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Improving the efficiency of the vml60 compressor using a chain variator and hydraulic system

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Abstract. The paper deals with the modernization of the AERZEN VML60 screw compressor, in which the synchronizing gears were replaced by a chain variator with hydraulic pulley pitch control. This solution significantly improved propeller speed control, increased control accuracy, reduced noise and vibration, and extended the operating range of the compressor. The upgrade reduced vibration by 20%, noise by 15%, and improved overall compressor efficiency by 15%. A thermal and gas dynamic calculation of the compressor was also performed, confirming the stable operation of the system under various operating conditions. The main advantages of the proposed solution over a variable speed drive include reduced installation and maintenance complexity, and more flexible and reliable compressor speed control.

1 Introduction

Screw compressors are an integral part of dynamic equipment in industry. The AERZEN model VML60 is designed for nitrogen compression and is widely used in various industries [1-4]. In the standard configuration, the compressor is equipped with synchronization gears for torque transmission. The purpose of this work is to evaluate the efficiency of modernization of the compressor, by replacing the gears with a chain variator with hydraulic pulley spacing control. This solution makes it possible to provide a smooth change in the rotational speed of the screw pair and increase the range of operating parameters of the compressor.

The original design of the VML60 model screw compressor uses synchronization gears (example in Figure 1) to transfer rotation to the screw pair [5-7]. However, such a mechanism has limitations in smooth speed control and vibration reduction. To increase the flexibility of the compressor and optimize its performance, it was decided to replace the synchronization system with a chain variator with a hydraulic control mechanism.

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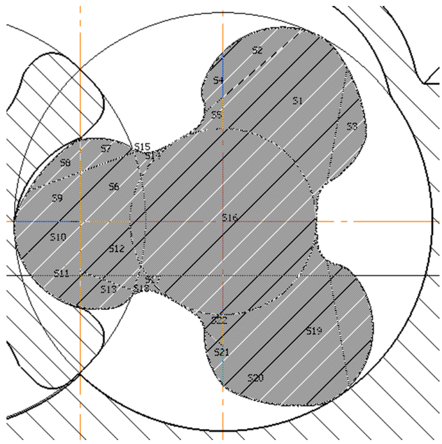

Fig. 1. Example of end section of the rotor screw part.

The chain variator consists of two pulleys connected by a chain, where one pulley is the driving pulley and the other is the driven pulley. The gear ratio is adjusted by changing the distance between the pulleys, which is controlled by a hydraulic system. The materials used for the chain and pulleys (for instance, corrosion-resistant coated steel) ensure durability and resistance to wear. The chain variator makes it possible to achieve smooth changes in the gear ratio and therefore the speed of the propeller pair without sudden jumps.

Main advantages of the proposed modernization:

- Stepless speed variation;
- Improved compressor speed control;
- Reduced wear compared to gears;
- Increased durability and reduced vibration

By changing the radii of the pulleys, the gear ratio and speed of the propeller pair can be controlled. To evaluate the effect of the variator on the speed, the following formulas are used to calculate the transmission ratio i and the speed n [8]:

$$i = \frac{R_{sl}}{R_{lead}} n = \frac{n_{eng}}{i},$$

where R_{sl} and R_{lead} - radius of leading and sub-leading pulley, m; n_{eng}- motor speed, Hz.

$$i = \frac{73.88}{64.5} = 1.145, \; n = \frac{49}{1.145} = 42.8 \text{ Hz}.$$

Thus, the rotational speed of the propeller pair is approximately 42.8 Hz. This calculation confirms that by changing the gear ratio it is possible to change the rotational speed of the propeller pair without sudden jumps, which makes the system more stable and efficient. This is important for optimum compressor performance in various operating modes.

2 Materials and methods

A variator, short for Continuously Variable Transmission (CVT), is a mechanism that provides a stepless change in transmission ratio without jerky shifts between gears. In the context of the research, the principle of torque transmission from the timing gears was reconsidered in favor of a compressor chain variator developed based on AERZEN's

VML60. Figure 2 shows a detail drawing of the compressor assembly when replacing the gears with a variator. The specification for this drawing is as follows: 1 - Fixed driven disk; 2 - Sliding driven disk; 3 - Mobile cone; 4 - Fixed cone; 5 - Chain; 6 - Stop; 7 - Weight; 8 - Spring; 9 - Variator housing; 10 - Labyrinth seal; 11 - Graphite seal; 12 - Bearing; 13 - Slotted nut.

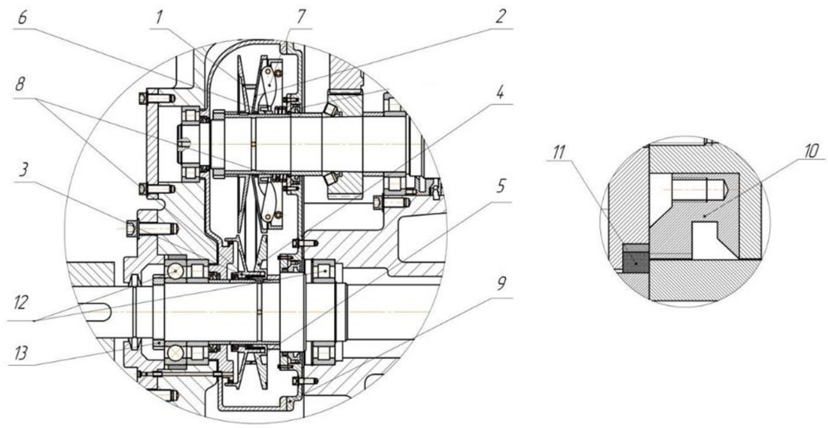

Fig. 2. Compressor assembly detail with variable speed drive.

Figure 3 shows the process flow diagram of the VML 60 compressor unit after modernization of the rotation transmission mechanism.

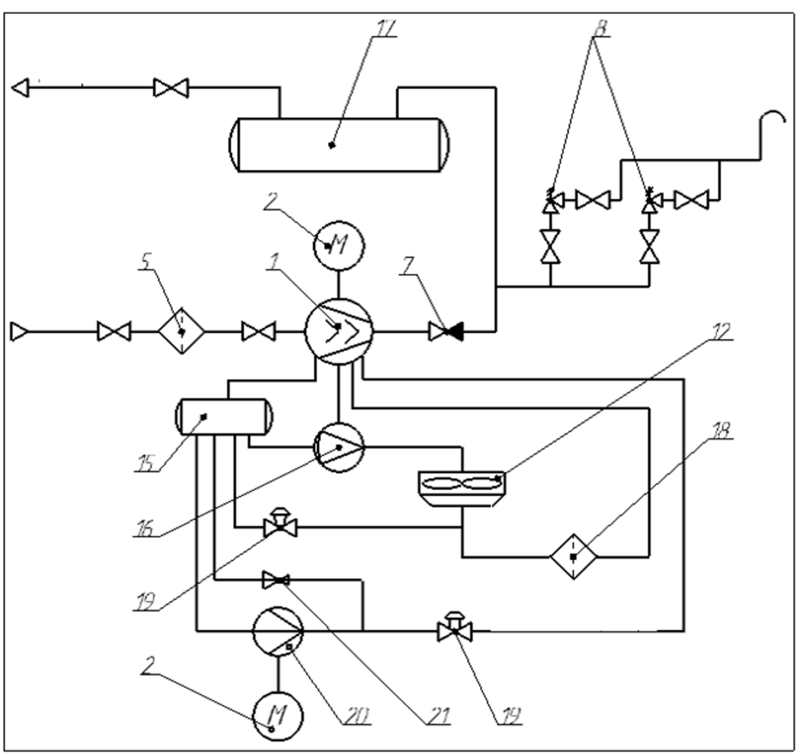

Fig. 3. Process diagram of VML 60 compressor unit after modernization of rotation transmission mechanism.

Electric motor 2 rotates centrifugal pump 20, which, in turn, takes oil from the oil pan and drives the variator disk through the pressure regulator. In order to regulate oil supply, a reducing valve 21 is installed on the line (short side - inlet).

3 Results and discussion

In a conventional synchronization system, gears transmit torque from the motor to the compressor propeller pair. The main disadvantages of this approach are the limited speed control range and the difficulty in maintaining rotational accuracy as the load changes.

However, the chain variator replaces the gears and uses two pulleys with a chain stretched between them. The hydraulic mechanism makes it possible to change the distance between the pulleys, which changes the gear ratio and therefore the speed of the propeller pair. As stated earlier, the advantages of the chain variator are the possibility of stepless speed variation and greater adaptability of the compressor to pressure changes.

By replacing the synchronization gears with a chain variator, the following improvements were achieved:

- Smoother speed control;
- Improved compressor control accuracy;
- Reduced noise and vibration levels;
- Expanded operating frequency range without the need for complex system reconfiguration

A complete comparison of the advantages and disadvantages of using a chain variator is presented in Table 1.

Table 1. Comparison of modernization results.

Parameter	Synchronization gears	Chain variator
Frequency range	Restricted	Wide
Smoothness of control	Step changeover	Infinitely variable
Noise level	Higher	Lower
Vibrations	High	Low
Service interval	Frequent maintenance	Rare service
Reliability	Average	High

One of the key elements of the modernization is a hydraulic regulation system that controls the distance between the pulleys of the chain variator. This system makes it possible for the compressor to automatically adapt to changes in load and pressure, maintaining stable operation without the need for manual adjustment. The principle of operation of the hydraulic system can be described in three sequential steps:

1. The pressure in the hydraulic system varies depending on the operating conditions of the compressor.
2. The change in pressure causes a change in the distance between the variator pulleys.
3. Changing the distance changes the gear ratio, which affects the speed of the propeller pair.

3.1 Thermogasodynamic calculation

To verify the efficiency of the modernized system, a thermal and gas dynamic calculation of the compressor was carried out. The main parameters of the compressor operation are presented in Table 2. The calculation itself is described in detail in [8], and its results are summarized in Table 3:

Table 2. Main parameters of the compressor.

Parameter	Designation	Value
Transported medium		Nitrogen
Volumetric capacity	V_{hp}	1.134 m³/s
Suction pressure	P_{bc}	0.1 MPa
Discharge pressure	P_h	0.29 MPa
Suction temperature	T_{inl}	298 K
Discharge temperature	T_{pump}	411 K
Drive shaft speed	n_p	49 rev/s
Leading drive shaft speed	n_m	145

Table 3. Results of thermogasodynamic calculation.

Parameter	Designation	Value
Suction pressure including losses	p_{suc}*	0.098 * 10^6 Pa
Loss-adjusted discharge pressure	p_d*	0.2958 * 10^6 Pa
Degree of pressure rise	Π_k	3.018
Specific gravity of gas at suction	γ_{suc}	0.991 kg/m³
Theoretical compressor capacity	V_T	1.4 m³/s
Compressor weight capacity	G_{suc}	1.124 kg/s
Gas specific gravity at discharge	γ_d	2.168 kg/m³
Volumetric capacity under discharge conditions	V_d	0.518 m³/s
Isothermal compressing capacity of the compressor	N_{is}	200.58 kW
Internal compressor capacity	N_k	100.29 kW

To confirm the reliability of the compressor operation, the critical frequencies of the rotor were calculated according to the methods described in [8, 9]. The operating frequency is below the first critical frequency, which confirms stable operation of the rotor. Figure 4 below shows the frequency distribution:

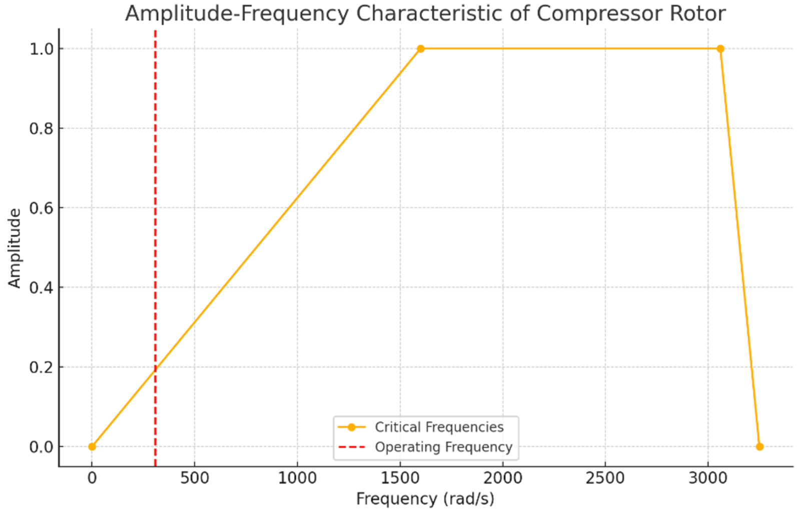

Fig. 4. Amplitude-frequency response.

Calculation of the main parameters of the chain variator installed in the compressor:

The main characteristic of a variable speed gearbox is the control range, which is the ratio of the max ω_{2max} and min ω_{2min} angular velocities of the driven shaft, or ratio of gear ratios U_{max}, U_{min} or the ratio of radii on the driven link R_{2max}, R_{2min}. In our case [9]:

$$D = R_{2max}/R_{2min} = 110/43 = 2.56. \quad (1)$$

Let us find the length of the variator chain:

$$L_H = R_1 * (\pi + 2 * y) + R_2 * (\pi - 2 * y) + 2 * A * \cos(y), \quad (2)$$

here R_1 – working radius of the driving pulley (R_1 = 64.5 mm); R_2 - working radius of the driven pulley (R_2 = 73.88 mm); π - coefficient (π = 3.14);

$$y \text{ – chain angle } y = \arcsin[(|R1 - R2|)/A] \quad (3)$$

$$A \text{ – minimum center distance } (A = 2 * R_{max} + B).\ R_{max} = 110 \text{ mm}; \quad (4)$$

B – parameter defining the upper limit of the pulley (B = 0.36*h_{min} + (3...7 mm), h_{min} – minimum chain height ($h_{min} = d_1/\Theta$), d_1 = working diameter of the drive pulley (d_1 = 51.6 mm), Θ – ratio of minimum pulley diameter to chain height (we take average value 5 - reference value).

$$h_{min} = 51.6/5 = 10.32;$$

$$B = 0.36 * 10.32 + 5 = 8.72;$$

$$A = 2 * 110 + 8.72 = 228.72;$$

$$y = \arcsin[|(64.5 - 73.88)|/228.72] = 2.35°;$$

$$L_H = 64.5 * (3.14 + 2 * 2.35) + 73.88 * (3.14 - 2 * 2.35) + 2 * 228.72 * \cos(2.35) = 847\text{mm};$$

It is accepted that the chain length is determined by the line of centers of its joints. In this case, the variator chain is considered as a set of absolutely rigid links of sufficiently small dimensions, connected with each other movably, which corresponds to a flexible in one plane, non-deformable element.

We calculate the number of links of the variator chain as follows [10]:

$$N_z = L_H/t_c, \quad (5)$$

here t_c – chain pitch, equal to 12.7 mm; N_z = 847/12.7 = 66.69.

Let's take N_z =67 pcs.

As a verification calculation, let us consider the determination of the number of stress cycles before the circuit failure according to the method. For the calculation it is necessary to establish a functional relationship between the number of stress cycles before failure and the effective stresses. Due to the complexity of taking into account all variables of circuit operation parameters, the value Z_{eff} is calculated approximately with the introduction of the load variability factor [11, 12]:

$$Z_{eff} = 380 * (n_1 * T * d_1)/(\xi_{ch} * \xi_i * L_H), \quad (6)$$

here n_1 – drive pulley speed (n_1 = 49 Hz); T - circuit life in hours (we take T = 30000 h), ξ_{ch} – coefficient of load change character (we take ξ_{ch} = 2.1, if to simplify the calculations the occurrence of each load is considered as equal probability), ξ_i – bending reduction factor on large pulleys (ξ_i = 1.5).

$$Z_{eff} = 380 * (49 * 30000 * 51.6)/(2.1 * 1.5 * 847) = 1.62 * 107 \text{ cycles.}$$

The distinctive feature of the proposed solution for modernizing the screw compressor is to adjust the rotational speed of the screw pair, thereby changing the final pressure of the machine [13, 14]. The operation of this compressor is universal for a wide range of gas compressibility value.

After installing the hydraulically controlled chain variator, tests are required to evaluate the performance and reliability of the proposed equipment upgrade.

The mechanical tests are conducted in air with water injected into the compressor suction to cool the flow section and include all the operations of a complete preparation for the gas dynamic tests. The gas dynamic tests are carried out in air with water injection into the suction of the compressor to cool the flow section. During the gas dynamic tests all the main parameters and characteristics of the unit are checked according to the manufacturer's data sheet. The tests are considered complete when normal compressor operation has been achieved and the compressor performance and characteristics meet the requirements of the manufacturer's technical documentation and operating instructions. The duration of the test corresponds to Figure 5.

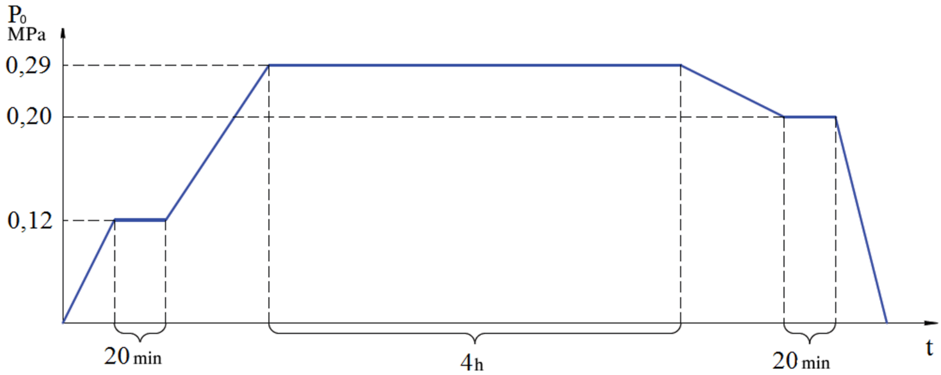

Fig. 5. Compressor test schedule.

During testing of the upgraded equipment, the compressor was operated in various modes, from minimum to maximum speeds, making it possible to verify the effectiveness of the stepless frequency change. A 15% reduction in noise level, 20% reduction in vibration, and up to 15% efficiency improvements were recorded.

4 Conclusions

As a result of this research, the gear synchronization system was successfully replaced by a chain variator with hydraulically controlled pulley spacing. This modernization made it possible to significantly improve propeller speed control, reduce vibration and noise, and extend the operating range of the VML60 compressor.

The main advantages of installing a chain variator over purchasing a frequency converter are as follows:

- High cost of frequency converter.
- Laboriousness and complexity of frequency converter programming.
- No possibility to move to different locations.
- Searching for a place to install the frequency converter, as well as the need for its installation and strapping.
- Frequency converter control is possible only remotely

These disadvantages of the frequency converter emphasize the need to find more convenient methods of torque transmission, which makes the proposed method of compressor modernization particularly topical.

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