The Space Congress® Proceedings

1969 (6th) Vol. 1 Space, Technology, and Society

Apr 1st, 8:00 AM

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Introduction

Aerospace technology — in particular space flight — has encouraged and sometimes made necessary the development of new devices and the continual improvement of present devices. One new device which may offer distinct advantages over existing devices in the area of rotating machinery is a recently developed DC brushless motor.[1] Some of its advantages are the elimination of electronic interference, constant torque generation, simplicity of construction, and the maintenance of performance specifications over wide ranges of load, input, and environment. Notice that the elimination of EMI/RFI interference is especially desirable to on-board communication systems. Other system malfunctions have been traced to unintentionally generated stray signals. It is conceded that there were several types of DC brushless motors in existence prior to this one, but these motors all have the serious disadvantage that the rotor sensing mechanisms require more complicated circuitry.[2-6]

Description of the DC Brushless HG Motor

In the most simple terms, motor action is obtained via the interaction of a rotor magnetic field with a stator magnetic field. Naturally these fields seek alignment. Thus the following somewhat oversimplified steps can lead to the development of a motor:

a. A means of establishing a rotor magnetic flux is implemented.

b. A technique for determining the rotor angular position is needed.

c. Utilizing the results of (a) and (b), a means is employed whereby a stator flux is established 90° (optimum torque angle) in advance of the desired direction of rotation.

In the present designs, step (a) has been accomplished by permanently magnetizing a machined rotor. Future larger designs could employ wound rotors with slip rings — still a much improved performance over brush commutation.

In order to execute step (b), Hall generators were displaced on the stator at 90° near the periphery of the rotor as depicted in Fig. 1. These devices, about as large as a small transistor, are four terminal devices which respond to the intensity and direction of a magnetic field. Although the Hall Effect was discovered in 1879, it is only within the last decade or two that renewed interest has led to new Hall devices and applications.[7-11]

The final step (c) is accomplished utilizing the simple circuit of Fig. 2. The Hall generators HG13 and HG24 can be used to directly drive transistors T1, T2, T3, and T4 which control the excitation to the stator windings. All other known schemes for sensing rotor position, such as optical or mechanical, require special circuitry in order to steer the control transistors.[1] This represents a substantial advantage for HG type devices.

All the previous steps are self-explanatory with the exception of the last one. Assume the rotor flux Φ_r advances in the direction θ as shown in Fig. 1. Then it can be assumed that the HG13 drive, which is approximately sinusoidal, can be connected to provide a flux as given by

$$\bar{\Phi}_{13} = \left(\pm\right) \Phi_m \cos\theta \ \bar{a}_y \tag{1}$$

where $\bar{\Phi}_{13}$ is the vector directed flux produced by W1 and W3 in the unit vector direction y. Similarly

$$\bar{\Phi}_{24} = \left(\mp\right) \Phi_m \sin\theta \ \bar{a}_x \tag{2}$$

The vector sum of (1) and (2) is precisely the stator flux. If connections are made which correspond to a (+) sign in (1) and a (-) sign in (2), then a constant stator flux Φ_m is established which is 90° in advance of the rotor flux and the motor runs counterclockwise. Reversal would require either the reversal of each HG drive pair or the reversal of the HG bias current. It is notable that for any electric motor, torque T is given by

$$T = K \Phi_r \Phi_s \sin\delta \tag{3}$$

where:

K = a proportionality constant

Φ_r = rotor flux

Φ_s = stator flux

δ = torque angle or the angle of Φ_s and Φ_r.

Since Φ_r is a constant, as is Φ_s (identical with Φ_m), the HG DC brushless motor is a constant torque device. This has been borne out in the laboratory with the exception of initial transients during starting when some saturation effects are noticeable.

Applications

The first device chosen for discussion

is a speed controlled DC brushless motor which is the first application that was developed.[1] Speed controlled devices might range from crude torquing devices to tightly regulated or even synchronous motor gyro drives.

Speed Controlled HG DC Brushless Motor

A typical speed-controlled HG type DC brushless motor is shown in Fig. 3.[12] The HG bias current is supplied via R4, R2, and R6. The HG signal components are amplified by T5, T6, T7, and T8 according to the feedback signal generated by T9 and T10. Diodes D1-D4 rectify the uniformly phased back-emf sinusoidal voltages developed across W1-W4. The resulting feedback voltage, e_{fb}, is proportional to frequency. The reference voltage, e_r, is the voltage established by the zener diode D5.

In order to determine the motor speed, first refer to Fig. 4. The nodal equation for the amplifier input is

$$\frac{e_{fb}}{R_1} - \frac{e_r}{R_2} = e_i\left[\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_1}\right] \doteq e_i \frac{1}{R_i} = i_{10} \quad (4)$$

since R_i and R_2 are much greater than R_i of transistor T10. From Fig. 3,

$$v = -\beta_{10} i_{10} R_3 \quad (5)$$

where β_{10} is the base to collector current gain of T10 and R_3 is defined as R9. Proportionality constants K_ω, and K_g, which are measurable in the laboratory, can be defined such that

$$\omega_o = K_\omega v \quad (6)$$

and

$$e_{fb} = K_g \omega_o \quad (7)$$

If the reference voltage is defined as an input and ω_o is defined as the output, then equations (4) through (7) can be combined to give

$$\frac{\omega_o}{e_r} = \frac{R_1 (R_3 \beta_{10} K_\omega)}{R_2 (R_3 \beta_{10} K_\omega) K_g + R_1 R_2} \quad (8)$$

or if the open-loop gain $(R_3 \beta_{10} K_\omega)$ is made large, then

$$\omega_o \doteq \frac{R_1}{R_2 K_g} e_r \quad (9)$$

If one applies the standard sensitivity definition; i. e.,

$$S_K^{\omega_o} \triangleq \frac{\frac{d\omega_o}{\omega_o}}{\frac{dK}{K}} \quad (10)$$

where $S_K^{\omega_o}$ denotes the sensitivity of ω_o to a parameter K, then the percentage change in output speed is given by

$$\frac{\Delta\omega}{\omega} \doteq S_K^{\omega_o} \frac{\Delta K}{K} \quad (11)$$

For the simple expression of equation (9), the sensitivities are magnitude 1 or the percentage changes in output speeds are exactly equal to the percentage changes in R_1, R_2, K_g, and e_r which are primarily a function of temperature. At high temperatures, winding resistances essentially cause a decrease in K_g or an increase in ω_o. Other variations depend on the temperature coefficients of the respective devices. The operating speed (or speeds) are established by the proper choice of e_r and R_1/R_2.

A simplified and linearized transient analysis can be obtained by assuming that circuit transients are much faster than any associated mechanical or rotor transients. With this assumption the rotor torque equation — in Laplace variables — is

$$T(S) - f_e S\, \theta_o(S) = J_e S^2 \theta_o(S) \quad (12)$$

where T is the torque developed by the motor and f_e and J_e is the total equivalent friction and inertia of the rotor with load. Thus a torque constant K_T can be defined via

$$T = K_T v = K_T \left(-\beta_{10} i_{10} R_3\right) \quad (13)$$

or

$$T(S) = K_T V(S) = -K_T \beta_{10} R_3 I_{10}(S) \quad (14)$$

Combining equations (4), (13), and (14) yields

$$\frac{S\,\theta_o(S)}{E_r(S)} = \frac{\omega_o(S)}{E_r(S)} = \frac{\left(R_1 R_3 \beta_{10} K_T\right) / \left(J_e R_1 R_2\right)}{S + \left(R_2 R_3 \beta_{10} K_T K_g + f_e R_1 R_2\right) / \left(R_1 R_2 J_e\right)} \quad (15)$$

The transient form of (15) has been checked in the laboratory. Typical responses for no load are on the order of 25 milliseconds.

In order to demonstrate the speed stability capabilities of the device of Fig. 3, the torque vs speed characteristics of Fig. 5 were measured under a fixed environment and supply. However, to further illustrate stability, it should be noted that with thermistor compensation and an additional zener reference supply, the basic circuit of Fig. 3 has been used to hold output speed at a thirty percent efficiency within one percent for supply voltage variations of two to one, temperatures from - 20° C to 55°C, and loads from full to no load. With temperature compensated zener diodes and an operational amplifier in the feedback loop, even better regulation is obtainable.

Synchronous HG DC Brushless Motors

An immediate extension of the speed controlled DC motor can be realized by the introduction of a crystal controlled oscillator in the feedback loop which is used to drive T1, T2, T3, and T4 after the motor has been brought up to speed by conventional HG action. Thus, a synchronous motor with a stability of 1 part per 10^6 is possible.

Other Applications

Unfortunately, further discussions of HG DC brushless motors could not be presented at the time of this publication because the information on other prototypes is classified as proprietary information by B. M. E., Inc. These results should become available as these devices become thoroughly tested and proved, and the appropriate patent applications have been filed.

Conclusions

In summary, a new class of DC HG brushless rotating machinery devices, which offer many advantages for aerospace applications, has been presented. The following pertinent conclusions are enumerated.

1. The low RFI/EMI (noise) characteristics make this device particularly attractive for space application.

2. The HG brushless motors are constant torque devices — a particularly desirable feature.

3. The rotor position sensing devices, Hall generators, produce signals which require no special circuitry to drive winding current control elements.

4. The inherent simplicity of these HG DC brushless motors is attractive from a manufacturing point of view. For low power applications the rotor is merely a machined permanent magnet. Furthermore, major motor design changes can be made via electronic package modification — which is rather inexpensive compared to retooling for corresponding design changes in competing devices.

5. The simplicity by which speed can be controlled by this device, changing a feedback resistor, indicates that in many applications mechanical gearing can be replaced by a more reliable and smoother electronic gearing control.

6. Further research should be and is being devoted to perfecting new applications in order to take advantage of the many outstanding features of the HG DC brushless motors.

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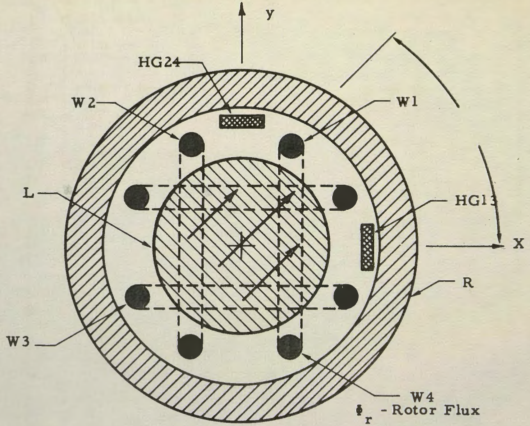

Φ_r - Rotor Flux

W - Windings 1 to 4 Magnetic Excitation Flux

L - Rotor

HG - Hall Generators

R - Magnetic Circuit

θ - Rotor Angular Position

Fig. 1 - Simplified DC Brushless Motor Schematic

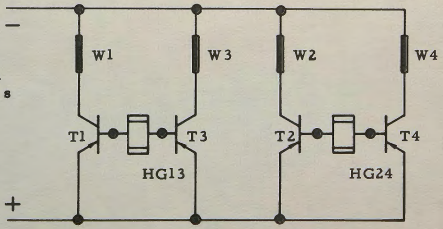

Fig. 2 - Basic Motor Circuitry

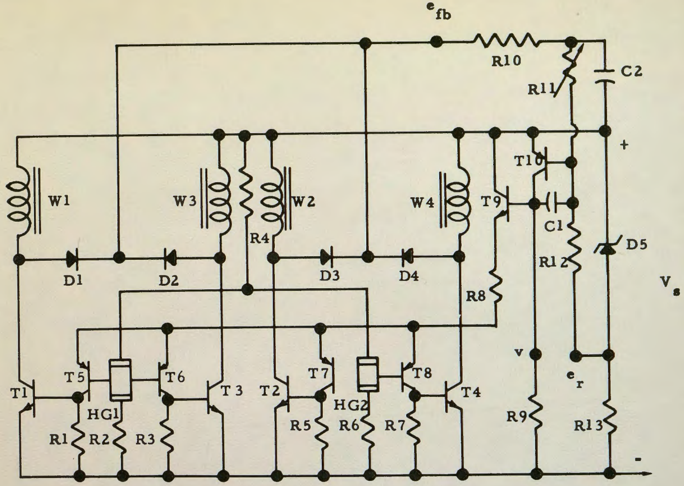

Fig. 3 - Speed Controlled DC Motor

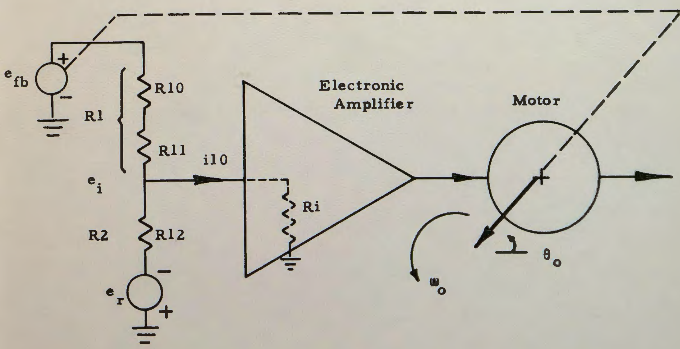

Fig. 4 - Simplified Speed Controlled Motor Schematic

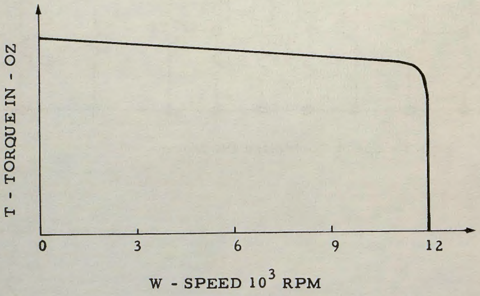

Fig. 5 - Torque Vs Speed of HG DC Brushless Motor