Spinning the world of 3D Printers

A smooth driving for a flawless printing

3D printing is a new approach for product prototyping. Technological improvements and lower costs are encouraging the technology to spread quickly to professionals and hobbyists. The demand for precision, speed, and smooth print-head movement is a challenge for mechanical systems. A new motor driver can meet all these requirements using a dynamic microstepping operation.

Dario Cucchi, Enrico Poli

More than just an alternative method for making objects, 3D printing is a new approach in product development. It uniquely closes the gap between modelling and production by quickly creating components and functional prototypes that can be evaluated and tested during product development. This can reduce costs, increase quality, and accelerate the introduction of the final product.

Starting from a 3D CAD model, a 3D printer can build an object by deposing layer after layer of a fused filament of plastic – or other – material. This printing is, in reality, an additive manufacturing process that allows, among its many benefits, the creation of complex shapes that might otherwise require a big investment of time and/or money. 3D printing can even enable the infill of the reproduced object, saving material and time in production.

The improvements in 3D printing technology, together with the new materials used and the cost reductions of equipment, have accelerated the adoption of the technology in industrial areas such as mechanics, automotive, aerospace, biomedical, as well as in educational. On top of the larger commercial and design organizations using 3D printing, the broad range of maker communities on the Web, which include hundreds or thousands of hobbyists, model builders and modern artists, are also successfully using 3D printers.

Quality in 3D printing

The quality of the printings is evaluated on how the final object matches the original CAD model and whether the print shows visible defects. Other mechanical characteristics, such as fragility and deformability contribute to the overall quality. Quality can be influenced by the material of the plastic filament, its melting temperature and how it is being extruded, the thickness of a single deposed layer, the stiffness of the printer structure, the accuracy of the motor controlling the extruder, and the dimensions of the printing area.

There are always tradeoffs. An important tradeoff is between precision and printing time. Depending upon the dimensions of the object being printed and its complexity, printing can require many hours, so the speed of the extruder must be optimized to achieve the appropriate balance. Moreover, since the extruder has its own inertia, it can introduce defects on square angles and sharp edges, unless the extruder is moved with specific acceleration/deceleration profiles to compensate. The mechanical system of a 3D printer, containing rails, gears, and motors, must be very precise and free of vibrations and deformations, and have tight tolerances to move the extruder quickly and precisely to fulfill the resolution requirements.

Fundamental to guaranteeing a 3D print without defects are stepper motors, and especially because the resolution of a single step is not precise enough, the motors need microstepping driving techniques to move the motor shaft by fractions of a single step. Naturally, the higher the microstepping resolution, the smaller fraction of a step the motor can handle. For example, a printer can better reproduce an area rich with details using a high micro-stepping resolution or change to lower-resolution stepping for less complex areas. The motor-driving technique should adapt and drive these changes of speed and resolution to optimize printing time and resolution. This is where choosing a motor driver IC that can support all these working conditions is crucial.

Smooth and reliable motion control

The requirements listed above—adaptable and precise motion control—are met by STMicroelectronics' STSPIN820 device. With an integrated controller that implements a PWM current control with fixed OFF time, adjustable by an external resistor, the integrated control logic can manage eight different microstepping resolutions from full step mode up to a resolution of 1/256th of a step. This guarantees very smooth, precise, and silent movement. No external power MOSFETs are necessary to drive the stepper motor since the STSPIN820 integrates two full-bridges rated to operate up to 1.5 Arms each. The device can work with a wide supply range, from 7V to 45V and includes overtemperature protection, overcurrent protection for each of the eight power MOSFETs, and undervoltage lockout, which prevents the device from working after a sudden supply-line voltage drop. Each protection mechanism triggers an open-drain pin, which signals the fault to the MCU. Figure 1 shows the basic STSPIN820 block diagram and the few external components required for a typical application.

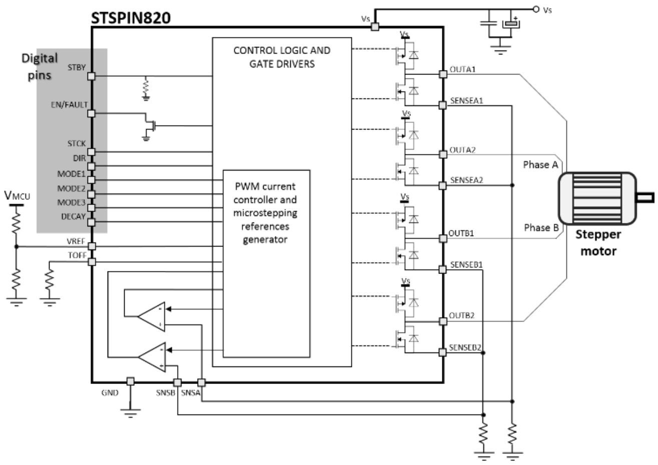

Figure 1: Block diagram of a typical application using the STSPIN820

The STSPIN820 comes in a compact TFQFPN 4 x 4 mm package. This small form factor, together with the reduced number of external components needed, saves PCB board size as well as the BOM count for the final application.

Improving precision with microstepping

Although the microstepping driving technique can achieve a high level of precision and reduction in vibrations, the higher micro-stepping resolution means that the MCU must manage the higher step clock (STCK). Since there are acceleration and deceleration profiles to be computed, the higher the STCK frequency, the higher the effort required by the MCU. When high speeds and high resolutions are involved, the required STCK frequency becomes very high, too. Although the STSPIN820 maintains step counting even at frequencies up to 4 MHz, decreasing the microstepping resolution could be an option to decrease the STCK frequency. In fact, when the motor rotates at high speeds, precision in the positioning is not as crucial, and the microstepping resolution can be decreased. Reducing the step clock frequency reduces the MCU overhead—a nice tradeoff between microstepping resolution and rotation speed. Choosing the right microstepping resolution provides a way to limit the step clock frequency without losing performance while still guaranteeing the desired acceleration and speed profiles. Microstepping driving techniques are key for reducing vibration and ensuring smooth movement for high-quality 3D printing.

Testing vibrational results

We mounted the LSM6DSL, which is an inertial module containing a 3-axis accelerometer and a 3-axis gyroscope in a single 2.5x3mm LGA package, directly on the stepper motor and tested the vibration at different microstepping resolutions and speeds. The LSM6DSL has a selectable full scale and a maximum output data rate of 6.66 kHz for both accelerometer and gyroscope. The axes orientation of the module, as it was mounted on the stepper motor, is represented in Figure 2. The measurement of the acceleration along the three axes can give an estimation of the vibration and resonances introduced by the motor shaft on the motor body, while the measurement of angular rate using the gyroscope can give further information about the mechanical response in the system.

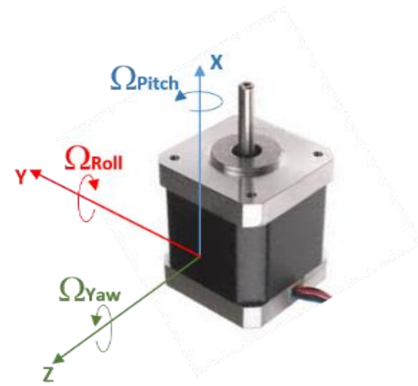

Figure 2: Axes orientation of the inertial module on the motor

The first analysis related to the mechanical response of the system is done by applying a single step on the motor, using the full step mode (the lowest resolution), and then the 1/256th step mode (the highest resolution). Figure 3 shows the mechanical response of the accelerometer (above) and the gyroscope (below) setting the STSPIN820 in the full step mode. A single step clock is applied to get the movement of one step: the motor shaft produces a jerky movement and the mechanical resonance is stimulated. When the shaft settles to the new step position, vibrations decrease so the mechanical response is a damped sinewave with a resonance frequency around 290Hz.

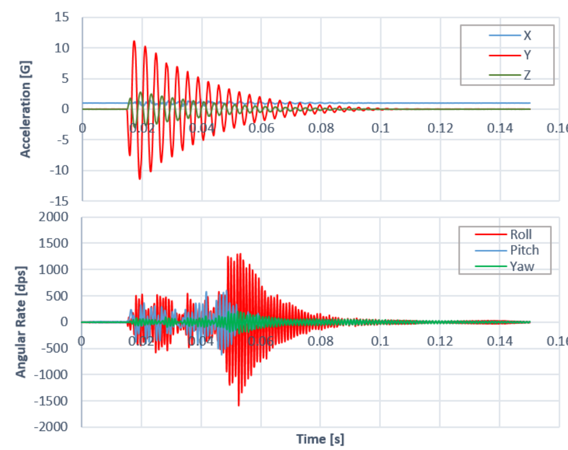

Figure 3: Mechanical response to a single step movement (Full Step resolution mode)

Setting the microstepping resolution to 1/256th of a step, 256 STCK pulses are needed to get the same movement of one mechanical step. In this case, the currents driving the motors are modulated smoothly—they increase with a sinusoidal profile in order to smoothly guide the shaft to the new step position without abrupt movements. The mechanical resonance is minimally stimulated and the mechanical response is cleaner, as shown in Figure 4. In this example, the STCK pulses are applied with a frequency of 12.8 kHz, for 20ms.

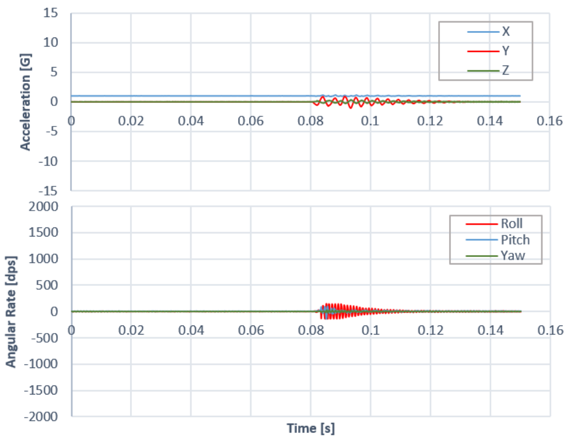

Figure 4: Mechanical response to a single step movement (1/256th Step resolution mode)

When multiple steps are performed consecutively, multiple vibrations occur and contribute to the overall mechanical response. The resonances and the vibrations can be stimulated depending on the speed rotation of the motor.

To analyze vibration versus speed, we consider only the accelerometer data and use five of the eight microstepping resolutions available in the STSPIN820: Full Step, 1/4th, 1/16th, 1/32th, and 1/256th of a step. The motor is driven with a continuous rotation at a specified speed, so for each microstepping resolution, the step clock is set accordingly. To combine the information coming from the three axes, the modulus of the 3D acceleration vector is computed:

$$V = \sqrt{(a_x - 1)^2 + a_y^2 + a_z^2}$$

where ax, ay and az are the values of the acceleration read on each axis, represented in G, the gravity acceleration (9.81 m/s2). The accelerometer also senses the gravity acceleration; as the motor is positioned as shown in Figure 2, the gravity acceleration lies along the X axis. Therefore, the value of gravity acceleration (1G by definition) is subtracted from the ax value. The chart shown in Figure 5 represents the trend of the vibration magnitude (the maximum measured value of vibration V) versus the speed of the motor (in rpm), for different microstepping resolutions. At lower speeds, the vibration can be limited by increasing the microstepping resolution. On the other hand, we see that when the speed is increased, the curves tend to converge, and the difference in vibrations between the different resolutions becomes smaller. This happens because at higher speeds, the reference current from the microstepping sequence is changed more quickly than the maximum current slew-rate of the system, which is limited by both phase inductance and back electromotive force. In this case, some of the microsteps (the point composing the sinusoidal current profile) are not physically performed. Consequently, there is no reason for such a high resolution.

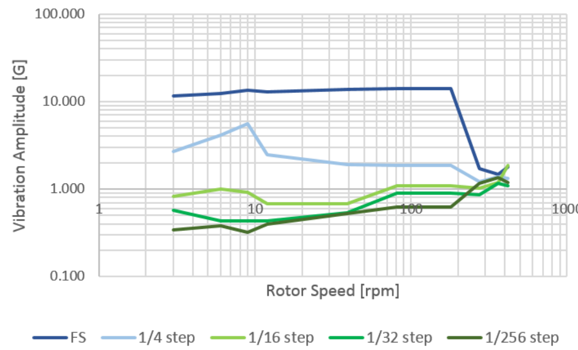

Figure 5: Vibration VS speed at different microstepping resolution

According to these results, higher speeds do not require high microstepping resolution since the advantage in terms of vibration and smoothness is not significant. However, it demands a lot from the MCU in terms of computational effort.

Changing microstepping mode "on the fly"

To optimize step-clock generation and movement precision, the microstepping resolution can be changed dynamically, according to what the application requires. The graph in Figure 5 shows that when small movements are needed, a high microstepping resolution can guarantee excellent vibration and smoothness results. On the other hand at higher speeds, the vibrations reduce, so a high-resolution mode is not required. The clock speed can be decreased without an excessive loss of precision and with the advantage of decreasing the MCU computation effort.

With the STSPIN820, the step mode can be modified "on the fly." Figure 6 illustrates an example where the speed of the motor is increased up to the target of 360 rpm. The motor used in the example counts 200 steps at each rotation. The acceleration profile is driven not only by increasing the step clock, but also by dynamically changing the microstepping resolution. In this way, it is possible to keep the step-clock frequency below 15 kHz, while limiting the vibration of the motor shaft and maintaining a high degree of smoothness in the whole movement. Figure 6 shows both the vibration (above) and the step clock frequency (below) versus the speed, when using a dynamic microstep resolution. The change from one-step mode to another is represented by the vertical dotted lines. The upper and lower limits obtainable are also shown in the charts. The highest vibrations (upper limit) occur in full step mode, while the lowest ones occur in 1/256th step mode. The dynamic microstepping selection provides a way to keep the vibrations close to the lower limit, thus improving precision. From the STCK point of view, the dynamic mode selection keeps the frequency in a reduced range: it never increases beyond 15 kHz, well below the upper limit.

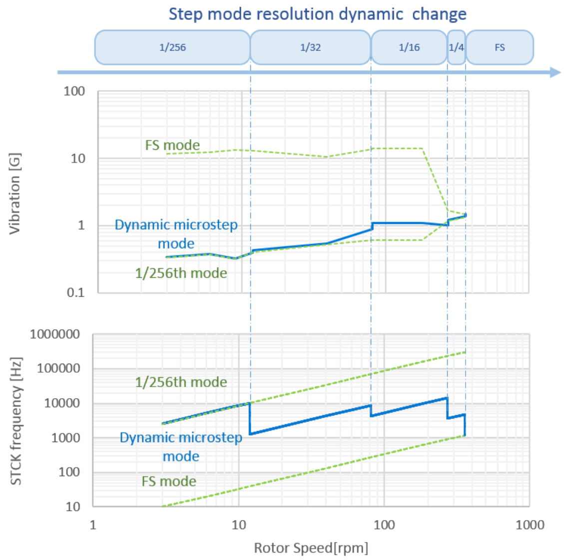

Figure 6: Scaling step clock and microstepping resolution

Once the target speed is reached, it is possible to switch to full step mode, increasing the torque with respect to the torque in microstepping mode. This is an important feature achieved by dynamically switching from microstep to full step mode. The change in full step mode must occur only when an electrical position of 45° is met—when the currents in the two phases of the stepper motor are the same. In this way, only the current amplitude changes without any change in the electrical angle.

The advantages of dynamically switching the microstepping mode are shown using the same example with a static setting: if we use the 1/256th step mode with a 360 rpm target speed, a STCK up to 307.2 kHz is needed. From the MCU point of view, this is very demanding, and there is almost no improvement using the highest microstepping mode at such speeds. On the other hand, setting the full step mode at low speeds results in a very noisy movement, unsuitable for the precise positioning requirements of 3D printing.

Moving to the next step

The new generation of stepper motor drivers, like the STSPIN820, resolves many of the challenges for a wide range of motor-driving applications. Together, the small 4x4mm package and a reduced number of external components equal very compact and cost-effective boards. The world of 3D printing is still evolving, requiring ever more precision and speed to improve prototyping. With a high microstepping resolution up to 256 microsteps and the ability to change step resolution "on the fly," the STSPIN820 proves itself an excellent choice for fast and precise 3D printing—as well as other tricky motor-drive applications.