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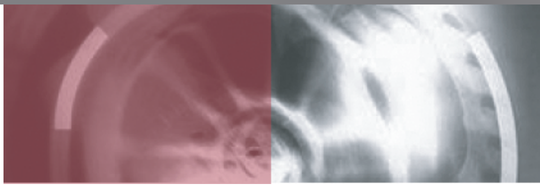
White Paper

Technical



Agile Systems SilentStep™ Technology

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Synopsis *– Stepper motor drive systems appeal to a wide variety of position and motion control applications, because of their inherent control simplicity and lower cost versus servo-system alternatives. The performance of conventional stepper motor drive systems is limited, excluding them from applications requiring high speeds, high acceleration rates and smooth motion. They are also prone to excite mechanical resonance, stall easily and emit discernible audible noise. Over the years added stall detection and electronic resonance damping features have provided partial improvements. This paper presents Agile Systems' SILENTstep™ Technology, which operates stepper motors in closed position loop without position sensors. It boosts stepper-motor performance into the range of servomotor performance while maintaining the inherent simplicity of the conventional stepper motor drive system.*

I. INTRODUCTION

Stepper motors and attendant drivers are the technology of choice for a multitude of industrial position and motion control applications. Low cost of motor and drive combined with the ultimate simplicity of open loop stepper control are the most compelling reasons for the application of stepper motor and drive systems versus competing, more complex servomotors and servo drives. Other stepper motor drive advantages include rugged motor construction, high reliability since no failure prone feedback devices are needed and short commissioning cycles since no servo-loop tuning is required. Of course, the simple open loop stepper motor drive cannot match the performance of a servomotor drive. Figure 1 presents a comprehensive list of stepper motor drive advantages and disadvantages.

Advantages	**Disadvantages**
Low cost	Excites machine resonance
Ruggedness	High audible noise
Control Simplicity	Potential position loss
High reliability	Prone to stall
Maintenance free	High torque and speed ripple
No tuning	Limited usable torque
No feedback components	Limited motor speed
High torque vs. size	

Figure 1, Stepper motor advantages and disadvantages

The typical low speed torque of a stepper motor is about twice as large as the torque available from an equivalent brushless servomotor, but it is not fully usable in a real world application. Because of the open-loop stepper motor's propensity to stall, it is generally necessary to select a stepper motor with ideally

50% torque margin, in order to avoid stall conditions with an adequate degree of certainty.

Over the years efforts have been undertaken to transform stepper-motor systems into pseudo servos [1], by adding feedback based closed loop control or implementing means of indirect stall detection and resonance damping. However, the proposed methods either increase system complexity by adding feedback devices or overcome some of the typical stepper motor disadvantages only partially by adding stall detection and resonance damping algorithms. The method presented here overcomes all conventional stepper-motor drawbacks without adding feedback components and thus maintaining the simplicity of conventional, open loop stepper motor drive systems.

II. OVERVIEW

The SILENTstep™ controller derives position feedback from back-EMF and phase current sampling and maintains the key stepper-motor advantages listed in Figure 1, including the inherent simplicity of conventional stepper-motor controls. Figure 1 lists the improvements obtained from the proposed method vis-à-vis disadvantages of conventional stepper-motor drives.

Stepper-motor Disadvantages	**Improvements**
Audible noise	Reduced by approximately 75%
Limited usable motor speed	Increased usable motor speed
Limited acceleration	Acceleration at full torque limit
Typically no or limited stall detection	Stall prevention
Potential to lose steps	No position loss during accel/decel and at speed
Prone to excite machine resonance	Elimination of machine resonance effects

Figure 2, Improvements

Stepper motors typically convert digital pulse inputs to analog output rotor movement. In response to an electric input pulse, the rotor of a stepper motor rotates by a design-specific number of degrees, or a step. This discontinuous stepping causes audible noise at higher speeds and it excites resonance effects in the mechanical systems connected to the motor shaft. Mechanical resonance can have a detrimental impact on machine life and in case of high rates of acceleration may cause the motor to stall. For an ideal motor with sinusoidal torque versus rotor position function, the maximum acceleration in steps per second squared is a trivial function of the resonant frequency of the motor and rigidly coupled load [2]. SILENTstep™ operates a stepper motor in flux-vector mode and closed position loop. The motor operates in continuous mode rather than conventional stepping mode. The audible noise and resonance effects associated with conventional stepping mode are effectively eliminated. The drive system is not limited to the acceleration given by the system’s resonant frequency in a conventional stepper-motor drive.

As SILENTstep™ derives position information based on motor back-EMF, which is proportional to motor speed, it is necessary to accelerate the motor from standstill to a speed sufficiently high to generate back-EMF voltage at a measurable level. The stepper-motor starts from standstill and accelerates to the back-EMF threshold speed in conventional micro-stepping mode. At the back-EMF threshold speed, the drive switches to closed-loop operation while retaining the position where the switch over took place. Since stepper motors have relatively high torque at low speeds and relatively high speed constants (high back-EMF) the switch to closed-loop operation typically takes place at frequencies (speeds) much below where audible noise and resonance effects become a problem.

The SILENTstep™ controller requires bipolar stepper motors with either twin full bridge drive circuits as shown in Figure 3, or 3 half bridges as shown in Figure 4. It is not applicable to unipolar stepper-motor designs.

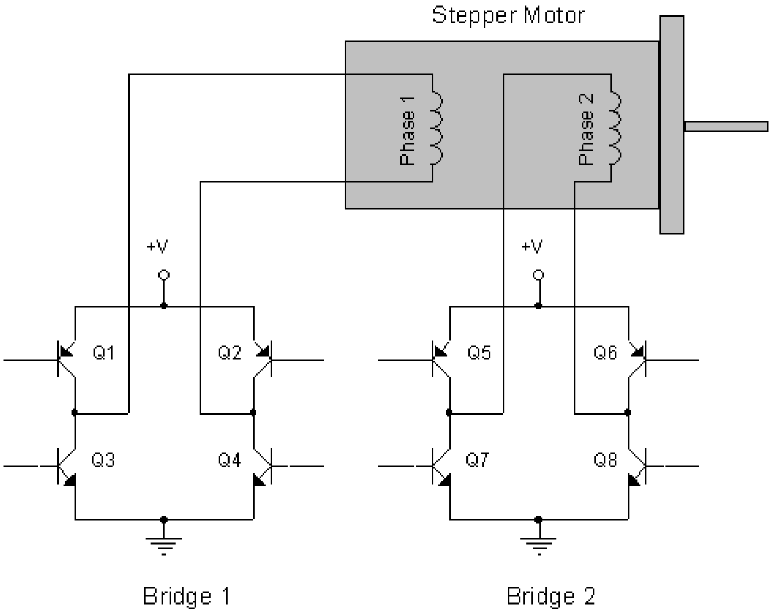

Figure 3, 2-phase bipolar stepper motor with twin full bridge drive circuit

Using three half bridges as opposed to two full bridges reduces the number of electronic components from 8 power switches and associated driver and control circuits to 6, and allows the control of stepper motors with power drive circuits commonly used for BLDC or AC induction motors. The half bridge formed by the 2 center switches is shared between the 2 phases, and as such this half bridge is used by both windings. Driving the motor with 3 half bridges has a disadvantage in that voltage applied to each phase is effectively half of what would have been available by using 2 full bridges. As such, it results in lower usable motor speeds than if 2 full bridges were utilized with the same power supply. However, the

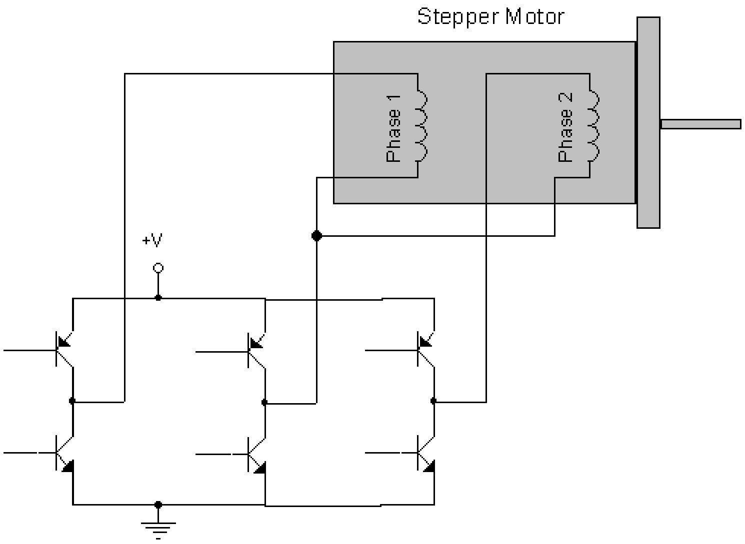

Figure 4, 2-phase bipolar stepper motor with 3 half-bridge drive circuit

employed flux-vector control method allows magnetic field optimization control to compensate for the voltage loss and extend the motor's speed range. The magnetic field optimization is not limited to the use of 3 half bridges and can be utilized in conjunction with 2 full bridges as well. For brevity the method presented is illustrated for 2-phase stepper motors. The method can be applied to motors with more than 2 phases just as well.

III. OPERATING PRINCIPLE

Figure 5 shows a 2-phase bipolar step motor and its equivalent circuit. The motor is simplified to a 2-pole motor, even though typical step motors have 50 or more magnetic poles. The number of magnetic poles has no impact on the operating principle. The proposed method will work as described regardless of the number of magnetic motor poles. The equivalent circuit applies to either a twin full bridge drive circuit as per Figure 3, or 3-phase half bridge drive circuit as per Figure 4. The difference between the 2 drive configuration is represented by the dashed line, where A, B and C in the equivalent circuit in Figure 5 are connected to the 3 half bridges as shown in Figure 4. Either drive circuit will regulate the current in phase A and phase B using pulse width modulation (PWM). The PWM duty cycle may be considered as a percentage from 0% to 100% of a time period when current is being supplied to a motor winding. From the duty cycle for each motor phase and measurement of the DC-bus voltage, the drive controller can calculate the voltages from A to A' (C) and from B to B' (C) in Figure 5 by multiplying the DC-bus voltage

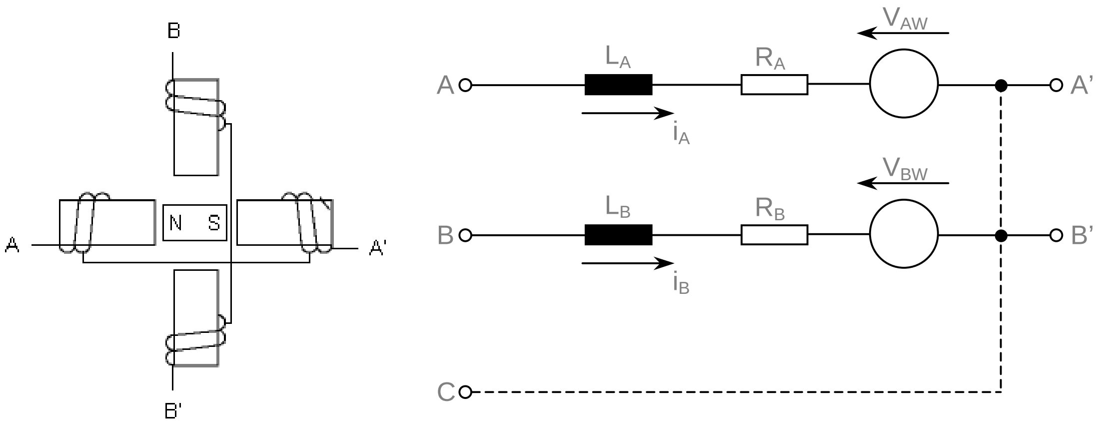

Figure 5, 2-phase stepper motor and equivalent circuit

and the PWM duty cycle percentage of phase A and phase B. The SILENTstep controller can easily measure the phase currents i_A and i_B with either shunt resistors in series with phase A and phase B or suitable current transformers.
Based on the equivalent circuit in Figure 5, the back EMF voltages for phase A V_{AW} and phase B V_{BW} are given by equations 1 and 2 for any instant in time.

$$V_{AW} = V_A - V_{A'} - L_A \, di_A/dt - R_A \, i_A \quad (1)$$

$$V_{BW} = V_B - V_{B'} - L_B \, di_B/dt - R_B \, i_B \quad (2)$$

The terminal voltage and the time derivative terms in equations 1 and 2 of the current flowing through the windings A and B can be estimated using a finite difference scheme. The resultant difference equations are of order $O(h^4)$. This means that the resultant error is directly proportional to the fourth power of the time step used. Average values are used for the inductance terms L_A and L_B in equations 1 and 2.

Integration of the back-EMF voltages yields the back-EMF flux vector corresponding to each winding denoted as λ_{AW} and λ_{BW} (equation 3 and 4), where C is an integration constant representing the initial flux vector.

$$\lambda_{AW} = {}_0\int^n V_{AW} + C \quad (3)$$

$$\lambda_{BW} = {}_0\int^n V_{BW} + C \quad (4)$$

The arc tangent of the ratio of the flux vectors of phase A and phase B represents the motor-rotor position. The difference between the rotor position at time n and at time n + 1 represents the motor speed at an instant in time. In this way the rotor position and speed feedback generated from current voltage sampling allows closing of position and speed loops.

The rotor position serves also as input to the flux-vector control function, providing smooth motor motion and eliminating the resonance effects and audible noise associated with open-loop stepping mode of conventional stepper-motor drives. Equations 5 and 6 describe the relationship between the phase currents i_A and i_B and the torque generating flux λ_Q and the direct flux λ_D. The angle θ represents the rotor position in equations 5 and 6.

$$\begin{bmatrix} i_D \\ i_Q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & -\cos(\theta) \end{bmatrix} \cdot \begin{bmatrix} i_A \\ i_B \end{bmatrix}$$

$$\begin{bmatrix} \lambda_D \\ \lambda_Q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & -\cos(\theta) \end{bmatrix} \cdot \begin{bmatrix} \lambda_{AW} \\ \lambda_{BW} \end{bmatrix}$$

The drive controller sets the torque generating flux λ_Q and the direct flux λ_D indirectly by adjusting the phase currents i_A and i_B. At lower speeds the drive controller will seek to maximize the torque generating flux λ_Q and to minimize the direct flux λ_D to ideally zero.

As the motor speed increases the voltage induced in the motor windings by the magnetic field of the motor rotor (back-EMF) increases in proportion to the speed. As this voltage reaches the level of the DC bus voltage further increases in motor speed are only possible, if the induced voltage is reduced. The SILENTstep controller achieves this through magnetic field optimization. The controller derives I_D and I_Q commands from the setpoint and actual position and speed. When the magnitude of the voltage vector reaches a maximum value, the controller will automatically phase adjust this vector, in order to maintain the proper setpoints and keep the motor running at the speed setpoint well beyond the speed where the motor would normally stall in open loop mode. The magnetic field optimization is a tradeoff between torque producing motor current I_Q and flux λ_Q and motor speed, where the drive controller reduces the torque producing current in order to raise the back-EMF imposed speed limit.

IV. RESULTS AND CONCLUSIONS

The SILENTstep™ controller generates a position resolution of about 4º electrical from motor current and voltage sampling, yielding an equivalent resolution of 0.08º mechanical with a 50-pole stepper motor. At low speeds and standstill full micro-stepping resolutions are available. The rotor position information derived form current and voltage sampling allows implementation of a flux-vector commutation scheme, which overcomes the negative effects of conventional open-loop operation of a stepper motor - audible noise and resonance effects.

With flux-vector control comes the ability to implement magnetic field optimization that allows an increase of the available motor speed by 100% above the back-EMF voltage imposed limit. Since the SILENTstep controller derives position feedback from internal current and voltage sampling, it maintains the control simplicity and low cost characteristics that make conventional stepper motor systems attractive.

V. References

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