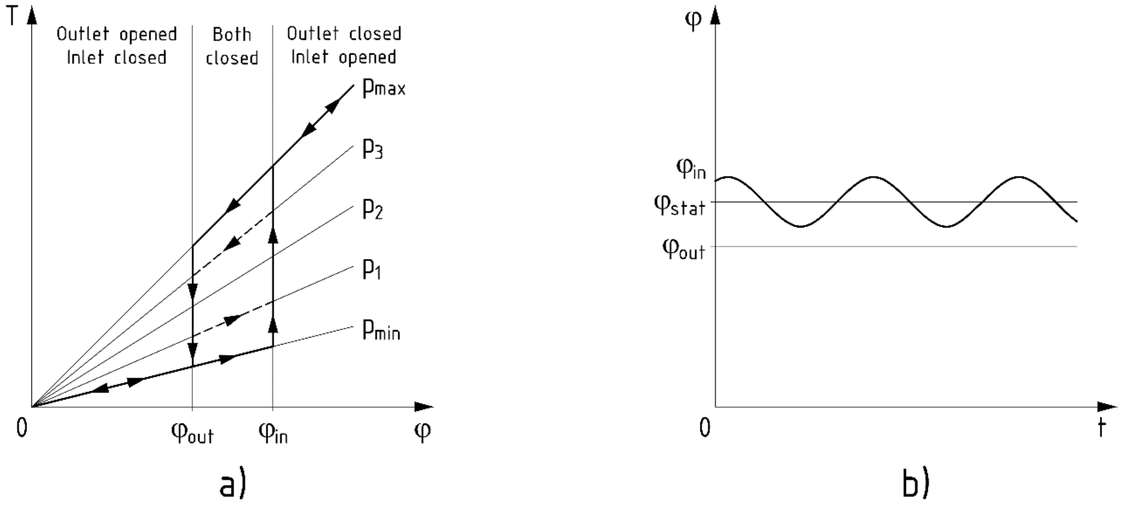

Fig. 4. Illustration of the mechanical constant twist angle control system working principle a) under static loading, b) under dynamic loading in steady state

The working principle of the coupling loaded with periodical load torque (consisting of static and dynamic component) is shown in Fig. 4.b). The graph in Fig. 4.b) shows a periodical course of twist angle $\varphi$ in time $t$. The control mechanism adjusted the pressure so that after reaching a steady-state condition, the static twist angle $\varphi_{stat}$ corresponding to the static load torque lies between the inlet and outlet angles. Properly set inlet angle $\varphi_{in}$ and outlet angle $\varphi_{out}$ must allow the coupling to oscillate within the deadband of the regulator without activating the valves. After changing the operating speed (static torque), the regulator automatically adjusts the twist angle back inside the deadband.

## 3. CONCLUSIONS

The greatest advantage of the presented coupling is that the fully mechanical regulator has a very simple design using only standard pneumatic components. Also, no electrical supply or expensive electronic control is needed. That is why we think that the presented coupling will be a useful contribution in the field of drives used in water transport.

From the presented information, we can also deduce some possible issues or let us say interesting ideas for future research:

- At first, the desired constant (static) twist angle cannot be set directly as with an electronic control system [5]. We only select the deadband in which the static twist angle should lie. This should be quite narrow, to have as small as possible difference of static twist angle from ideal value. But it cannot be too narrow because the twist angle time course in a steady state must fit into the deadband. Therefore, these angles must be properly determined to ensure proper function in the full operation speed range. In the future, a more sophisticated mechanical regulator capable of working with the mean value of twist angle could be developed.
- Another possible issue is that between the neutral position and the outlet angle, the coupling works at minimum pressure. This can be resolved by using more complicated cams or adjustable cam systems which provide preliminary inflation of the coupling at a specific angle smaller than the outlet angle.

In the follow-up research, the authors plan to test the coupling under static and dynamic loading to compare assumptions presented here with the actual measured results and subsequently develop a method for the reliable determination of the inlet and outlet angle based both on preliminary torsional analysis and experiments.

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- KEGA 044TUKE-4/2024: Application of virtual and augmented reality into education in order to innovate mechanical engineering study programs.

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