1. Ondřej ŠIMON[1,2], 2. Miroslav POPELA[1,2]

Department of Radio Electronics, Brno University of Technology (1)
Department of Communication Technologies, Electronic Warfare and Radiolocation, University of Defence (2)
ORCID: 1. 0000-0002-6837-5461; 2. 0000-0002-5979-009X

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Precision control of stepper motors for tunable waveguide shunt

***Abstract**. This article deals with the issue of precision control of stepper motors. Stepper motors are used in many applications due to their properties in terms of accuracy and speed control. In this paper, an application is proposed for the precise positioning of a tunable waveguide shunt. A special type of stepper motor called linear actuator is used for this application.*

Streszczenie.** Artykuł dotyczy zagadnienia precyzyjnego sterowania silnikami krokowymi. Silniki krokowe są używane w wielu aplikacjach ze względu na ich właściwości w zakresie dokładności i kontroli prędkości. W niniejszym artykule zaproponowano aplikację do precyzyjnego pozycjonowania przestrajalnego bocznika falowodu. Do tego zastosowania używany jest specjalny typ silnika krokowego zwany siłownikiem liniowym..* (Precyzyjne sterowanie silnikami krokowymi do przestrajalnego bocznika falowodu***)

Keywords: Stepper Motor, Waveguide Shunt, Linear actuator
Słowa kluczowe: silnik krokowy, falowóc, bocznik.

Introduction

Stepper motors are currently used in a wide range of applications such as 3D printers, car dashboard displays, CNC machines, etc. This is due to their ability to provide very precise positioning and speed control [1]. The motion of a stepper motor operates on the principle of converting a digital signal to the position of a rotor. Its motion would therefore appear as discontinuous at very low speeds. Due to the step-by-step motion, these motors can be used for very precise position adjustment (e.g., in 3D printers, the height of each layer adjusted by a stepper motor is 0.15 mm or less). The speed control of the motor and the precise adjustment of its position is essential in many everyday applications, be it the already mentioned 3D printers or robotic arms in automated factories. In terms of speed control, stepper motors have high accuracy compared to other types of motors (DC, synchronous, asynchronous). Its control is realized only by a pulse signal, where the frequency and number of pulses determine the speed and the angle of rotation [2].

Stepper motors have several advantages over other types of motors. They are brushless, which greatly increases their durability, since brushes are one of the most damage-prone components in conventional motors. Furthermore, these motors are load independent which means that the stepper motor will spin at a constant speed regardless of the load until the maximum torque for the given motor is exceeded. Another advantage is the Open Loop Positioning, which means that the position of the motor shaft is always known even without any feedback. This is due to the fact that the motor moves in predefined increments or steps. It is also worth mentioning the holding torque that keeps the shaft in a stationary position [3].

This paper is focused on the precision control of stepper motors, specifically with a practical application to the precision control of waveguide shunt in microwave applications. Stepper motors are used here to move the piston that sets the position of the waveguide shunt, or rather a special type of stepper motor called a linear actuator is used for this application. This paper is divided as follows. This introduction is followed by second part, in which the basic concepts of stepper motor theory and waveguide shunt are discussed. Following part describes the selected components for the proposed application. Following this, next section deals with the setup of the measurement station and the design of the waveguide shunt control application. In the last part summary and conclusion are made.

Basic theory of stepper motors and waveguide shunts

In this section, the basic concepts of stepper motors and waveguide shunts necessary for understanding the addressed problem will be described.

First the stepper motors will be discussed. When selecting a stepper motor for the required application, various parameters need to be considered. Some of the most important ones are the step size and torque characteristics of the motor.

Step size is one of the most important parameters when selecting the type of stepper motor. This parameter is based on the accuracy requirements for the final application. It is determined by the number of teeth on the rotor, the number of stator poles and the number of stator phases (equation 1). Generally, the number of steps per revolution is given. The current standard is 200 steps/revolution (equivalent to a step of 1.8°) for hybrid stepper motors (the most commonly used type). This resolution can be further fine-tuned in a software manner using so-called microstepping. Stepper motors, used for linear motion, are called linear actuators, where this type of motor is adjusted for a rotating shaft. These motors have a high resolution even with basic step size (more in following sections), due to the conversion of rotary motion to sliding motion, where the gearing subtlety is based on the rotary shaft gearing [3, 4].

$$\theta_m = 360 / (mzp) \tag{1}$$

Equation 1 gives the motor step size θ_m in degrees, where m is the number of stator phases, z is the number of rotor teeth, and p is the number of rotor poles.

Torque characteristics are another important parameter sin the selection of stepper motors. Since the motor speed is independent of the load until the maximum torque is exceeded, it is important to select a motor with sufficient characteristics for the given application. In order to avoid so-called step loss (exceeding the maximum torque), it is necessary to select motors with sufficient margin in these parameters. This usually results in the selection of stepper motors that significantly exceed the requirements of the application. This is inefficient from many aspects (motor size, wasted power and heat) [3, 5, 6].

A stepper motor has several types of torques [3]:

- Holding torque – The torque required to rotate the shaft while the windings are powered.
- Detent torque – The torque required to rotate the shaft without powering the windings.
- Pull-in torque – The starting torque that a stepper motor is able to provide to the shaft without loss of step.
- Pull-out torque – The maximum starting torque available to the motor shaft without loss of step for cases where there is no change in rotational sense.

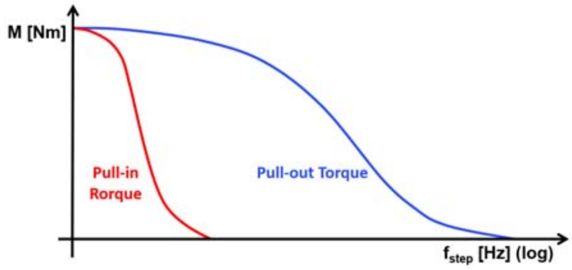

Fig.1. Torque characteristics of stepper motor

Stepper motors can be basically divided into variable reluctance stepper motors, permanent magnet stepper motors and hybrid stepper motors. In this article only the hybrid type will be discussed, as it is currently the most widely used type and is in principle a combination of the previous two types. This type of motor can be seen in Fig. 2. On the rotor shaft made of non-magnetic material are pressed two pole extensions between which an axially polarized permanent magnet is placed. The rotor pole attachments have grooves around their circumference forming the rotor teeth. Around each stator pole there are two windings to change the polarity of the magnetic field depending on the direction of the current. The change in the magnetic field (variation in the switching of the windings) causes the rotation of the rotor. The principle of motion is based on a variable reluctance motor. By adding an axially polarized permanent magnet, the torque characteristics of the stepper motor are increased. This combines the advantages of the previous two motor types (fine step, high torque) [1, 3, 4].

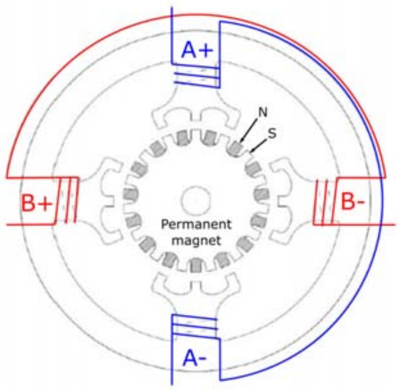

Fig.2. Hybrid stepper motor

In the proposed application, a bipolar (four-lead) stepper motor control is used. The other type is unipolar (five-lead), but this will not be discussed in detail in this paper. The advantage of bipolar control is that the current flows through the entire winding (only half of the winding in unipolar control is used) and thus more torque is achieved. However, this results in more complex control circuits, due to the need for bidirectional current flow (reversal of current polarity). However, in the present application and other possible applications (see Section V), the requirement for sufficient torque is crucial. Nowadays, affordable integrated control circuits for bipolar motors are available, thus removing the main disadvantage associated with more complex control circuits. The principle of bipolar control is shown in Fig. 3 [1, 3, 4].

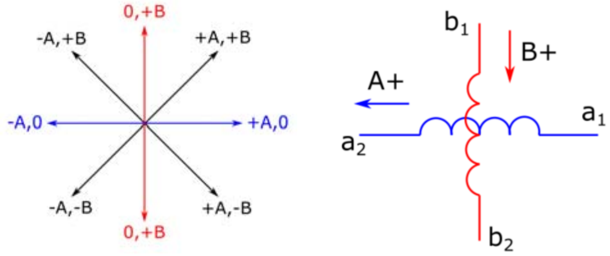

Fig.3. Representation of windings, currents and magnetic field for bipolar stepper motors

The motor itself can then operate in three control modes in terms of the number of steps per revolution [1]:

- Full Step Mode – The basic step size given by the manufacturer (for hybrid motors usually 200 steps/revolution = 1.8°), using excitation of only one winding at a time.
- Half Step Mode – Alternates between single and dual phase excitation, resulting in twice the resolution of the basic step size.
- Microstepping Mode – Increasing motor resolution by varying the direction and magnitude of the current through each winding. Based on Half Step Mode, but unlike Half Step Mode, in this mode we excite two phases with intentionally different current magnitudes (in Half Step Mode, two phases are energized with the same current magnitude).

Although stepper motors have many advantages over conventional motors in certain applications, these types of motors also have certain undesirable effects. One of the main undesirable effects that is taken into account is motor vibration. This vibration can also manifest itself as acoustic noise. Ideally, a stepper motor would move at a constant speed or torque [7, 8]. However, in practice, there is an incomplete matching of the control signal with the physical characteristics of the motor, resulting in variations in speed or torque. There are a number of publications that address this issue, either by allowing the control system to compensate for vibrations or by applying various optimization methods to the control signal itself [7, 8, 9, 10]. Another problem associated with vibration is mechanical resonance at lower stepper motor speeds, which drops off at higher rotational speeds. Therefore, stepper motors are not used in applications requiring smooth motion at low speeds [11]. The above mentioned issues in the context of the proposed application will be discussed in later section.

Proposed applicating will serve for setting of tunable waveguide shunt, which is one componet used in matching of waveguide path. Impedance and phase matching are very important in a waveguide path. If a tapping component is used in the waveguide path, a tunable waveguide shunt is used. A tunable waveguide shunt (Fig. 4.) is used in impedance matching (improving the characteristics) of the waveguide path. A waveguide shunt is a technical solution where a dielectric plate (piston) is placed in the waveguide and moved in the longitudinal direction, which is important for measuring very small reflections. The displacement of the dielectric plate changes the length of the waveguide and thus the reflection itself.

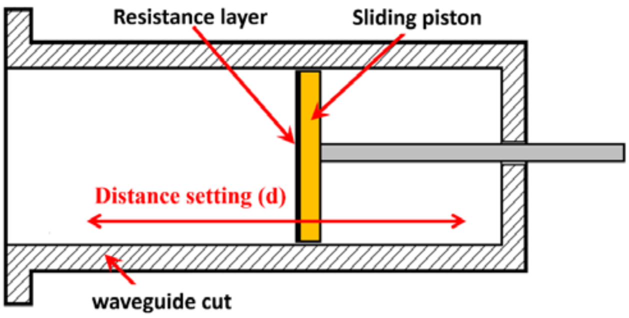

Fig.4. Tunable waveguide shunt

Components used in proposed application

In this section, the various components used in the proposed application for controlling the displacement of the waveguide shunt will be discussed.

Arduino UNO is one of the most used and versatile boards in the Arduino portfolio. It can be seen in Fig. 9. This board uses the ATmega 328P processor. It has 6 analog pins and 14 digital I/O pins. The number of pins is quite sufficient for the proposed application. Due to the small size of the control program, the memory of this board is also adequate. The advantage is the use of EEPROM memory, which is used in the solved application to store the motor positions even if the designed setup is disconnected from the power supply. There are different ways of powering this board, in the proposed application the USB power supply from PC is used. More detailed specifications can be found in [11].

Driver TB6600 (see Fig. 9) is used for bipolar control of two or four phase hybrid stepper motors of different sizes. It is a low cost driver that can control the output current in 8 levels (0.5 - 3.5 A, 0.5 A resolution + 2.8 A range). It has 8 microstepping levels for standard stepper motors with 1.8° steps (200 - 6400 steps/revolution). The main advantage of this driver is its versatility. If it is necessary to replace a used motor with a more powerful one, it is sufficient to simply replace the motor without changing the program. For more detailed specifications, see [13].

Stepper motor LA351S12-A-UIAP is a special type of stepper motor, called a linear actuator, which converts the rotary motion of the rotor through the gear shaft into a sliding motion (shown in Fig. 9). This principle is used in the designed application for precise adjustment of the displacement of the waveguide shunt. Specifically, a SCREW-ABA-UIAP-200 shaft is implemented. The basic step size of the motor is typically 1.8°. When using a gear shaft, one step corresponds to a displacement of 0.003048 mm. This implies that there is already a very high precision from the basic step size and there is no need to use microstepping for higher precision. Microstepping would only have an effect in terms of smoother running of the motor and thus reducing any vibration. The power supply can be 24 VDC or 48 VDC at a nominal current of 1.2 A per phase. Further specifications can be found in [14, 15].

Design and setup of measurement station

In this section, the design and setup of the testing station for accurate setting of the waveguide shunt will be described.

From the components described in the previous section, the testing station has been designed. Its block diagram is shown in Fig. 5.

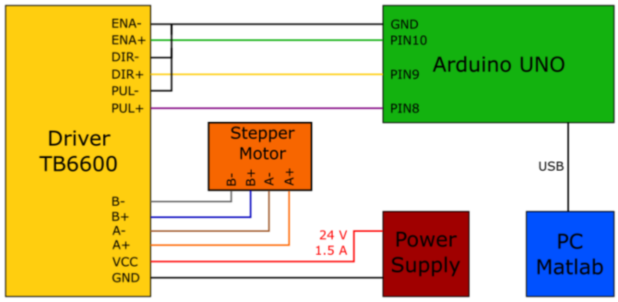

Fig.5. Block scheme of testing station

As can be seen from Fig. 4 the individual windings of the stepper motor are connected to the TB6600 driver. The power supply to the motor through the driver is provided by a Matrix MPS-3005L-3 DC power supply. Since the TB6600 driver operates at a voltage range from 9 VDC to 42 VDC, a supply voltage of 24 VDC was chosen for the stepper motor. It can derived from the torque characteristic in [14] that there is not a significant difference in torque for 24 VDC and 48 VDC supply voltage, and 24 VDC is sufficient for the proposed application. Considering the need of 1.2 A rated current per phase, a current range of 1.5 A is chosen on the driver. For the control pins, a simplified circuit is chosen according to [13], where the positive control pins are connected to the digital I/O pins of the Arduino UNO board and the negative pins are connected to ground (GND). The control itself is then handled by a PC. The testing station itself was manufactured on a 3D printer. Its design can be seen in Fig. 6. The design represents the half of the waveguide into which the waveguide shunt is inserted. The piston to move the shunt creates the rotating shaft of the linear actuator. A high accuracy metal ruler is used to check the accuracy of the displacement setting. For the actual 3D printing andsubsequent assembly of the parts, the accuracy is in the order of tenths of mm (0.4 mm in the horizontal plane, 0.15 mm in the vertical plane). The accuracy of the stepper motor displacement setting will be discussed in the following paragraphs.

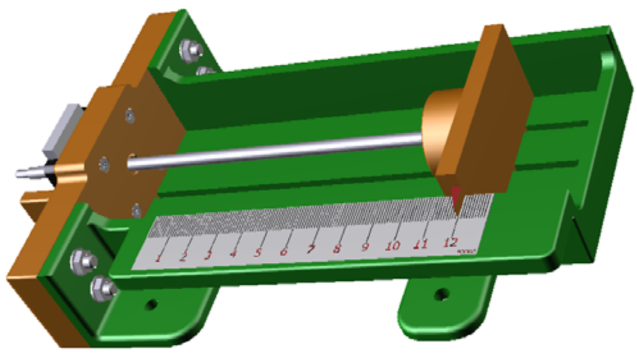

Fig.6. Design of testing station for 3D printing

As mentioned in the previous paragraphs, a PC is used for the actual program control. Specifically, a combination of MATLAB and Arduino IDE development environments is used. The control program itself is loaded on the Arduino UNO board, which is connected to the control pins of the TB6600 driver. A user interface is then created in the MATLAB environment for entering control parameters. The power supply of the Arduino UNO board via USB is also used for communication between the PC and this board. The proposed user interface in MATLAB environment is shown in Fig. 7. Two buttons are used for controlling the control. START will move the sliding shunt to the desired position. RESET is used to return the piston to the zero position. The graph shows the current position of the sliding shunt in the selected range (in this application 0 - 120 mm). It is possible to compare the theoretically set value with the actual value on the sliding scale with an accuracy of 0.5 mm (acurate scale resolution). In software, the resolution of the displacement setting is set to 0.1 mm, but for the proposed application a minimum displacement change of 1 mm is assumed. The calculation of the gear ratio between motor steps and piston displacement was performed in MATLAB environment. At the same time, statistical analysis (linear approximation) was performed to evaluate the error in the displacement setting. The result of the statistical analysis and the calculated gear ratio (from the linear approximation equation) can be seen in Fig. 8. As can be seen from Fig. 8, even at the base step (200 steps per revolution), the displacement setting error is negligible and hence no further refinement of the step is required for this reason.

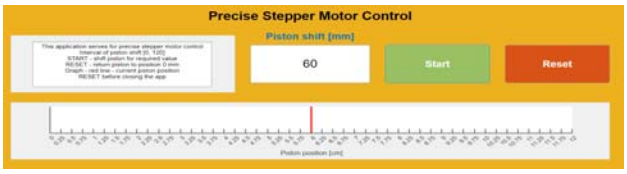

Fig.7. User interface in MATLAB

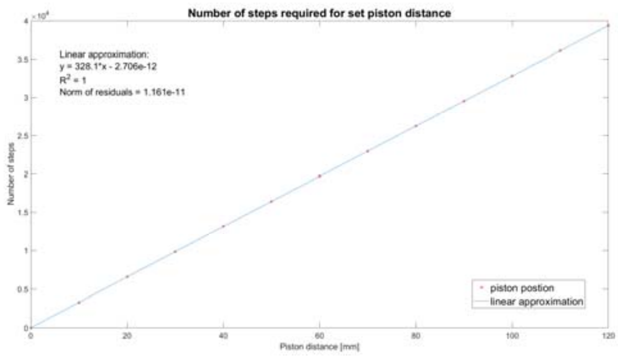

Fig.8. Linear approximation for number of steps

An assembled test station can be seen in Fig. 9. The design is based on the block diagram in Fig. 5. For the Arduino UNO board and the circuit boards for interconnecting the individual components, cases were printed for mounting on the pad. To eliminate vibration and smooth the sliding process, a cutout in the waveguide model and a guide link for the shaft behind the motor case were made. Vibration elimination by any of the methods mentioned in Section II was not required. The main reason is that the proposed application is used when the waveguide shunt position is fixed (motor is not moving). It is only necessary to accurately set the piston position and maintain it, which is achieved as shown in Fig. 8. Thus, no further application of various optimization methods, etc. is required. The resulting vibrations when the piston is moved are negligible and have no effect on the functionality of the application.

Fig. 10 shows a detail of the measurement scale for the verification of the accuracy of the step setting. The functionality of this prototype was verified during the actual measurement with a minimum position change of 0.5 mm.

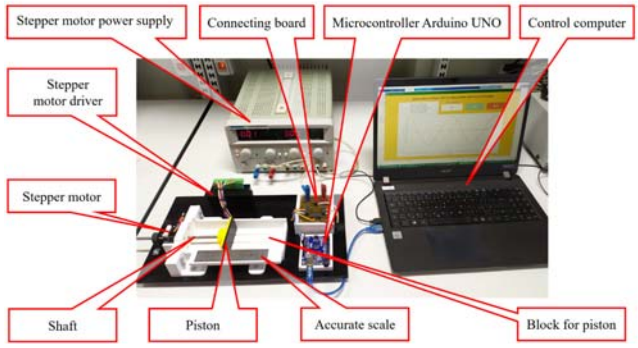

Fig.9. Testing station for precise stepper motor control

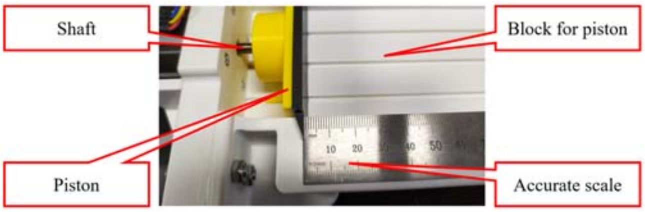

Fig.10. Detail of measurement scale

Fig. 11 shows real assembled tunable waveguide shunt where the distance setting is provided by linear actuator. Functionality of such prototype was verified. Piston movement and distance setting coresponds with results obtained on 3D printed model.

Fig.11. Tunable waveguide shunt connected to linear actuator

Conclusion

In this paper, the issues of stepper motor control accuracy were addressed. Various methods of increasing the accuracy of stepper motor control were mentioned. However, the main focus of the paper was an application for precise positioning of a tunable waveguide shunt. A special type of stepper motor called a linear actuator was chosen for this application. To verify the functionality of the proposed application, a test station was designed using 3D printing. After verification of functionality, a realistic circuit of the tunable waveguide shunt in combination with the linear actuator was constructed. Statistical analysis showed the effectiveness of this solution. This analysis and practical tests showed that for this type of applications, more advanced methods (e.g., optimization methods) to improve accuracy are not needed. This application can serve for a variety of different purposes by simply changing parameters in the program without the need for major modifications. In the future, the authors plan to use slightly modified application in the design of circulator-based phase shifters, where a tunable waveguide shunt is used to adjust the phase shift.

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***Authors**: Ing. Ondřej Šimon, Department of Radio Electronics, Brno University of Technology, Brno, Czech Republic, Department of Communication Technologies, Electronic Warfare and Radiolocation, University of Defence, Brno, Czech Republic*
E-mail: ondrej.simon@unob.cz, Ondrej.Simon1@vutbr.cz
Ing. Miroslav Popela, Department of Radio Electronics, Brno University of Technology, Brno, Czech Republic, Department of Communication Technologies, Electronic Warfare and Radiolocation, University of Defence, Brno, Czech Republic
E-mail: miroslav.popela@unob.cz, Miroslav.Popela@vut.cz

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