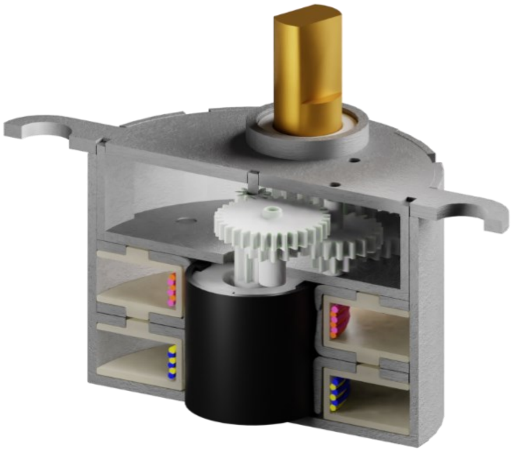

28BYJ-48 Datasheet

Unipolar Stepper Motor

THIS IS A <u>THIRD-PARTY</u> DATASHEET FOR THE 28BYJ-46 STEPPER MOTOR. GENTIAM ELECTRONICS DOES NOT PRODUCE THIS PRODUCT.

1 General Description

The 28BYJ-48 stepper motor is an inexpensive device that is easy to use and can handle comparably high loads. It also provides reasonably good accuracy for its size and cost, making it ideal for a variety of consumer applications. The motor contains a stator comprised of 32 teeth and a surface-mounted permanent magnet rotor. In typical variants, the rotor shaft is coupled to an output shaft, flattened to allow for easy coupling, through a reduction gear ratio of approximately 1:64. The geared stepper motor unit can be moved in as little as 5.625°/64 increments, completing a full revolution in 4096 steps. The 28BYJ-48 stepper motor can be powered by either 5V or 12V supplies. The 28BYJ-48 motor is compatible with a variety of ULN2003 stepper motor drivers and can be controlled using the Arduino Stepper library.

2 Features

- Low cost
- 5V and 12V compatibility
- Position or speed control
- Easy setup
- Small size

3 Applications

- Small robotic arms
- Point trackers
- Sliding platforms
- Raspberry Pi stepper motor projects

Disclaimer

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Figures, Equations, and Tables List

Revision History

Rev.	Release Date	Description	Pages
V0	May 2022	Document Creation	All
V1	Sept 2022	Document Published	All

4 Purpose

The 28BYJ-48 stepper motor is widely used, both in various consumer applications and for custom or Do-It-Yourself (DIY) projects. However, the information publicly available regarding this motor is either largely inconsistent between publications, inconsistent with the properties of the actual hardware, or, at-times, inconsistent between parameters defined in the same publication.

The problem is further complicated by the fact that multiple manufacturers, from various locations and likely using different processes, produce this motor, making it difficult to standardize the **produced motor**. In addition, the extent of variations in the commercially available hardware clearly indicates different design-intent solutions, further making it difficult to establish a standard for the **designed motor**.

Another challenge for the end-user is that the terminology used is not consistent across the public literature. The terms or phrases used may not be internationally common, nor are they described in detail in any given document. Alternatively, terms that are commonly known are not being used in a consistent way across publications.

As a result, the end-user is forced to make purchase, design, and use-case decisions, or take other actions, either out of ignorance or based on incorrect interpretations and assumptions, all of which may result in damage to their hardware or system.

The goal of this datasheet is to address these challenges as best as possible, primarily by evaluating and cross-referencing public resources in detail. The values reported in this document **may not be completely accurate** for a particular 28BYJ-48 stepper motor being used by a given end-user. However, by providing the most reported values, the aim is to present specifications likely to be correct for most of the motors, most of the time. Another aim is to identify the phrases used in various references to describe a parameter, provide its meaning, and thereby unify terminology used in the various publications.

5 Parts and Mechanical Layout

In Figure 1, a mechanical breakout of individual components that make up the 28BYJ-48 stepper motor is presented.

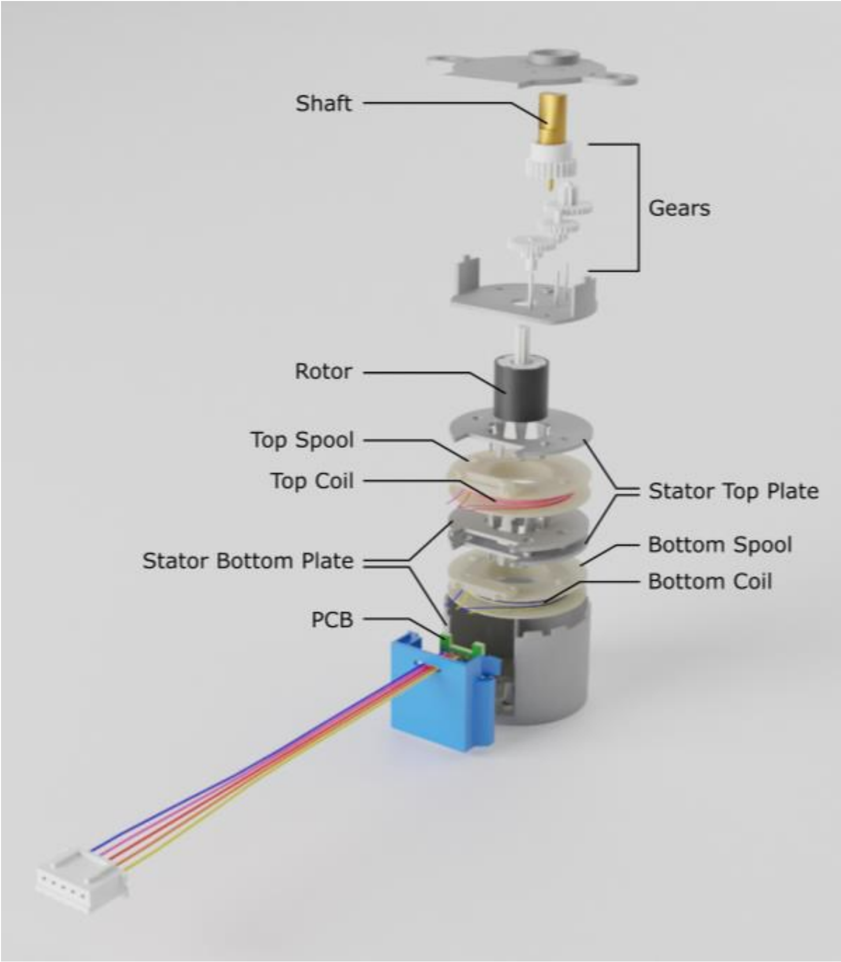

Figure 1: Mechanical breakout of the 28BYJ-48 stepper motor.

There are two separate spools of wire (top and bottom) in the motor, each containing two overlapping copper coils that may be energized at different times. The rotor is comprised of a set of surface-mounted permanent magnets assembled cylindrically about the circumference. The stator teeth are connected to the top and bottom stator plates, folded in to be parallel to the central axis. There is typically a small printed-circuit board (PCB) containing the coil connections.

The mechanical dimensions of the casing and mountings of a particular 28BYJ-48 motor are dependent its manufacturer, from whom these values might be obtained. An example dimensional drawing for the 28BYJ-48 motor is presented in Figure 2.

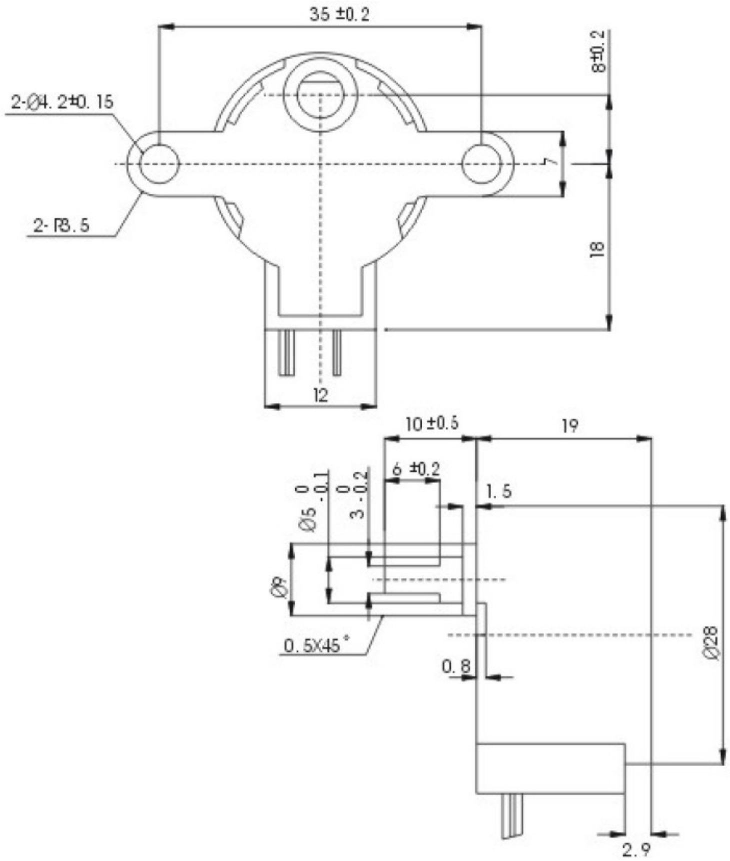

Figure 2: Example 28BYJ-48 stepper motor dimensional drawing [1].

6 Pinout

In Figure 3, the wire colors and pinout numbers for a typical 28BYJ-48 stepper motor are shown. The commonly used configuration for each pin number in the pinout are presented in Table 1.

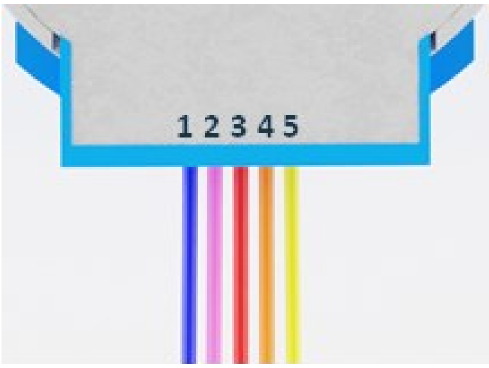

Figure 3: 28BYJ-48 stepper motor pinout and wire colors.

Table 1: Pin configuration list.

Pin #	Name	Wire Color	Description
1	Coil 1	Blue	Electromagnet Coil 1
2	Coil 3	Pink	Electromagnet Coil 3
3	V_{CC}	Red	Supply Voltage
4	Coil 4	Orange	Electromagnet Coil 4
5	Coil 2	Yellow	Electromagnet Coil 2

7 Functional Diagram

In Figure 4, the internal electrical schematic for the 28BYJ-48 stepper motor is shown. Note that the two coils on the same spool are center-connected to V_{CC}, resulting in the coil being energized when connected to a lower voltage (e.g., ground).

Figure 4: Internal electrical schematic with wiring connections.

8 Motor Specifications

8.1 General Specifications

Table 2: General Motor Specifications.

Stepper Motor Type	Unipolar
Rotor Field	Permanent Magnet
Shaft Type	Flattened
Wire Termination	XH JST Female Connector
Num. Phases	4[2]

8.2 Mechanical Specifications

In Table 3, all the mechanical specifications found for the 28BYJ-48 motor are provided. Note that these specifications were obtained by cross-referencing multiple public resources in detail, as stated in the Purpose of this document. Greyed out cells in the table denote a "Not Applicable" cell, while a cell containing a hyphen, "-", denotes that the information for that cell could not be found. The specifications are listed in Table 3 by considering the maximum and minimum values across the variants as best as possible. An asterisk, "*", beside a number denotes there are additional notes for this specification that the end-user is highly recommended to read before using the specification for any application.

Table 3: Mechanical Specifications.

Parameter	Description	Min	Typ	Max	Unit
Steps per Revolution	Full-steps		2048[3]		
	Half-steps		4096[3]		
Gear Ratio	Speed-reduction ratio between rotor and output shaft (approx. value).		1:64*[2]		
Backlash	Maximum amount of lost-motion due to the meshing of the gears.	-	±3**[4]	-	Deg
External Diameter	Outer diameter of complete motor assembly.	-	28[3]	-	mm
Shaft Diameter	Diameter of output shaft.	-	5[3]	-	mm
Shaft Length	Length of output shaft.	-	10[3]	-	mm
Step Angle	Angle of one full-step.		11.25/64[3]		deg
	Angle of one half-step.		5.625/64[2]		
Weight	Weight of full motor assembly.	-	35[5]	-	g
Temperature Rise	Maximum rise in motor temperature at 120 Hz.	-	40[2]	60[7]	K
Noise	Maximum noise emitted from motor at 120 Hz, no-load conditions.	-	35[2]	40[8]	dB

* See Section 9.2.1.
** See Section 9.2.2.

8.3 Electrical Specifications

In Table 4, all the electrical specifications found for the 28BYJ-48 motor are provided. Note that these specifications were obtained by cross-referencing multiple public resources in detail, as stated in the Purpose of this document. Greyed out cells in the table denote a "Not Applicable" cell, while a cell containing a hyphen, "-", denotes that the information for that cell could not be found. The specifications are listed in Table 4 by considering the maximum and minimum values across the variants as best as possible. An asterisk, "*", beside a number denotes there are additional notes for this specification that the end-user is highly recommended to read before using the specification for any application.

Table 4: Electrical Specifications.

Parameter	Description	Min	Typ	Max	Unit
Supply Voltage	Voltage required to operate the motor.	5[2][4]	5[2][4]	12[4]	V
Supply Current	Current draw during loaded half-step operation.	-	240[9]	256[10]	mA
	Current draw of loaded full-step operation.	40*[1]	200[10]	-	mA
Rated Frequency	The nominal electrical frequency for which the motor was designed.		100[2]		Hz
Rated Speed	The nominal mechanical speed (at the rotor shaft) for which the motor was designed.		187.5[2]		RPM
Resistance per Phase	Electrical resistance of the coils or phase (some variants). Errors +/- 7% at 25C.	50**[2][11]	200**[8]	300**[1][7]	Ω
Insulated Resistance	Minimum resistance of winding insulation measured using a 500V test.	10[2]	-	-	MΩ
Dielectric Strength	Result for a test measuring leakage current with 600 VAC applied for 1 s	-	1[2][7]	-	mA
No-Load Pull-In Frequency	The maximum frequency at which the motor can pull into synchronism.	500[1][7]	600[2][8]	-	Hz
No-Load Pull-Out Frequency	The minimum value of the maximum frequency the motor can handle before pulling out of synchronism.	-	1000[1][2][8]	-	Hz
Holding Torque	Maximum torque that the motor can maintain while stationary.	-	29.4†[5]	-	mNm
Cogging Torque	The torque ripple experienced when the rotor is turned with the coils unenergized.	-	34.3†[2][7]	-	mNm

Pull-In Torque	Maximum torque at which the motor can start rotating when being commanded to move. Value at a frequency of 500 Hz or 937.5 RPM.	29.4†† [2][7]	-	-	mNm
Pull-Out Torque	Maximum torque the motor can maintain before it starts slipping and falls out of synchronism. Value at a frequency of 120 Hz or 225 RPM.	34.3†† [2]	-	-	mNm

* See Section 9.4.2.

** See Section 9.1.2.

† See Sections 9.3.5 and 9.3.6.

†† See Sections 9.3.7 and 9.3.8.

9 Detailed Description

9.1 Terminology

9.1.1 Unipolar vs Bipolar

The terms **unipolar** and **bipolar** are defined in a variety of ways in the published literature. In addition, other common terms used to describe motors, such as **homopolar** and **multipolar**, may add to the confusion. It is therefore useful to clarify the usage of these terms.

In [12][13], the term **multipolar** is used to indicate motors with multiple pairs of magnetic stator poles, each pair containing a north pole and a south pole. The term **homopolar** is used in [14][15] to indicate motors with a single pair of magnetic stator poles that do not change direction.

In [16], the term **bipolar** is used to describe a motor with two magnetic stator poles. In this context, the term **unipolar** would be meaningless as magnetic monopoles (i.e., a north pole without a south pole, or vice versa) cannot exist in nature.

Alternatively, numerous references including [17] use the term **bipolar** to indicate motors containing coils that can be energized to have current flow in either direction or "polarity". In this context, the term **unipolar** can be used to indicate motors containing coils that may only be energized in one direction or polarity; this is the definition used in this document. Consequently, prefixes indicating more than two directions (e.g., tri-, quad-, etc.) are not possible and cannot be used.

9.1.2 Resistances and Dielectrics

The **resistance per phase** is the DC resistance of a single coil or phase of the 28BYJ-48 stepper motor. In Figure 4, this is the resistance measured between V_{CC} and any of the coil terminals. This parameter may also be called **coil resistance**, **resistance per coil**, **phase resistance**, **DC resistance**, and **stator resistance** in the publications. Resistances presented in Table 4 vary widely across different references, with values ranging between 50-300 Ω per phase. If a precise resistance per phase value is required for the application, it is recommended that the end-user measure it using an appropriate measuring device.

The **insulation resistance** is a measure of the quality of the insulation around a conductor and indicates the electrical resistance value as measured from the conductor inside the insulation and a conductor that may be directly outside it (e.g., ground). It is typically measured in a test by applying a 500V potential between the two sides of the insulation [2][7].

The **dielectric strength** is a measure of the quality of the insulation being used internally in the motor. It is frequently determined by measuring the amount of leakage current in a test after applying 500-600VAC for 1 min [18]. However, for the 28BYJ-48 stepper motor, it is often reported for a 600VAC test for 1s [2][7].

9.2 Gearbox

9.2.1 Gear Ratio

The rotor is connected to a reduction gearbox which is then connected to the output shaft. The reduction gearbox reduces the speed of rotation to allow for increased stepper motor torque output. The ratio for any geared stepper motor can be calculated by multiplying the ratio of each of its inner gear meshes, as shown in Equation 1.

$$\begin{aligned}\text{Gear Ratio} &= \text{Product of inner gear ratios}\\ &= \frac{32}{9}\cdot\frac{22}{11}\cdot\frac{26}{9}\cdot\frac{31}{10}\\ &= 63.684\end{aligned}$$

Equation 1: Motor gear ratio.

In Equation 1, each fraction represents a ratio of a pair of the inner gear meshes. The internal gearbox of the **typical** 28BYJ-48 stepper motor, along with its inner gear meshes and the number of teeth on each gear, are presented in in Figure 5. Notice that each fraction is greater than 1 and each gearset increases the ratio. The gear ratio is often rounded to 64 for ease of use in calculations. It is noted that variants with other gearbox configurations also exist for this motor.

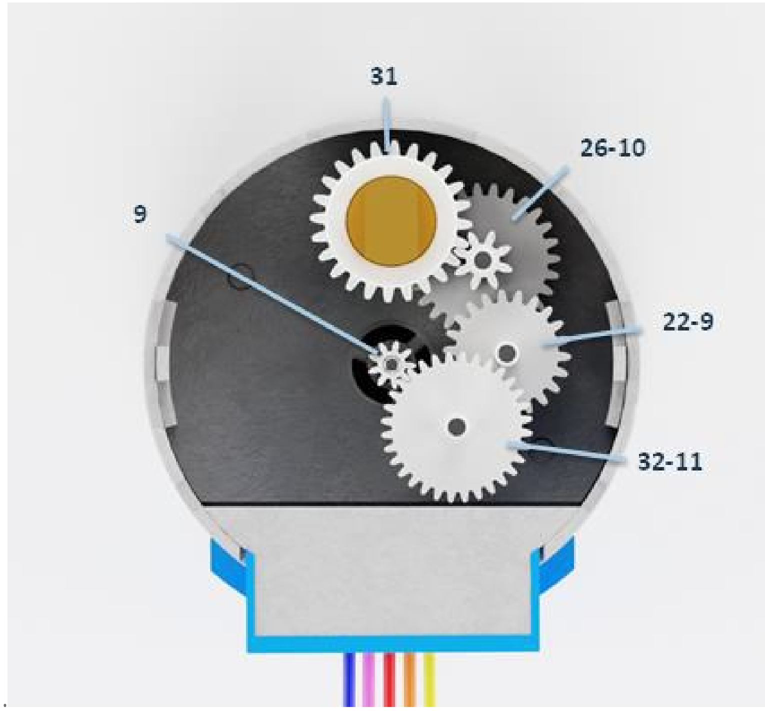

Figure 5: Motor internal gearbox. Hyphenated values are for next gear stage.

9.2.2 Backlash

Backlash represents the clearance between the meshing gears in a gearbox. The total **backlash**, accounting for all the backlash stages of the inner gear meshes, represents the total resistance-free play on the gears as the shaft is turned between two angles. **Backlash** is a result of manufacturing and assembly processes, as well as lubrication requirements and can never be reduced to zero.

In Table 3, the backlash of the motor is specified as ±3°, as found in [4], which specifies this angle to be that at the output shaft. Based on hands-on observation, however, the resistance-free play appears to be significantly lower than ±3° for this motor. It is instead believed that the reference value of ±3° is the backlash value at the rotor shaft, as opposed to the output shaft. This backlash value translates to approximately ±0.005° on the outer shaft, which appears to align closer to observations.

9.3 Speeds and Torques

9.3.1 Motor Speed

The speed of the stepper motor, in RPM, is related to the number of steps taken in one minute. This speed refers to the speed of the rotor and the rotor shaft, before the gearbox, and can be found using Equation 2.

$$\text{Motor Speed (RPM)} = \frac{\text{Steps Per Second} \cdot 60}{\text{Steps Per Revolution}}$$

Equation 2: Motor speed in RPM.

where it is noted that **steps per second** is also the electrical frequency. The motor's **angular velocity**, useful for calculating its output power, is obtained from the motor speed by

$$\text{Angular Velocity (rad/s)} = 2\pi/60 \cdot \text{Motor Speed (RPM)}$$

Equation 3: Motor angular velocity in rad/s.

9.3.2 Electrical Frequency

In any electrical motor, there is at least one conductor winding in which a time-varying excitation, typically sinusoidal voltage or current, is applied. The electrical **frequency** typically refers to the **frequency** of this excitation for a particular phase or coil. However, in the case of most published materials related to the 28BYJ-48 stepper motor, this frequency is instead related to the following equivalent values:

- the **frequency** at which the rotor moves to align with the next stator tooth position.
- the inverse of the period or width of one coil excitation pulse.
- the number of steps taken per second
- the number of pulses fired by the driver circuit per second in all coils or phases

In Figure 8, the pulses applied to each of the 4 coils/phases of the 28BYJ-48 stepper motor are shown. The frequency refers to the speed at which the pulse for the next phase is fired, as opposed to the **frequency** of pulses in the same phase. Accordingly, in some publications, the **frequency** may also be referred to as **steps per second** (SPS) or **pulses per second** (PPS) [1][7].

This frequency is related to the motor speed as follows:

$$\text{Motor Speed (RPM)} = \frac{\text{Frequency} \cdot 60}{\text{\# of Stator Teeth}}$$

Equation 4: Motor speed from frequency.

where the frequency is the number of steps per second, a factor of 60 is used to convert the units to number of steps per minute, and the number of stator teeth represents the number of steps per revolution. Note that this equation is not universal and is presented here as only being applicable to a unipolar stepper motor.

9.3.3 No-load Pull-in Frequency

The **no-load pull-in frequency** refers to the maximum electrical frequency that can be applied to an unloaded stationary motor and still have it start spinning (i.e., get "pulled into synchronism"). In some publications, this parameter may also be referred to as **idle in-traction frequency** [2][8], **max freeload pull-in frequency** [4], **pull-in rate** [7], or **maximum starting frequency point** [19].

9.3.4 No-load Pull-out Frequency

The **no-load pull-out frequency** refers to the maximum electrical frequency that can be applied to an unloaded spinning motor and still have it continue spinning. Beyond this frequency, the motor becomes unstable or uncontrolled and gets "pulled out of synchronism". In some publications, this parameter may also be referred to as **idle out-traction frequency** [2][8], **max freeload pull-out frequency** [4], **pull-out rate**, or **maximum running frequency point** [19].

9.3.5 Holding Torque

There are several different descriptions in the public domain for **holding torque** [20][21]. This term represents the maximum load torque that the motor can bear at standstill (i.e., zero speed) conditions, with its windings fully energized (i.e., with maximum current), above which the motor will move in the direction of the load.

To understand the usefulness of this parameter, it is helpful to consider this term by way of example. In general, stepper motors are an ideal low-cost option for applications where a reasonably good amount of position accuracy is required. These applications may include robotics (such as for vending machines), 3D printing, etc., where it is necessary to keep an arm at a particular position, even as its load suddenly changes. An example may be a vending machine containing a platform, on the end of which a large drink has fallen. The **holding torque** must be sufficient to allow the motor to bear the torque spike experienced and keep the arm at the required position.

Based on the definitions used in this document, **holding torque** cannot be less than or equal to cogging torque, since **holding torque** is approximately the sum of the cogging torque (without current) and the maximum applied torque resulting from the maximum current. However, the specifications in Table 4 conflict with this and one of these two torque values is believed to be an error.

9.3.6 Cogging Torque

Cogging torque [22] is experienced in a de-energized motor (i.e., one with zero current in its windings) as it is being rotated, which it may be by hand. This torque is a result of the electromagnetic interactions between the stator teeth and the rotor magnets. In some publications, it may also be referred to as **detent torque** [7][20][21], **self-positioning torque** [2][8], or **residual torque** [17].

The average **cogging torque** in a spinning motor is always approximately zero, so it does not help accelerate a load. It also increases the vibrations and harmonics in a motor, so a high **cogging torque** is generally not preferred. On the other hand, cogging can contribute to the holding torque, allowing the motor to stay in place under load with lower current. The ideal cogging torque must therefore be decided based on the application.

Based on the definitions used in this document, **cogging torque** cannot be greater than or equal to holding torque, since holding torque is approximately the sum of the **cogging torque** (without current) and the maximum applied torque resulting from the maximum current. However, the specifications in Table 4 conflict with this and one of these two torque values is believed to be an error.

9.3.7 Pull-in Torque

The definitions for **pull-in torque** are generally consistent in the literature [17][19][21][23], although it may be helpful to further clarify these definitions. **Pull-in torque** is concerned with a motor *initially at rest* and is the maximum torque it can provide given a certain electrical frequency is instantly applied to its terminals. If the load on the motor is higher than this **pull-in torque**, the motor will not start turning. This value is typically reported at an applied frequency of 500Hz or 937.5 RPM for the 28BYJ-48 stepper motor.

Pull-in torque should always be less than pull-out torque since **pull-in torque** is concerned with the motor initially at rest whereas pull-out torque is concerned with the motor in motion. In addition, while the difference between **pull-in torque** and pull-out torque may not be large at a given speed, it is expected to be significantly different at two very different speeds. However, the specifications in Table 4 indicate these two values to be quite similar at speeds of 225 RPM and 937.5 RPM. It is therefore believed that one of these values is in error.

9.3.8 Pull-Out Torque

Unlike for pull-in torque, **pull-out torque** is concerned with a motor that is initially spinning at an electrical frequency [17][19][21]. It represents the maximum torque the motor can apply (or load torque it can bear) at that frequency, beyond which the motor will start slipping steps. The load torque must therefore always be lower than the **pull-out torque** at any given electrical frequency to allow the motor to keep spinning in a controlled manner. Consequently, this is one of the key parameters for a stepper motor. In some publications, the **pull-out torque** may also be referred to as **in-traction torque** [2][8] or **engine torque** [11]. This value is typically reported at an applied frequency of 120Hz or 225 RPM in the 28BYJ-48 motor publications.

Pull-out torque should always be greater than pull-in torque since pull-in torque is concerned with the motor initially at rest whereas **pull-out torque** is concerned with the motor in motion. In addition, while the difference between **pull-out torque** and pull-in torque may not be large at a given speed, it is expected to be significantly different at two very different speeds. However, the specifications in Table 4 indicate these two values to be quite similar at speeds of 225 RPM and 937.5 RPM. It is therefore believed that one of these values is in error.

9.3.9 Friction Torque

A range of values for **friction torque** is reported in [2], which is the only known reference where this range is reported. It is unclear what this range represents in [2]. Typically [18], **friction torque** represents the torque lost due to friction, either from a braking device or passively from air (i.e., windage), gear, and bearing friction, among others. In [17], a **friction torque** load example is presented, wherein the term refers to a load experienced by the motor that is primarily frictional in nature. Pertaining to either of these definitions, the value reported in [2] appears too high. Indeed, it is too high compared to the pull-out torque values presented in the references or Table 4.

9.4 Operating Characteristics

The following terminology refers to the operating characteristics of a DC motor drive system, comprised of a DC power supply, a motor driver, and an AC motor. The DC power supply feeds the motor driver, which converts it to AC power. The AC power is then fed to the AC motor, which converts the electrical power to mechanical power at the rotor shaft. The rotor shaft spins one side of the gearbox, which steps up the torque and steps down the speed. The output of the gearbox is connected to the output shaft, which spins the mechanical load. The DC motor drive system using the 28BYJ-48 stepper motor is illustrated in Figure 6.

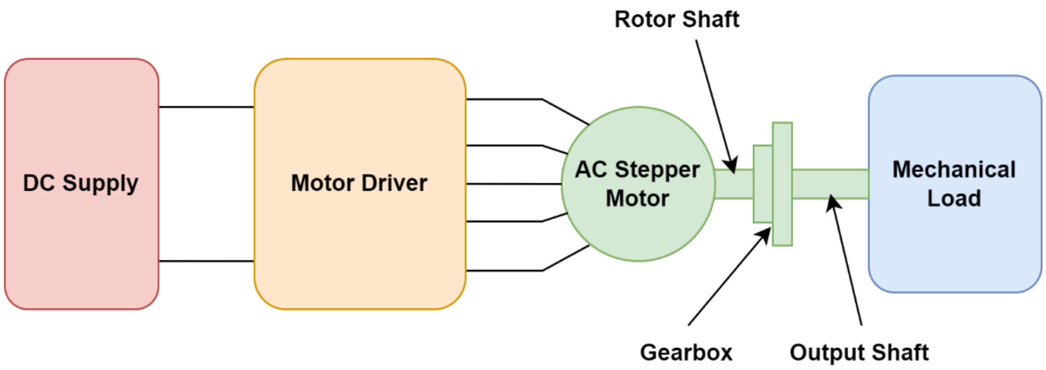

Figure 6: DC motor drive system.

9.4.1 Supply Voltage

The 28BYJ-48 stepper motor is driven by a DC supply through a motor driver circuit. This DC supply voltage is intended to be held as constant as possible for optimal operation. It is recommended that the end-user ensure the system stays within the limits of the DC supply provided in Table 4 to avoid damage. The 28BYJ-48 stepper motor is typically powered using either a 5V or 12V stable power supply. Typically, applications requiring higher torques or speeds will require the 12V power supply.

9.4.2 Supply Current

The DC motor drive **supply current** is directly proportional to its input power, assuming the supply voltage of the motor is being held constant during operation. Under these conditions, the current will vary depending on the motor speed and its applied torque.

When the motor is powered off and at rest, no current will flow. When it is powered on and spinning without a connected load (called the "no-load condition"), it will draw a small amount of current needed to overcome various "drag" losses (such switching, friction, air, and magnetic losses, among others). When the motor is powered on with a connected load that is high enough to keep the rotor fixed in place (called the "locked-rotor condition"), it will draw a large amount of current. It is therefore important to ensure that the supply being used for the motor is capable of meeting or exceeding the current ratings provided in Table 4.

In Table 4, the **supply current** for full-step operation is typically specified as 200 mA [10]. However, [1] states that the "Rated Current" is 40 mA without any indication of operating conditions.

In [11], a specification for "Consumption" of "55 mA" is reported for the 28BYJ-48 stepper motor, presumably being a maximum value. It is believed this represents an input current value. Although it is unclear, this is presumably a "rated" value for the rated speed listed in Table 4, and for a chosen rating of nominal torque, the value for which is also currently unclear.

9.4.3 Output Power

The **output power** of any motor depends on its torque and speed. Higher torque and speed results in higher **output power**, which is calculated using Equation 5.

$$\text{Output Power (W)} = \text{Torque (Nm)} \cdot \text{Angular Velocity (rad/s)}$$

Equation 5: Motor output power.

9.4.4 Input Power

The **input power** of a motor drive depends on its output power and its losses. It can also be determined by the drive's supply voltage and supply current. In a DC motor drive, such as one using the 28BYJ-48 stepper motor, the **input power** is

$$\text{Input Power (W)} = \text{Supply Voltage(V)} \cdot \text{Supply Current (A)}$$
$$= \text{Output Power (W)} + \text{Losses (W)}$$

Equation 6: DC motor drive input power.

where it is noted that the input power includes the losses in the 28BYJ-48 stepper motor and the motor driver.

9.5 Step Angle and Step Count

9.5.1 Full-Stepping Mode

Because the 28BYJ-48 stepper motor has a stator with 32 teeth, a full rotation of the rotor in **full-stepping mode** is completed after 32 steps. Using Equation 7, the step angle is calculated as 11.25°.

$$\text{Rotor Shaft Step Angle} = \frac{360°}{\text{Number of Stator Teeth}}$$
$$= \frac{360°}{32} \text{ or } 11.25°$$

Equation 7: Rotor shaft step angle.

Taking the gear ratio into account, the step angle of the output shaft can be determined using Equation 8. One step of the stepper motor's rotor shaft will rotate the output shaft by 0.1758°.

$$\text{Output Shaft Step Angle} = \frac{\text{Rotor Shaft Step Angle}}{\text{Motor Gear Ratio}}$$
$$= \frac{11.25°}{64} \text{ or } 0.1758°$$

Equation 8: Output shaft step angle.

The total number of steps in a revolution of the output shaft can then be calculated using Equation 9. Each step requires an electrical pulse on the next stator phase to be delivered by the motor controller. Therefore, the total number of steps per revolution is sometimes also referred to as the Pulse Per Revolution (PPR). In this case, the number of **steps per revolution** is 2048.

$$\text{Steps Per Revolution} = \frac{360°}{\text{Output Shaft Step Angle}}$$
$$= \frac{360°}{0.1758°} \text{ or } 2048 \text{ steps}$$

Equation 9: Steps per revolution.

To find the total number of steps required to rotate the shaft by a specific angle, θ, Equation 10 can be used.

$$\text{Steps} = \frac{\theta}{360°} \cdot 2048$$

Equation 10: Number of steps for a specific angle.

9.5.2 Half-Stepping Mode

In **half-stepping mode**, the rotor position can move to align with either the fields through one of the 32 stator teeth **or** one of the positions between them. As a result, the rotor can move to a total of 64 positions. Each half-step will therefore rotate the output shaft half of the original **Output Shaft Step Angle** defined in Equation 8; the new step angle will equal 0.0879°. The shaft also takes twice as many steps to complete a revolution, resulting in 4096 steps per revolution.

10 28BYJ-48 Motor Variations

10.1 Variation Description

The 28BYJ-48 stepper motor is manufactured by several different companies. As such, there are multiple variants of this motor currently available on the market. The changes in these variants are sometimes clearly indicated by the vendor, but that may not always be the case. Table 3 and Table 4 lists the specifications by considering the maximum and minimum values across the variants **as best as possible**. The range of a specification for a particular motor may be smaller. It is recommended that the end-user be aware of the possible variants and their capabilities.

10.2 Adafruit Variant

Aside from the most commonly available 28BYJ-48 stepper motor variants previously discussed, another well-known and documented variant is supplied by Adafruit [6]. This variant is distinct due to its 1:16.128 gear ratio, which consequently affects many of the other specifications. Table 5 shows many of the specifications that are significantly different than what is presented in Table 3 and Table 4.

Table 5: Adafruit Variant Specifications.

Parameter	Description	Min	Typ	Max	Unit
Steps per Revolution	Full-steps		516[6]		
	Half-steps		1032		Steps
Gear Ratio	Speed-reduction ratio between rotor and output shaft (approx. value).		1:16[6]		
Weight	Weight of full motor assembly.	-	37[6]	-	g
Holding Torque	Maximum torque that the motor can maintain while stationary.	-	14.7[6]	-	mNm

11 Example Application

11.1 Component Layout

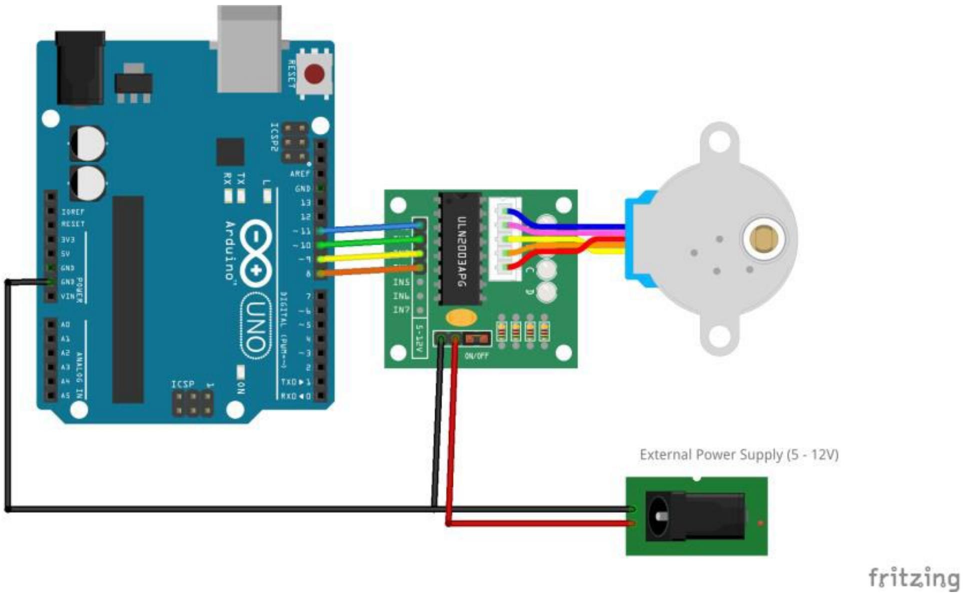

Figure 7: Example stepper motor wiring with Arduino UNO using Fritzing software [24].

The 28BYJ-48 stepper motor can be controlled by an Arduino UNO and a ULN2003 driver board. The two are collectively referred to as the "motor driver" in this document. The ULN2003 driver board accepts low-power control signals from the Arduino UNO and accordingly establishes high-power connections between the motor coils and the DC supply voltage terminals.

In Figure 7, the 28BYJ-48 stepper motor is plugged into a ULN2003 driver board using its built-in connector. It is important to ensure that the red power supply wire, V_{cc}, is connected to the ULN2003 driver board correctly as shown. The driver board input pins are connected to digital pins D8 to D11 of the Arduino. It is generally recommended that an external power supply is used to power the 28BYJ-48 motor instead of the Arduino 5V pin. Otherwise, under heavy load, the motor can draw enough current to damage the Arduino UNO. To program the Arduino UNO as a motor controller, the Stepper library provided by Arduino may be used.

11.2 Full-Stepping Control

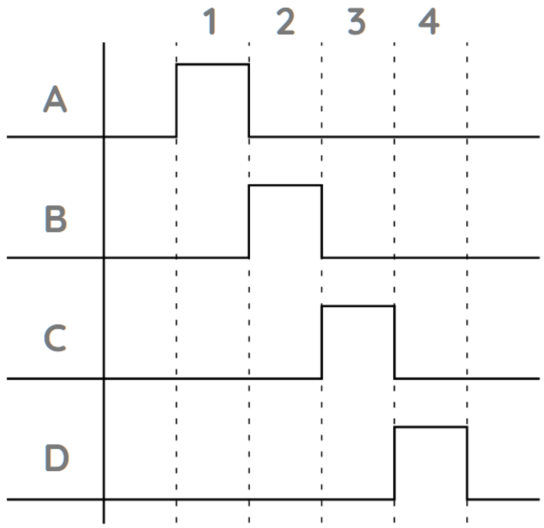

Figure 8: Full-step signal timing diagram.

Referring to Figure 4, in typical applications of the 28BYJ-48 motor, the coils are connected to V_{cc}, requiring the signals in Figure 8 to be inverted. The inversion is done by the ULN2003 driver board.

In full-stepping mode, each coil is turned on and off sequentially so that no two coils are on at the same time. The stepping signal diagram and the correlated truth table are used to visualize the sequence of the electrical pulse on each coil. The cycle repeats once the last coil is turned off. Since the 28BYJ-48 stepper motor has 32 teeth, this cycle repeats 8 times for 1 full rotation of the rotor. For a full rotation of the output shaft, this pattern will need to be repeated approximately 8 x 64, or 512, times. In Table 6, the equivalent truth table for the full-step signal sequence is shown.

Table 6: Full-step signal truth table.

Step #	A	B	C	D
Step 1	1	0	0	0
Step 2	0	1	0	0
Step 3	0	0	1	0
Step 4	0	0	0	1

12 Additional Information

Gentiam Electronics provides lots of great and free content on various topics related to DIY electronics projects, including Arduino, Engineering Design Best-Practices, Stepper Motors, Magnetics and Inductances, various General Electronics topics, and many more. If you are interested in learning more, please visit our LEARNING HUB or any of our social media channels for lots of great additional information.

Additionally, if you have any comments or suggestions on how to improve this document or spot any mistakes, you can contact us at info@gentiam.com.

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