MEASURING OF ROTARY AIR MOTORS CHARACTERISTICS

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In the article the construction of an experimental device for measuring the characteristics of small rotary air motors is described. Further a measurement methodology and measured data processing is explained. At the end of the article using of the measured characteristics for mathematical modelling is presented.

KEYWORDS

air motor, measurement, mathematical model

1 INTRODUCTION

Rotary pneumatic motors can be divided into several categories by motor design. In this case we can divide the rotary pneumatic motors in following basic categories: vane, axial and radial piston, gear and turbine design. The objects of our research were mainly small radial piston motors with power up to 500 W and nominal speed up to 1000 min^{-1}. An example of design of these motors is shown in Fig. 1. These motors are used in many branches of industry (food industry, chemical and pharmaceutical industry, paper and textile production etc.) where they are used for mixing, lifting, as a conveyor drive and many other applications.

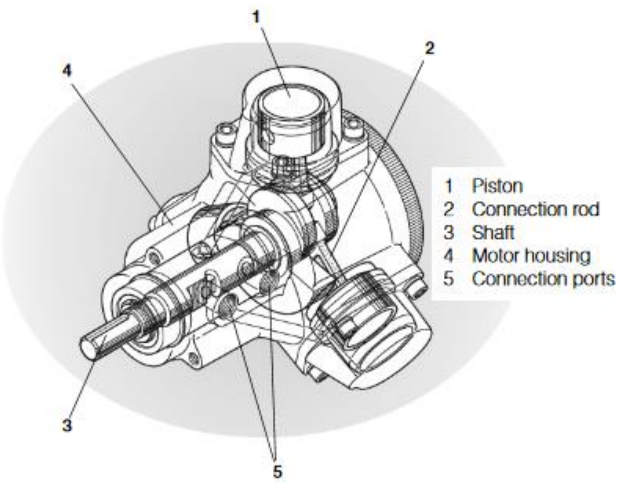


Figure 1. Radial piston air motor [Parker 2016]

During the rotary air motors characteristics measuring it is necessary to determine the following parameters: an inlet pressure and eventually an outlet pressure, a motor torque, a rotation speed and an air consumption. The processing the measured data is described below. The result of measurements is the rotary motor characteristic, which is mainly a torque and power dependence on a rotation speed, Fig. 2. This characteristic may be complemented by an air consumption and an efficiency, this is then called a complex characteristic of the rotary motor.

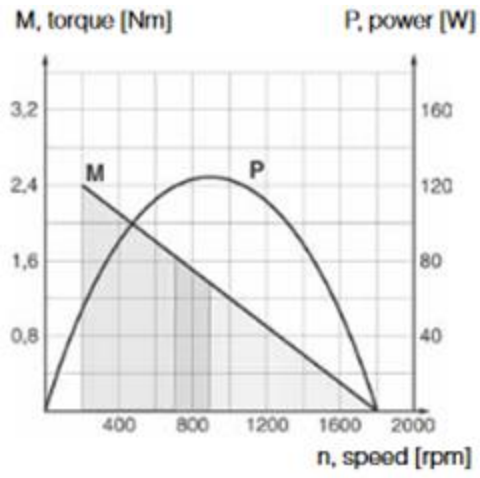
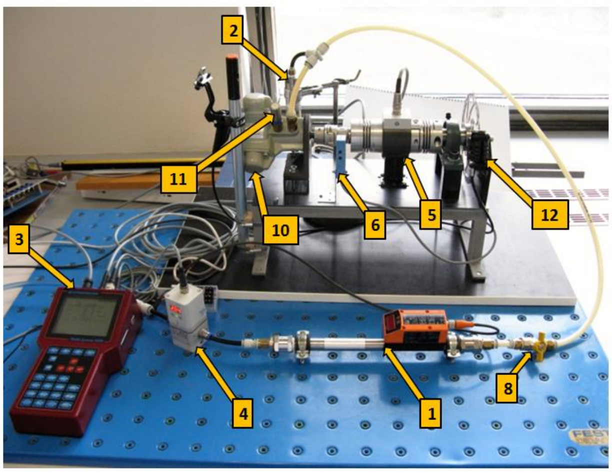


Figure 2. Torque and power characteristics of motor [Parker 2016]

2 TEST EQUIPMENT, MEASUREMENT METHODOLOGY AND RESULTS

During the measurement of rotary motors it is necessary to change the load of the output shaft continuously. This can be achieved by some types of brakes as a electrodynamometer, hydrostatic or hydrodynamic brake and also friction brake. For the motors with power up to 500 W the friction brake is quite sufficient. Therefore bicycle break has been chosen. Specifically type-ZEE BR-M640 from Shimano in combination with disc SM-RT 66 with a diameter of 160 mm was chosen. According to the producer the brake was tested for rotation speed up to 1350 min^{-1} and guaranteed braking power is 800 W.

To measure a torque the sensor T22 / 50 from HBM with a measuring range of +/- 50 Nm was chosen. Furthermore, the pressure sensor PR 15 with a measuring range of -1 to 6 bar, the speed sensor DS 03 and the recording device M5050 ware chosen, all made by company Hydrotechnik. The flow measurement was realized by the sensor SD 6000 from IFM electronic with measuring range 4-1250 dm^3·min^{-1} (ANR). A frame to which were mounted all the necessary parts was also designed and built. The device is shown in Fig. 3, a circuit diagram is in Fig. 4.



1 - flowmeter, 2 - pressure sensor, 3 - recording device, 4 - reduction valve, 5 - torque sensor, 6 - speed sensor, 7 - FRL unit, 8, 9 - ball valve, 10 - pneumatic rotary motor, 11 - silencer, 12 - disc brake

Figure 3. Test equipment

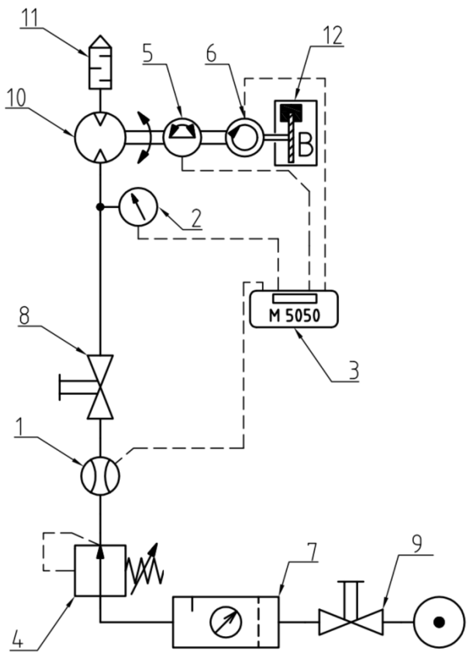


Figure 4. Diagram of the test equipment

The basic requirement for the measurement is to keep a constant pressure at the inlet of the motor. Therefore, the pressure regulation was realized by proportional pressure valve VPPE-3-1-1 / 8-10-010-E1 made by Festo. By selecting the control voltage the measurements ware then carried out at a pressure level of 3, 4, 5 and 6 bar.

At each pressure level the torque was increased using the friction brake and after each change a record of all measured variables (pressure - p, torque - M, speed - n, flow rate - Q_N) was made for 3 seconds with sampling period of 0.1 second. From the measured values the mean values were calculated. These were directly plotted into the graph, or were used to calculate the power P, the overall efficiency η and specific consumption. An equation for the calculation of individual parameters is shown in equations 1 to 3.

The motor mechanical power on the output shaft can be calculated from the torque and speed

$$P = \frac{2 \cdot \pi \cdot n \cdot M}{60} \qquad [W] \qquad (1)$$

where M is torque [Nm] and n is speed [min^{-1}].

The motor overall efficiency is the ratio of mechanical output power to pneumatic input power. Due to the volume flow rate dependence on the pressure, it is necessary to recalculate the flow rate to the level of working pressure.

$$\eta = \frac{P}{p \cdot Q_p} \qquad (2)$$

where P is power [W], p working pressure [Pa] and Q_p is volume flow rate of compressed air [$m^3 \cdot s^{-1}$].

Specific air consumption is air consumption related to output power. In this case, it is necessary to use flow rate recalculated to normal atmospheric conditions (ANR – atmospheric normal reference).

$$\overline{m} = \frac{Q_N}{P} \qquad \left[dm^3 \cdot min^{-1} (ANR) \cdot W^{-1}\right] \qquad (3)$$

where P is power [W] and Q_N is air consumption [$dm^3 \cdot min^{-1}$ (ANR)].

Fig. 5 shows the torque characteristic of the measured motor. The torque significantly decreases from a maximum value at zero speed (starting torque). The value of the starting torque is depending on the size of the pressure. At the inlet pressure of 3 to 6 bar the starting torque varies from 2 to 3.8 Nm. From the course of the power in Fig. 6 it is obvious that the maximum power is achieved in the range of revolutions from 1100 to 1200 min^{-1}.

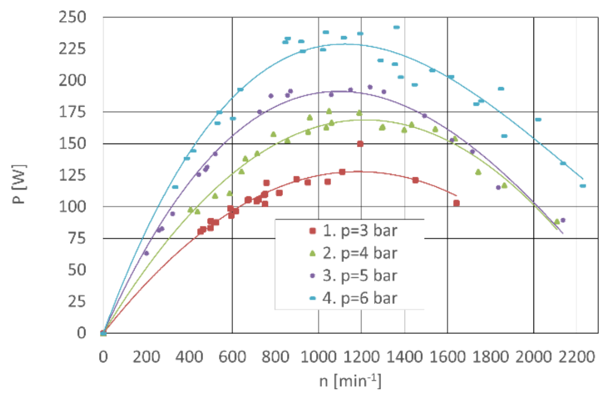


Figure 6. Power characteristic

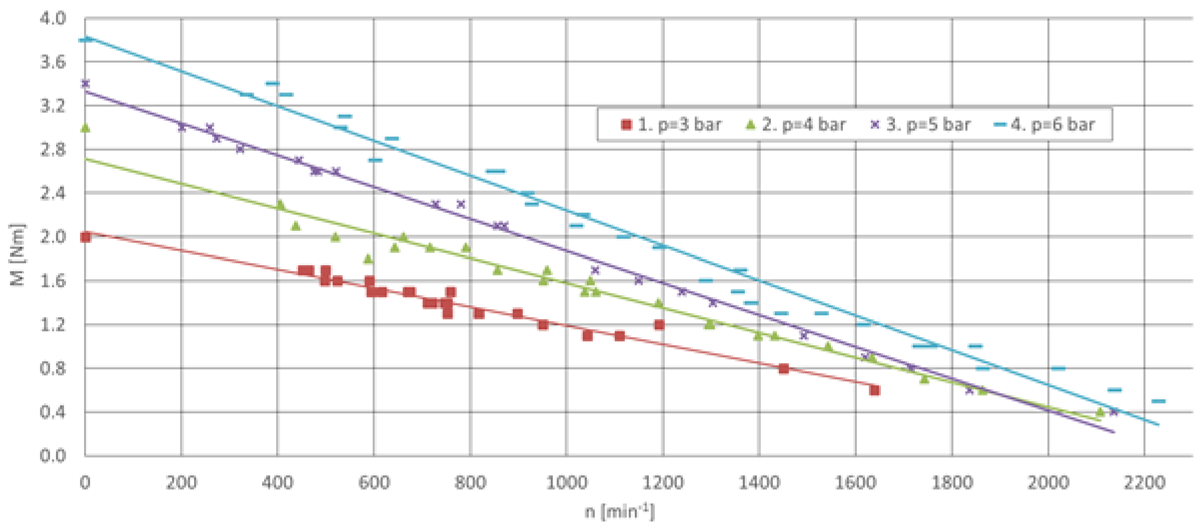


Figure 5 . Torque characteristic

Fig. 7 shows the course of overall efficiency of the measured motor. The maximum efficiency for different pressure values is in the range of 48-55%. These values are achieved in the speed range from 500 to 750 min^{-1}.

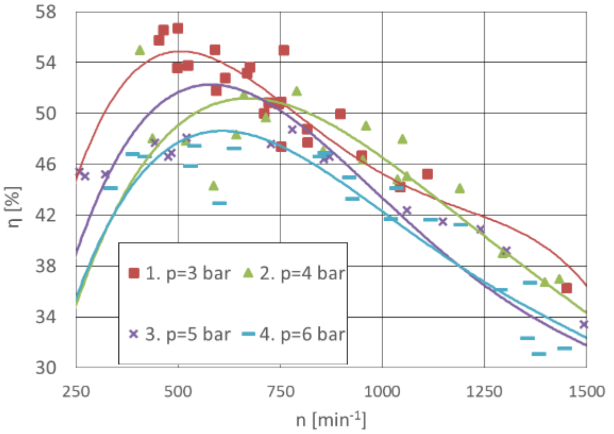


Figure 7. Overall motor efficiency

From the above it is clear that the area of maximum efficiency is shifted in comparison with the area of maximum power to the lower speed. Generally, the optimum working range of the motor is located between maximum efficiency and maximum power. The maker states that the optimum range is from 700 to 900 min^{-1}, which corresponds with the measured values.

As mentioned above, the torque decreases depending on the speed. Theoretically, the torque does not depend on the speed, but the problem is the pressure. With increasing speeds, the work space of the motor is not filled enough, see Fig. 8. This leads to a reduction in the pressure and hence the torque. Into the calculation of parameters then enters so called filling efficiency. Fig. 9 shows course of measured motor filling efficiency.

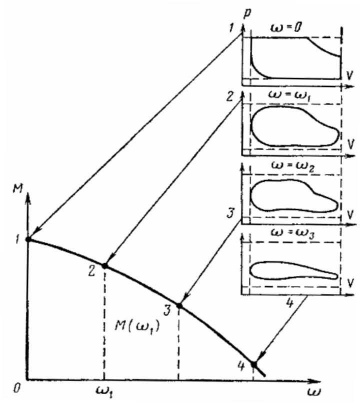


Figure 8. Influence of speed to filling of work space

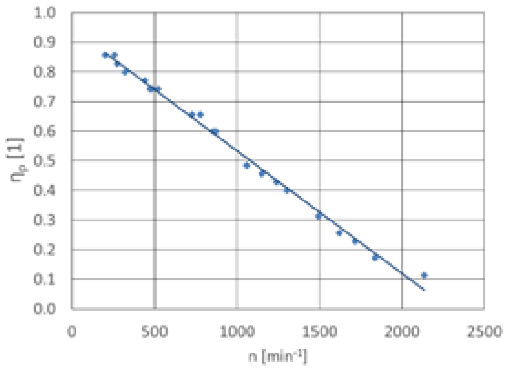


Figure 9. Filling efficiency of measured motor

If we know displacement of the motor, the real value of torque can be calculated from equation 4 and the power from equation 5, more see [Řeháček 2016], [Dvořák 2017]

$$M = \frac{1}{2\pi} \cdot V_g \cdot p_{it} \cdot \eta_p \cdot \eta_m \qquad (4)$$

$$P_S = V_g \cdot n \cdot p_{it} \cdot \eta_p \cdot \eta_m \qquad (5)$$

where V_g is displacement of motor [m^3], p_{it} theoretical indicated pressure [Pa], n speed [min^{-1}], η_p filling efficiency and η_m is mechanical efficiency.

3 MODELING OF A PNEUMATIC SYSTEM WITH A ROTARY MOTOR

In addition to the measurements we carried out verification of the possibility of mathematical modeling of pneumatic systems with the rotary motor. The Matlab-Simulink Simscape was used for modeling. Simscape contains models of the basic pneumatic components including the rotary air motor model "Rotary Pneumatic Piston Chamber". Into this model, it is necessary to specify Displacement (volume per unit angle), Initial angle, Dead volume and Chamber orientation (direction of rotation). The model consists of three following equations [Matlab]. The continuity equation is

$$G = \frac{V_0 + D \cdot \theta}{R \cdot T} \cdot \left(\frac{dp}{dt} - \frac{p}{T} \cdot \frac{dT}{dt} \right) + \frac{D}{R \cdot T} \cdot p \cdot \frac{d\theta}{dt} \qquad (6)$$

where G is mass flow rate at input port [kg· s^{-1}], V_0 initial chamber volume [m^3], D piston displacement (volume per unit angle) [m^3·rad^{-1}], Θ piston angle [rad], p absolute pressure in the chamber [Pa], R specific gas constant [J·kg^{-1}·K^{-1}], T absolute gas temperature [K] and t is time [s].

The energy equation is

$$q = \frac{c_v}{R} \cdot (V_0 + D \cdot \theta) \cdot \frac{dp}{dt} + \frac{c_p \cdot D}{R} \cdot p \cdot \frac{d\theta}{dt} - q_w \qquad (7)$$

where q is heat flow due to gas inflow in the chamber [J·s^{-1}], q_w heat flow through the chamber walls [J·s^{-1}], c_v – specific heat at constant volume [J·kg^{-1}.K^{-1}], c_p – specific heat at constant pressure [J·kg^{-1}.K^{-1}].

The torque equation is

$$\tau = p \cdot D \qquad (8)$$

Mechanical, flow neither filling efficiency is not included into the mathematical model of the motor. It causes that the simulation results are not good. The torque at zero speed corresponds to the real motor but the torque characteristics depending on the speed do not decrease linearly. Larger differences are then in power characteristics. Maximum calculated power is several times greater than the real power and it is also achieved at higher speeds. With the above model we have not achieved real results.

The manual for Simulink (Help) contains another model, "Pneumatic motor". There is chosen a completely different approach of motor parameters definition. Into the model it is necessary to enter vector of rotational speeds, vector of torque values, vector of volumetric flow rates and pressure differential at which the torque and flow data were measured. By this way the characteristics of the motor can be very precisely defined. The disadvantage is in obtaining these values by measurement.

An example of measured and calculated values is in Fig. 10. In this case, at the time of 1.4 s the valve has opened. At the time of approximately 2 s the steady speeds was achieved. During the acceleration the torque has risen to 1.9 Nm due to the inertia of the rotating parts, after the acceleration the torque reached the level of 1.1 Nm.
Subsequently, the accuracy of the simulation was validated in the case where during the rotation the load was increased, for example from 0.7 Nm to 0.95 Nm. This change in torque has resulted in the decrease of speed from 1245 min^{-1} to 980 min^{-1}, see Fig. 11.

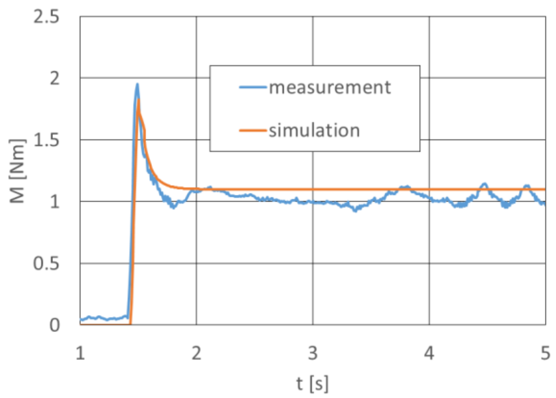


Figure 10. Torque during motor acceleration

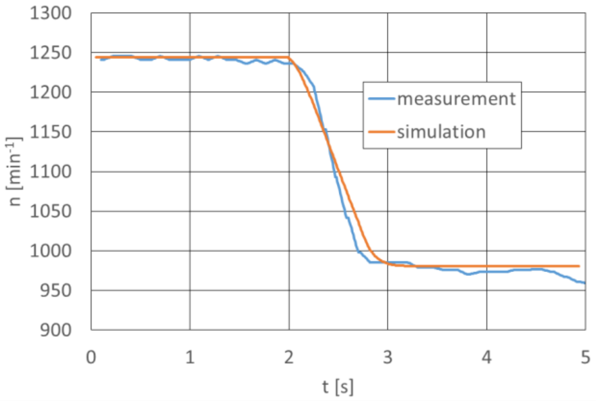


Figure 11. Speed during load increase

4 CONCLUSIONS

One of the disadvantages of pneumatic rotary motors is the change in speed depending on load variation. It is therefore advisable to know the characteristics of the motor when choosing a motor for various applications. The characteristics are listed in the motor's catalogs. By the help of software, such as Matlab-Simulink, based on the measured characteristics it is possible to predict the behaviour of the system, for example, when changing the torque, moment of inertia, etc. It has been mentioned in the article that the model "Rotary Pneumatic Piston Chamber" does not deliver so good results. If this basic model would supplemented mainly with filling efficiency, better results can be achieved. In the future, we will continue to address this issue.

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