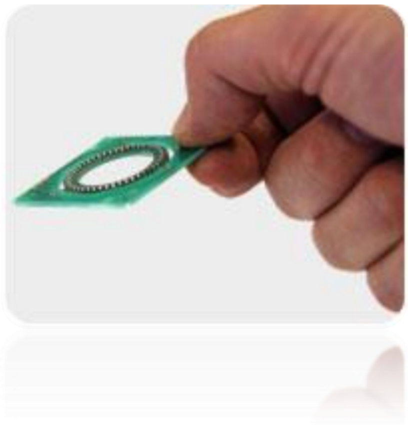
How to Reduce Motor Size by Integrating Accurate, Low Cost Piezo Motors



A White Paper for Electronic, Mechanical & Design Engineers

Encouraging new designs & reducing costs

Mounting piezo motors directly on PCBs

Revolutionizing electronic motion

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Executive Summary

Today's challenge is to make electronic applications smaller, cheaper and more accurate. PCBMotor builds accurate and high resolution, motors *directly onto* the PCB itself.

In addition to a world of new design opportunities, this new motor technology significantly reduces the size, building height and cost of applications while maintaining a high torque motor without slack.

Are these challenges relevant to you?

- Do you have an electronic application that requires movement?
- Would you like to integrate several motors directly onto a single printed circuit board?
- Do you need precise control of a lens, valve, laser, mirror, pointer or the like?
- Does your system require high resolution and high holding torque with no power?
- Would you like to reduce the height of your application or otherwise improve the look-and-feel of your product?

If your answer to one or more of the above questions is 'yes', then a PCBMotor will help you reach your goals – innovatively and profitably.

Get a competitive advantage and increase your profit margin

- Make your application smaller by integrating motion and all electronics into one printed circuit board.
- Reduce your bill of materials – PCBMotor's direct drive eliminates the need for gears.
- Innovate using the unique and ultra-slim form factor of the PCBMotor.
- Since the piezo components for the PCBMotor are SMD-mounted directly on the PCB, you further reduce your bill of materials by eliminating screws, wires, connectors and manual assembly.

Start a new revenue stream, now!

What to do next

We realize that you're probably gathering information and have questions you need answered.

Send an email with your questions to Henrik, hso@pcbmotor.com, or to arrange for an assessment of your application's requirements…no strings attached!

Email Henrik…

We've also developed several ready-to-go evaluation kits to help people with different application requirements start prototyping with PCBMotors.

See our website for an overview of our Evaluation kits…

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Technical Details

The block diagram below (Figure 1) shows an example Printed Circuit Board (PCB) containing stator, controller, driver and customer application electronics – all on the same PCB.

The PCBMotor system consists of the following

- PCB mounted with piezo components which acts as the stator/resonator (Patented)
- Application-specific rotor mounted on top of the stator
- Driver, sensor and motor built as a very compact unit with the electronics placed on a separate PCB (see Figure 1)

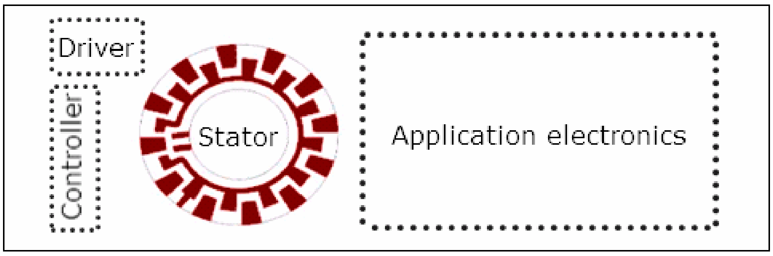

Figure 1 - Integrating electronics and mechanics

How it works

PCBMotors use the *traveling wave* principle to create the motion in the stator (see Figure 2).

1. The stator, made from the PCB itself, holds the actuators (piezo components) and electrical connecting circuit. The PCB can also hold the driver.

2. The application rotor, pressed onto the surface of the stator, delivers the mechanical output. A traveling wave is generated over the stator surface, acting as a flexible ring to produce elliptical motion on the rotor interface. The elliptical motion of the contact surface propels the rotor and the connected drive-shaft.

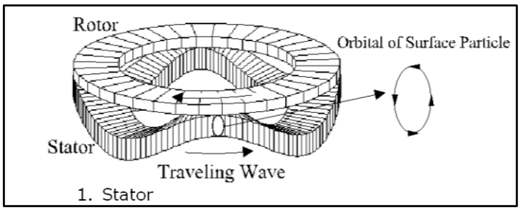

Figure 2 - Traveling Wave

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Elements of the Stator

Printed Circuit Board

The PCB used for a PCBMotor is made of standard FR4 material and can be from one to multiple layers depending on the application's requirements. Manufacturing processes are well known and most PCB manufacturers can deliver to well-defined specifications.

Piezo Ceramics – commercially used since World War II

If you've never heard of piezo's before, you might think they're something new and exotic. In fact, piezo ceramics have been around for decades; they were actually invented during World War II. The most interesting characteristic of a piezo ceramic component is that it acts as a transducer, transforming electrical energy into mechanical energy - expanding in one dimension and contracting in another.

Today, piezo ceramics are used in many shapes and forms and in many applications: cars, cell phones, sonars, PCs, PDAs, positioning applications, cameras, medical, audio and countless others. In other words, piezo ceramics are mainstream materials.

Mechanical characteristics

PCBMotors use the *traveling wave* principle to create motion in the stator.

Figure 3 (right), illustrates a mode shape for a 6-wave stator – a 30 mm diameter, FR4 material stator with 48 piezo elements on each side.

The motor is driven by resonance from the mechanical system. The driver generates a 2-phase voltage that matches the resonance frequency in the stator (mechanical system).

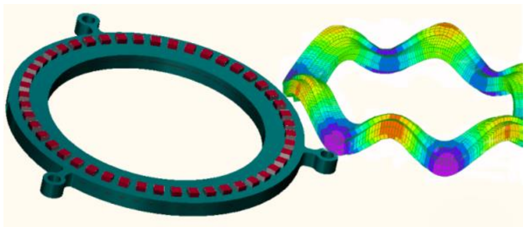

Figure 3 – 30mm stator ring (left) and 6-wave stator model

The resonance is determined by the stiffness of the PCB material, the motor's diameter, the thickness of the PCB, and the size and location of the piezo components mounted onto the PCB.

While it looks easy it's not simple

On the surface it might seem like designing a stator is simple. In fact, it's actually a very complex process and with many parameters that need to be taken into consideration to achieve the best resonance frequency.

Parameters such as:

- materials
- physical dimensions
- size
- thickness
- ring width
- piezo component placement
- bridge length
- shape and form

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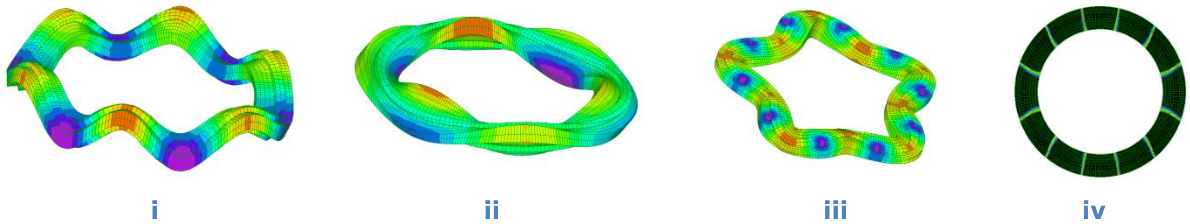

Figure 4 - Traveling wave principle at different frequencies 1 to 3, 4th is sand pattern for good resonance frequency.

Figure 4.i (above) shows a traveling wave with good resonance, 4.ii & 4.iii show a non-working traveling wave where the Eigen frequency is close to a good/working resonance. Finally 4.iv, to the right, shows the sand patterns of a standing wave with a good/working frequency.

Use our engineering expertise and customized design tools
The optimization of these parameters goes far beyond any standard layout tools and is the reason why PCBMotor can swiftly deliver and expedite the required layouts for your applications.

Electrical characteristics of piezo components used in the PCBMotor
The performance of the motor (such as speed & stall torque) is closely related to the total DC current supplied to the output stage transformers. The optimum frequency can be determined by measuring the supply current as a function of frequency.

Figure 5 (below) compares the current measurements for two ordinary 330 pF capacitors (one for each phase) with a free stator (also approximately 330 pF).

The current measurement for the two capacitors shows the expected minimum at the electrical resonance of the output stage, while the free stator (with the piezo elements) has a peak at the same frequency. This behavior is due to the *mechanical* resonance of the stator with the piezo elements. The peak represents the quality of the mechanical resonance.

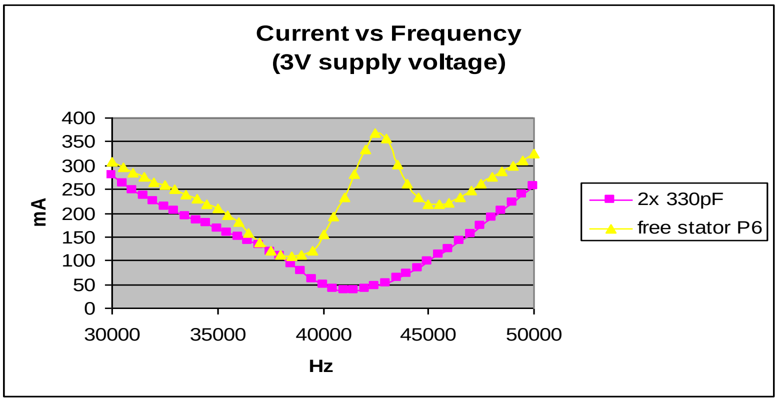

Figure 5 – Current vs. Frequency

The curves above illustrate a power efficiency of approximately 85% in the driver alone, as the 2 x 330pF current shows the loss involved in driving the stator.

The mechanical resonance varies with temperature, self-heating and operational lifetime etc., and the electrical driver needs to match the mechanical resonance for optimal performance. See also the Tracking controller section below.

Note: *The overall efficiency, from electrical input to power, on the shaft of the motor is in the range of 5-10%.*

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Stator Manufacturing

Figure 6 – Stator with piezo components in center

Stators are manufactured using standardized methods from the electronics industry. The piezo components are simply another set of electronic components added to the library in the layout tool. All that's required to produce the stator is some additional milling for the stator ring.

The surface mounting of the piezo components (SMD's) is also a standardized and fully-automated process.

For low volume series, the piezo components are supplied as Tape & Reel which fit standard *Pick & Place* machinery. This is a flexible and efficient solution for changes in the supply chain.

For high volume applications, a dedicated production line mounted with sorting and feeding equipment is also an option instead of Tape & Reels.

Figure 7 – Piezo components on Tape and Reel

Control Driver Electronics

The motor resonates at approximately 45kHz – supplied by a 5V power supply. It generates a two-phase sinusoidal wave that is stepped up through two transformers to a drive voltage of 100-200 V_{rms}.

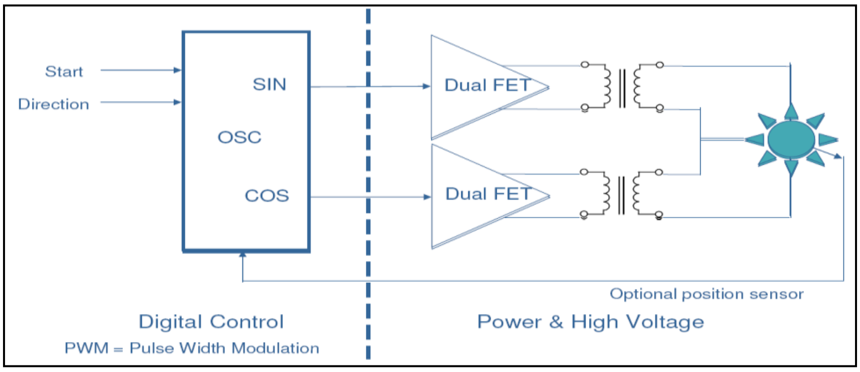

Figure 8 – Driver diagram

The V_s-supply for the motor can be adjusted for optimum motor speed. However, when the rotor is mounted on the stator, a minimum drive voltage is required to overcome the static friction between rotor and stator and start the motor turning.

There is a 90 degree angle of difference between the phases. Since the resonance is slightly dependent on the temperature of the PCB, the driver frequency control should take this into account. One solution is to measure the DC supply current to the motor driver.

The motor resonance frequency is primarily determined by the mechanical constants of the PCB-material and it's necessary to compensate for the change in resonance frequency to optimize performance over the entire temperature range.

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For optimal performance, the tracking feature implemented in all kits (except the Test Kit) is an effective way of setting the optimum frequency to compensate for the motor's self-heating. The frequency tracking feature can be easily implemented in your own microcontroller.

Tracking Controller

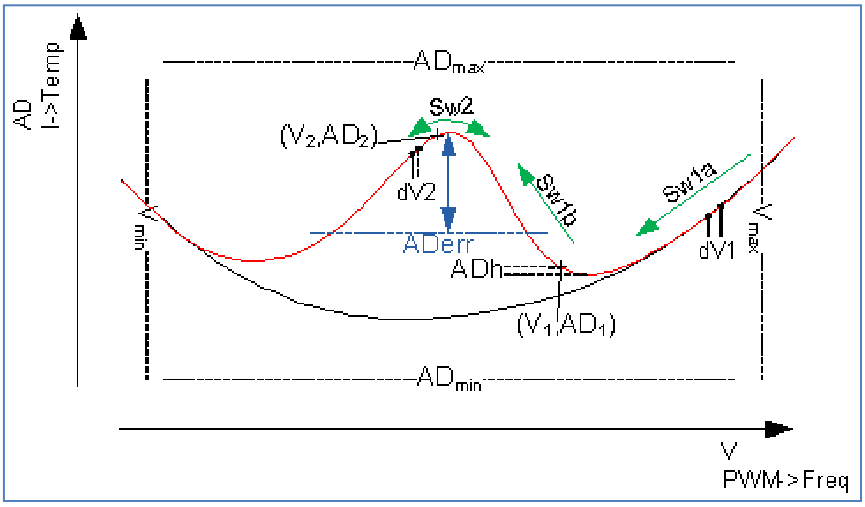


Figure 9 – Resonance tracking principle

The tracking controller, PIC16F684, is a microcontroller-based extension to our standard driver. The controller adjusts the frequency for maximum current, which gives optimum performance in the motor regardless of temperature and voltage.

When power is applied, the controller turns on the motor and makes an initial frequency sweep to find/store the resonance frequency. The motor is then stopped. The next time the motor is started manually, the stored frequency is used and optimized while the motor is running. When stopped, the last frequency is stored.

We've included some features in our new tracking controller to locate the resonance on the fly while "spinning" the motor up.

The red curve in the above diagram shows the current consumption of the motor.

When the motor is started, the controller will follow the *Sw1a-Sw1b* arrows until the maximum current is found. Then tracking will start and follow the resonance frequency versus changes in temperature and voltage.

By properly setting the parameters, the Sw1a-b process takes a fraction of a second. In practice, it operates as a "soft" start of the movement.

The Rotor

Rotors are generally application-specific and, therefore, need to be customized to fit the specific application.

Principle

To utilize the traveling wave generated in the stator, the rotor needs to be spring-loaded against the stator to convert the sub-micron waves into rotational movement.

A good principle is to have a rigid stator firmly connected to the application's axle. With the rotor placed against the rigid stator and guided by two or more guide pins located at maximum distance from center, a spring-loaded rotor locked toward the stator ensures the necessary pre-tension.

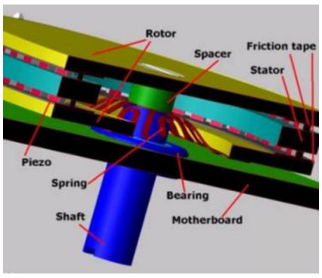


Figure 10 – Cross section of motor construction

The spring in the center of the upper rotor presses both rotors towards the stator. This force needs to be sufficient to ensure that there's a good contact between the rotors and the piezo components on the stator perimeter. However, if it's too strong it will act like a brake and block the motor.

Connecting the motor mechanically to the application should not disturb this balance. Ideally the mechanical design should ensure that the rotor only transfers rotational forces to the axle. A load of 75-150g mounted directly on the rotor will be OK, especially if the motor axle is vertical.

If the axle is horizontal, the mechanical load could make the rotors tilt whereby some of the piezo elements could lose contact with the rotors. This results in reduced motor performance and probably also increased acoustical noise level. Therefore, the load on horizontal axles should be lower and preferably mounted as close to the rotor as possible.

Resonances from the stator do have an impact of the rotor design, to avoid acoustical noise.

To achieve optimum friction properties, we recommend using our friction tape as an interface between the rotor and the stator. This will ensure the correct electrical insulation between the rotor and stator, motor performance and the lowest acoustical noise.

Rotor examples

Figures 11.1 to 11.5 (below) show various rotor examples with spring and encoder.

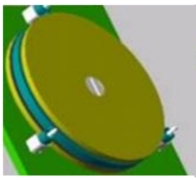
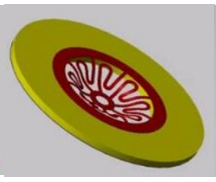


Figure 11.1 Rigid.

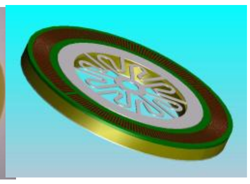


11.2 Spring rotor.

11.3 FR4 & steel spring.

11.4 Rotor & Spring FR4.

11.5 FR4 encoder.



11.6 Rotor w/spring & encoder

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Hollow shaft and hollow center rotors

Figure 12 (right) shows an example of a 10mm hollow shaft rotor that fits to a 30mm stator. The rotor includes *locking taps* for a tight axle fit, steel springs and encoder markings around the perimeter.

Figure 12 – Close-up of hollow shaft rotor.

A kit with this fitting is available in our E-Shop, based upon a 30mm motor.

Figure 13 (right), shows the principle for a maximum free hollow center. The rotor is made of FR4 and the kit also includes an encoder and spring blade.

A kit with this fitting is available in the shop with a free 40mm free center based upon a 60mm stator.

Figure 13 – 40mm hollow center rotor.

Rotors with lead screw

Figure 14 shows and example of how a lead screw can be implemented with a PCBMotor.

Please note that the rotor includes the encoder and the top hat determines the stroke length of the lead screw.

A lead screw demonstration kit is available in the E-Shop.

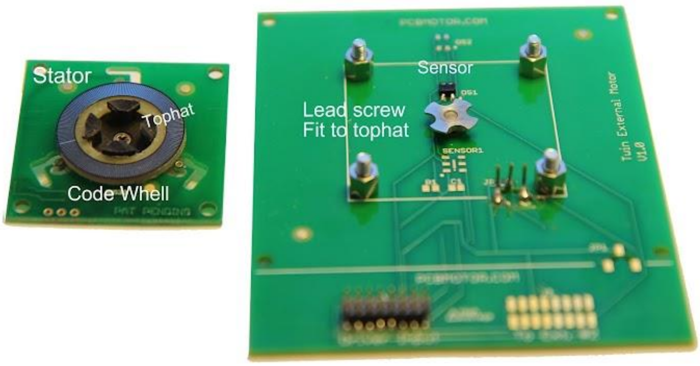

Figure 14 – Rotor and lead screw

The above rotor figures are just examples of various rotor solutions. PCBMotor's mechanical design service can assist you moving from prototype development to (volume) production.

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Key Features

Direct drive, low RPM without any slack

PCBMotor's direct drive technology eliminates the need for gears and clutches and reduces the occurrence of slack errors resulting from gear wheels. Direct drive on-board motors, therefore, can be more accurately (and easily) integrated into applications than conventional motors, which significantly reduces engineering and production bill of materials.

This, combined with the PCBMotor's low speed output (up to 120 RPM), makes it perfect for motion control systems and applications that demand superior positioning, ultra-high resolution and very fast start/stop actions.

Full holding torque without power

PCBMotors utilize the *traveling wave* principle combined with a spring-loaded rotor to generate the rotational output. PCBMotors only require power when in operation and maintain full holding torque (100%) when in *power-off* mode which ensures that the motor holds its position.

Infinite resolution

The ultra-high resolution of the PCBMotor is only limited by the controller and the actual load of the motor.

In 2011 PCBMotor set a technology record of 2.6 million steps per revolution using the High Resolution Twin Motor Kit with a digital position sensor, proving that ultra-high micro pulsing is not only a reality, but a viable option.

A fully-integrated solution

Motor, drivers & electronics all in one place

At the core of the PCBMotor is surface-mounted piezoelectric components mounted like any other electronic component. All electronics can, therefore, be located on the same printed circuit board, which significantly reduces the overall size and space required by applications.

Also, by surface mounting actuator components directly onto the PCB, there are no additional assembly costs for screws, wires, connectors and manual mounting. This also means an improvement to the application's overall height and size, and a significant reduction to the bill of materials, and assembly time.

Design freedom

If your end-product's dimensions require a more innovative, compact design, **PCBMotor's unique form factor** gives system designers greater flexibility and the freedom to customize and design movement into their applications & products.

The unique, hollow, ultra-slim form factor enables designers, engineers and product managers to further reduce application dimensions (size, space, weight, and height).

The **motor's *ring shape* has a number of advantages**. For instance, you can place a lens in the center of the motor and turn the motor to focus the lens.
See our hollow center motors (through-hole devices) & other customized designs online…

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Motor Sizes, Speed and Output Power

The diameter of the motor can vary. The standard range is from 20–90mm.

A powerful motor requires a large diameter, because more piezos generate more power. However, with a longer distance to travel, speed is reduced. High speed can be obtained with a smaller diameter.

Torque and Speed vs. Motor Current

Figure 15 (right) shows the relationship between speed and torque, and the resulting output power for a Ø30mm stator.

It gives a free speed of approximately 2 rev/sec with no torque, and a stall torque of approximately 25Nmm – depending on the spring load of the motor.

Figure 16 (right) highlights the relationship between speed and torque at different current settings with the same spring load.

Figure 15 – Speed, torque & Power for Ø30mm stator

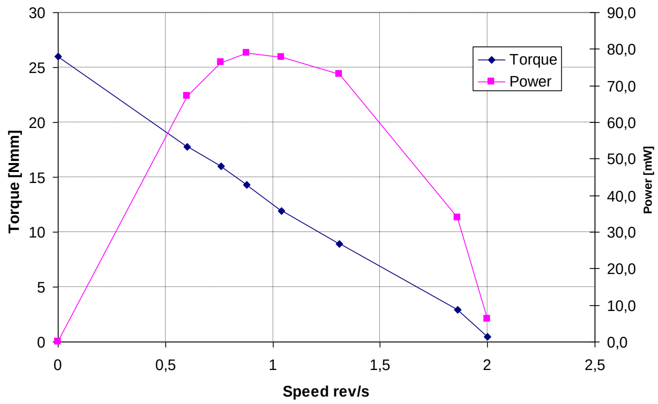
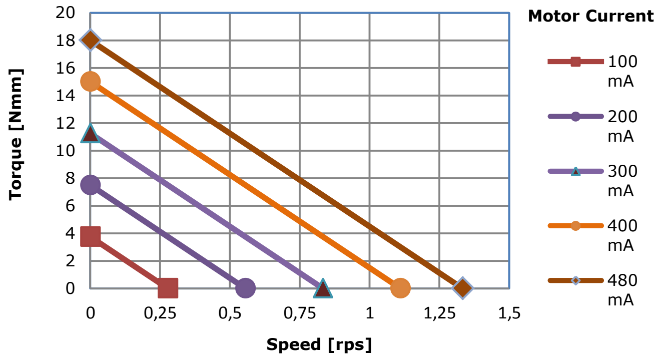


Figure 16 - Torque and Speed vs. Motor Current Ø30mm stator



Stall torque vs. temperature

Figure 17 (right) shows the relationship of mean stall torque and current consumption over a temperature range of +20-70 °C.

The drop in torque can be offset with an adjustment to the voltage supply.

An operating temperature range of **-40-85 °C** has been tested and confirmed in some customers' applications.

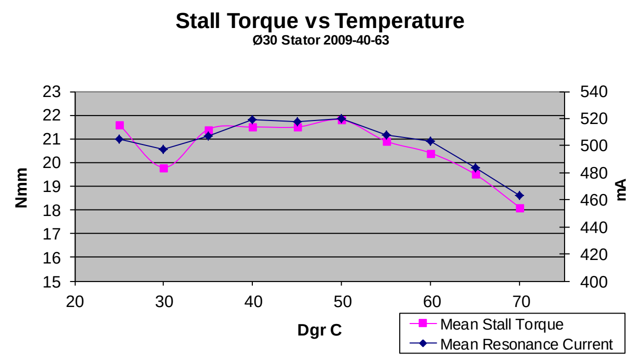


Figure 17 – Stall torque versus temperature

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Lifetime test

The PCBMotor is a friction motor. It is the friction layer that determines the lifetime.

Applications that require high torque (and force) have, in generally, a shorter lifetime than applications having lower torque requirements.

The final application and its actual operating environment ultimately determine the motor's life expectancy.

High force application has demonstrated lifetime of >1000 hrs. in continuous operation.

Valve application: +1000 Hours

Figure 18 shows the test setup and time in minutes and seconds *(Tid min:sek)*.

This test was performed on a Ø30mm PCBMotor in a valve application with a measuring gauge. The PCBMotor activates the valve with a force of 100N via a spindle. The graph shows how long it takes for the motor to activate. The motor stood still for 5 seconds between each activation.

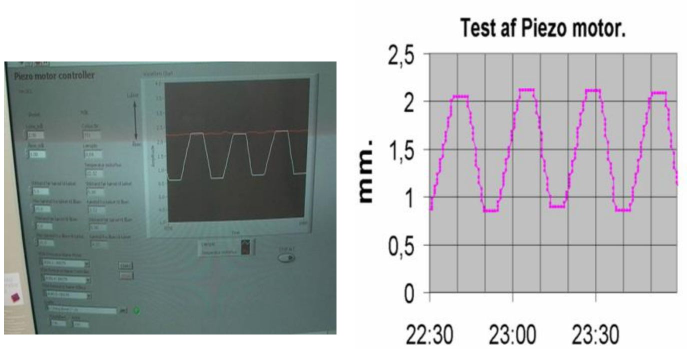

Figure 18 – Test of Ø30mm valve application +1000 Hrs. ~125,000 activation

The test was performed at approx. 50% duty cycle to lower the temperature rise due to self-heating.

The total operation active time equates to more than 1000 hours of continuous operation. The motor passed the customer's lifetime test, and was still working when the test was completed, although there was clear sign of wear on the friction tape.

Room temperature – no sign of end-of-life

Figure 19 shows a number of Ø30mm motors in a setup for continuous operation at room temperature, where current consumption was measured over time.

The Ø30mm motors ran continuously, logging data every 10 min.

Note: The experiment shows no changes (End-of-life) in the given timeframe.

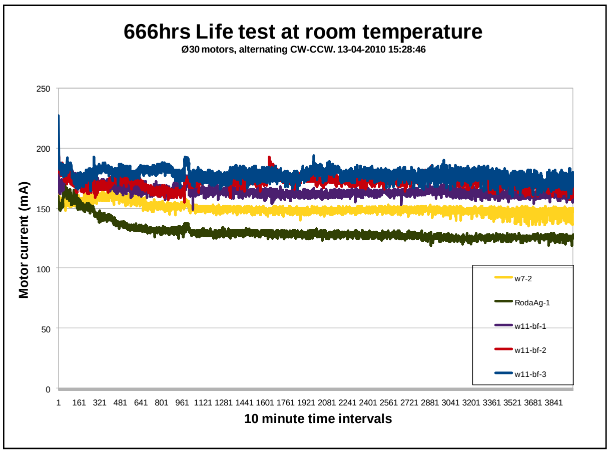

Figure 19 – Test of Ø30mm motors for continues operation at room temperature

Performance

Table 1 - Stator diameters, number of piezos, speed, torque & output power relationships.

Outer Diameter mm	Inner Diameter mm	#Pz/Stator	Free Speed rev/sec	Stall torque Nmm	Max Output Power mW
20	14	64	1.6	8	40
25	19	80	1.3	13	50
30	22	96	1.0	18	59
40	32	128	0.8	32	79
50	42	160	0.6	50	99
60	52	192	0.5	72	118
70	62	224	0.4	98	138
90	82	288	0.3	162	177

Table 1 - *The calculations in the table above are based on a 6-wave, double-sided, 30 mm diameter stator*

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Design service

Stator Design

Despite looking simple, the stator design process is in reality quite complex. Our automated design tools facilitate an in-depth, dynamic and finite element analysis **for each individual design** to ensure that the stator only supports the resonance frequency wanted.

This means we can quickly make the design needed for your project including prototypes.

Controller

Our experienced engineers will jump start your project and help you to customize the driver or controller for your application.

You'll receive the best knowledge we've built up over the years, at a fraction of the cost and time **and** a secure path for further migration so you can focus on your application's electronics.

Firmware

The main controller used in the High Resolution Twin Controller, PIC 18F2520, has a rich set of commands that can solve most tasks needed to control the motor and position sensor.

Before you start programming your own controller, we can quickly and easily modify or add new command features to the controller. Any modifications can be made either as a firmware change, or as a part of a customized controller, with the interface you need.

This means you can focus on the application's firmware & secure a path for future migrations.

Software

Regardless of how you want to communicate with the PCBMotor – either through a high-level, PC software program, or directly to the controller – our engineers deliver the solution that fits your specific requirements.

Rotor

The ultrasonic frequencies, from the stator, add an additional design dimension to the mechanical construction before it can deliver the desired output to your application.

You can also get a head start on your project schedule by using our design service to help customize your application's rotor elements.

Read more about How We Work on our website – under 'steps to success' – and see how we can help your project into the next phase.

Conclusion

This white paper has demonstrated how a new generation of highly accurate and low cost piezo electric PCMotor's can be used for a variety of applications.

The PCBMotor utilizes the best from well-established technologies - piezo electric components and printed circuit boards - and combines this into a low cost, high resolution and high torque motors ideal for volume applications where economies of scale starts from only a few hundred units and upwards to millions of motors.

Choose the right motor for your application and

- ✓ Lower assembly costs by automating assembly
- ✓ Lower your bill of materials with fewer parts and SMD Piezo ceramics
- ✓ Reduce your application's building height
- ✓ Get more design freedom
- ✓ Integrate a smaller form factor with motor, driver & electronics on one PCB
- ✓ Improve motor resolution and accuracy with
  - Direct drive – no slack
  - Higher torque
  - Holding torque when power is off

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Getting Started

If you're gathering information and have a few questions…no worries, that's why we're here.

Do send me (Henrik) an email with your questions and I'll reply ASAP – no strings attached! I'll even throw in our *Piezo Motor Technology Presentation* for you to pass on to your co-workers.

EMAIL ME & GET OUR FREE TECHNOLOGY PRESENTATION

An ideal place to start – PCBMotor Start kit

To fast-track your specific application's development, try our **Start Kit.** Available with a 30mm stator, this kit is a quick path to exploring the different possibilities and is easily altered to meet your needs.

Includes: Driver PCB, mounted piezos, rotor, 200-line encoder & position sensor
Website: http://pcbmotor.com/evaluation-kits/start-kit-30-mm/

Hollow center kit with 22mm free aperture, up 0.0625 degree and home position

Our newest product - and the ultimate way to test our ultrasonic piezo motor technology - is **The High Resolution Hollow center kit.** Simply plug it in to your PC and it's ready to go.

It's that easy and includes all the bells and whistles you need to answer the question "can it meet our requirements?" Experience its precision, high resolution & several motors controlled by one driver.

Includes: Twin PCBMotors, driver, software, USB cable
Website: http://pcbmotor.com/hollow-center-motors/30mm-diameter-stator-22mm-free-hollow-center-2880-counts-encoder/

We've a passion for sharing our knowledge and experience, so contact us today to find out how you can get started with a PCBMotor.

Henrik Staehr-Olsen, CEO
hso@pcbmotor.com

Intellectual Property Rights

Some of the processes described in this document are patent protected, or may become subject to patent protection. If you purchase piezo ceramic components from PCBMotor ApS, you will be permitted to use our patents to manufacture PCBMotors with such purchased components.

PCBMotor ApS's General Terms, available at www.pcbmotor.com, apply to any such purchases, as well as any other purchases of products or services from us.

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