Electromagnetically Driven UltraFast Tool Servo*

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Abstract

This paper presents an ultra-fast motor design for actuating tool servos. In comparison with conventional fast motors, higher acceleration and better-structural design can be achieved. Based on the ultra fast motor, a linear ultra-fast tool servo is designed for diamond turning. The material selection, real time computer, and power amplifier design for the ultra-fast tool servo control are also described.

Introduction

Fast Tool Servo (FTS) technology plays important roles in precisely manufacturing complicated free-form surfaces for the modern optics industry. The increasing complexity of surfaces requires more components in shorter spatial wavelength, and thus drives simultaneously the need for high bandwidth, high acceleration and high accuracy of the FTS. The conventional drive solution for an FTS is high-voltage driven piezoelectric stacks [1], which suffer from structural resonance modes and large hysteresis energy loss and are thus challenging to operate at high frequencies. As an alternative solution, variable reluctance actuators can be used with fast tool servo [2]. In earlier paper, we demonstrated an electromagnetically actuated fast tool servo with 163G acceleration and 10kHz bandwidth [3]. This paper presents a new design of electromagnetically driven ultra-fast tool servo, which has been significantly improved over the first prototype. The power amplifier design and the real time control issues are also addressed.

Ultrafast Motor

Electromagnetic motors have significantly higher force density in the air-gap normal direction than in the shear direction. However, a motor working on normal stress has of necessity a relatively short motion range. For fast tool servo application, such a short stroke is generally acceptable.

A typical normal force solenoid-type actuator is shown in Fig 1. This actuator has a very strong nonlinear characteristic: the actuating force is proportional to the exciting current squared and inversely proportional to the air gap squared. In order to control such a strongly nonlinear actuator, a biasing current is usually applied. However, the actuator is then linear to exciting current only at the neutral position (equal air gap on both sides of the armature) with a constant biasing current. When biasing force is applied with dynamic feedback linearization, the actuator can be linearized globally and dynamically [4]. However, this linearity suffers at high frequencies where significant modeling errors exist.

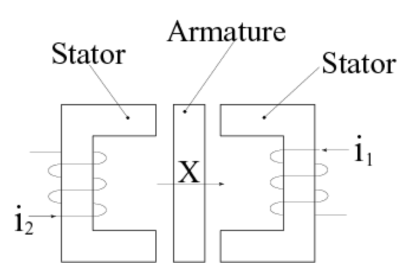

Fig 1. Solenoid-type fast motor

Flux bias can be utilized to achieve better linearity and power efficiency. Fig 2 shows a hybrid motor design using permanent magnets to generate biasing flux. As opposed to the solenoid-type actuator, the actuating

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force is linear with both air gap and exciting current, because the permanent magnets permeability is near that of air, and thus the DC bias flux doesn't change significantly with armature position.

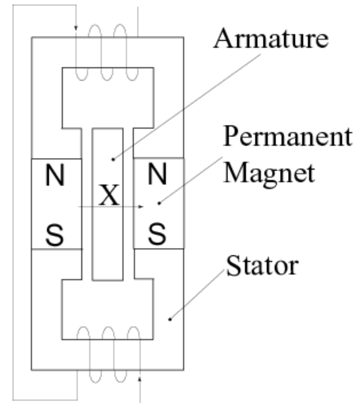

Fig 2. A hybrid fast motor

All of these motors above have a common problem: the middle part of the armature is part of the flux path but has no contribution to the force generation. This leads to excess inertia, thus limiting the achievable acceleration. Moreover, the middle part cannot be reduced in size because the bias flux will saturate the armature or stator if the middle part of the armatures in Fig 1 and Fig 2 are too narrow.

In order to fully realize the potential of a normal-stress motor, we have developed the ***ultra-fast motor*** as shown in Fig 3. This motor is linear in principle, *e.g.* the actuating force is a linear function of both exciting current and armature displacement. Further, the moving part is a combination of armature and motion backbone with high specific stiffness. All of the armature normal area in this motor generates normal force, since the flux bias is brought in through the radial faces of the armature. Moreover, the excitation coils are fully enclosed by the armature pole faces. Thereby, more coil area can be accommodated, and the leakage flux is significantly reduced. Consequently, more actuating force can be generated without overheating the coils or saturating the flux path in the solenoids.

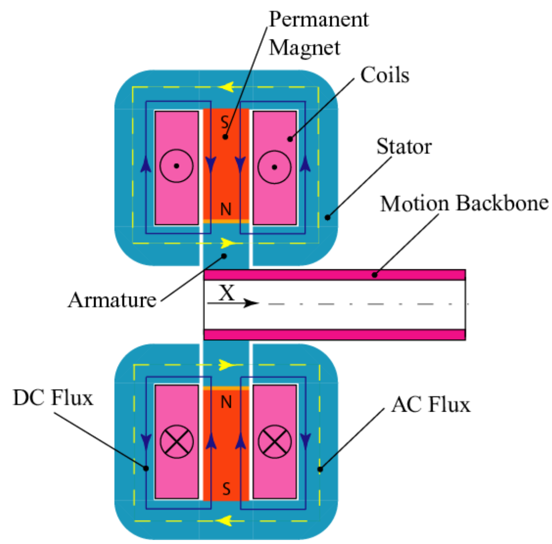

Fig 3. Ultra-fast motor working principle

Since the ultra fast motor does not require the middle part of the armature in the flux path, the motor can easily be paralleled with multiple armatures. For example, Fig 4 shows a prototype rotary ultra fast motor with multiple armatures demonstrating such parallelism.

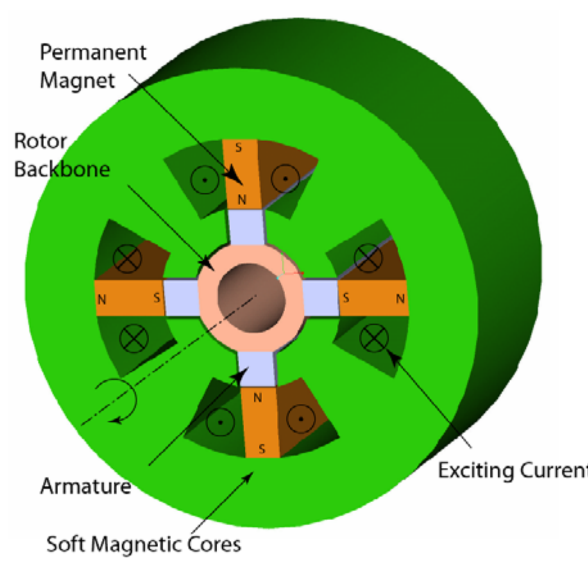

Fig 4. Rotary ultra-fast motor concept.

UltraFast Tool Servo

The design details of our ultrafast tool servo are shown in Fig 5. The moving part is composed of the armature, the moving backbone, and the diamond tool holder. The moving backbone is made from ceramic with high specific stiffness. The moving part is supported by a front spring steel flexural bearing and a rear rubber sheet bearing of the type proposed by Rivin [5]. A capacitance probe directly senses the tool holder motion from behind. Therefore, the tool can be controlled accurately and independently of structural length variations induced by thermal expansion or cutting/inertial forces.

The actuating force F is a linear function of exciting current I and the armature position X, which greatly simplifies the associated control laws. By normalizing these variables with F_0, I_0, and X_0, the force relation can be formulated as:

$$f = \eta\lambda,\ \ \lambda = i + \eta x$$

where f, η, λ, i, and x are normalized force, permanent magnet biasing strength, flux, and excitation current as defined below:

$$f = F/F_0,\ \ i = I/I_0,\ \ \eta = B_{pm}/B_0,$$
$$x = X/X_0, F_0 = A_e B_{sat}^{\ 2}/2\mu_0,$$
$$B_0 = B_{sat}/2, B_{pm} = B_r A_{pm}/2A_e,$$
$$I_0 = 2X_0 B_0/\mu_0 N.$$

Here X_0 is the air gap at neutral position, B_{sat} is the saturation flux of the armature, B_r is the remanence flux of the permanent magnet, A_e is the effective armature pole face area, A_{pm} is the pole face area of permanent magnet, and N is the turn number of excitation coil winding. From this result, it is clear that the actuating force f is more directly related to flux λ than to exciting current i. By using a flux feedback method as shown later, we can thus achieve better linearity than using current control alone.

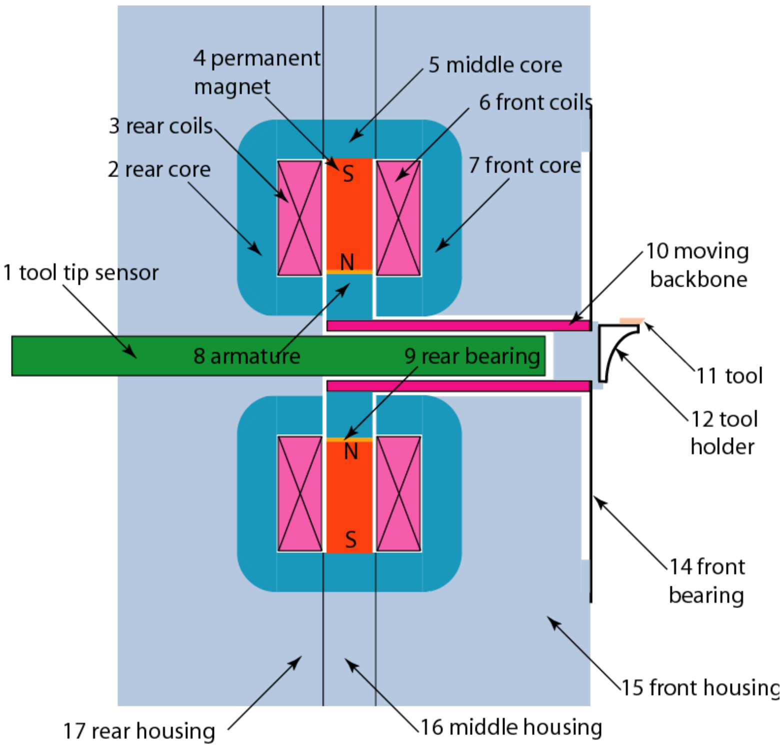

Fig 5 Linear ultra fast tool servo design details.

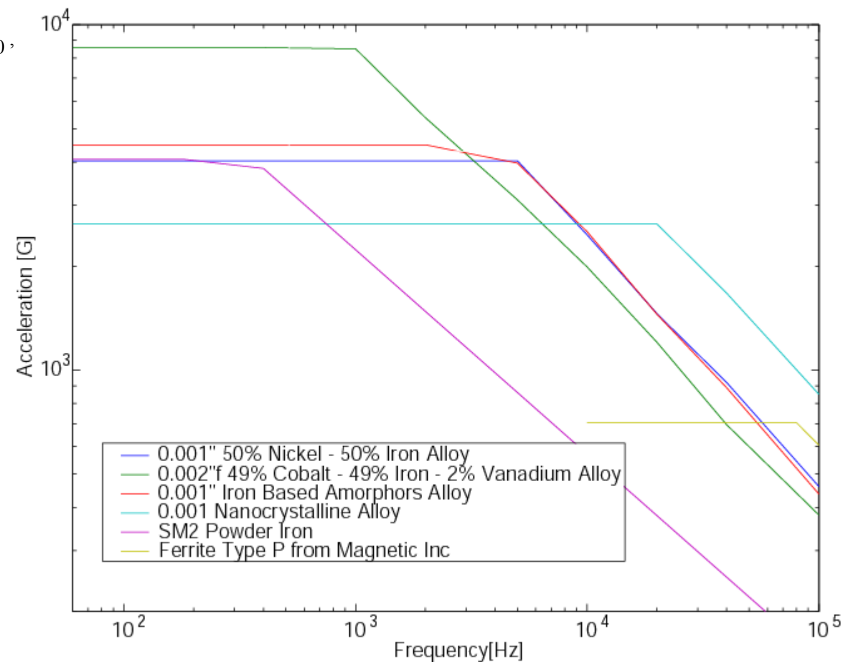

Fig 6. Typical soft magnetic materials acceleration performance. The energy loss is limited by $0.25 W/cm^3$.

Magnetic Materials

A key issue for the ultra fast tool servo design is soft magnetic material selection. Promising candidates include silicon-iron, nickel-iron, metallic glass, and powder iron. In order to reduce the eddy current loss, the soft magnetic material is either laminated or in powder format. The laminated material shows much lower core loss, especially the nanocrystalline material developed by Hitachi Metal. But the powder iron has structural advantages and can easily be accommodated in a 3-D flux path. Fig 6 shows the calculated maximum acceleration over frequency for different materials for 3mm armature thickness. At low frequencies the acceleration is limited by the material saturation flux, while at high frequencies acceleration is limited by eddy current and hysterisis induced heat.

Real Time Computer

In order to control this ultra-high bandwidth FTS, we have designed a real time computer with a total computation power of 5.4GFLOPS by using 3 DSPs running in parallel at 300MHz. A 1MHz control loop speed has been achieved with 1.8us total delay. The total harmonic distortion of the A/D and D/A is less than –88dB up to 50kHz. This real-time computer will support FTS tool servo research up to 50kHz bandwidth.

Power Amplifier

We have designed a 1kW linear amplifier to drive the FTS using four APEX PA52A amplifiers in parallel to drive the excitation coils. Using fluxing sensing coils [6], a flux sensing circuit is integrated into the current feedback path as shown in Fig 7 to feed back the generated flux at high frequencies. Thereby, this amplifier works in current mode at low frequencies, and works in flux mode at high frequencies where the current feedback signal rolls down and the flux feedback signal rolls up. Consequently better linearity can thereby be achieved at high frequencies. Additionally, armature position x is fed back to compensate the negative spring effect of the ultra fast motor with an analog feedback loop, which has higher bandwidth than a digital implementation.

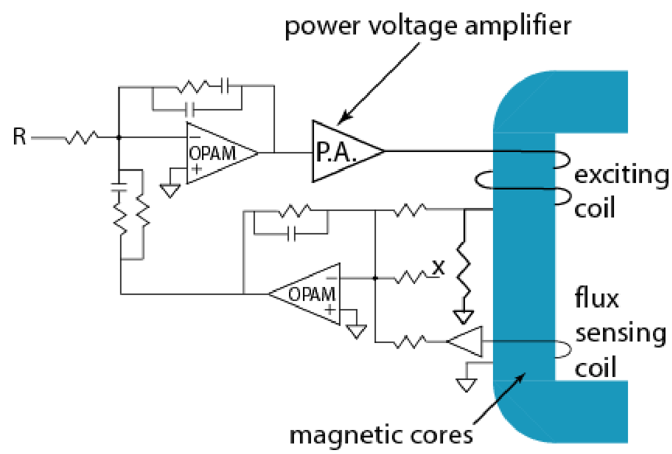

Fig 7. Power amplifier control circuit with flux feedback..

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