A Digital and Wide Power Bandwidth H-Field Generator for Automatic Test Equipment

Fengming Zhang*
fzhang@ece.neu.edu
L. Schiano*
lschiano@ece.neu.edu
F. J. Meyer*
fmeyer@ece.neu.edu

Y. J. Lee*
yjlee@ece.neu.edu
M. Momenzadeh*
mmomenza@ece.neu.edu
F. Lombardi*
lombardi@ece.neu.edu
Phil Perkinson†
phil_perkins@ltx.com

T. Kane†
thomas_kane@ltx.com
Y-B Kim*
ybk@ece.neu.edu
S. Max†
sol_max@ltx.com†

Department of Electrical and Computer Engineering, Northeastern University
Boston, MA 02115. Tel: 617-373-4159, Fax: 617-373-4431

†*LTX Corporation, University Avenue, Westwood MA 02090*

Abstract

Recent research on modeling timing jitter has raised a requirement for a predictable, high magnitude, uniform, and wide bandwidth H-field. In this paper, a novel H-field generator design methodology is proposed. It consists of a single layer air core solenoid and a digital power switch driver that takes advantage of low power, wide bandwidth, and big current-driven capability. With input overdrive voltage, the digital switch can drive rail-to-rail voltage with output current up to 16A and power bandwidth more than 3 MHz.

This paper demonstrates a novel solenoid driver circuit to generate an accurate H-field by comparing digital and analog approaches and comparing the experimental data with the theoretical data.

1. Introduction

Current advanced technology has integrated test functions of automatic test equipment (ATE) into the testhead board so that the volume, cooling requirement, and power consumption of ATE are reduced dramatically while functionality is increased greatly. As a result, very powerful DC-DC converters are used very often on the testhead board for ATE.

[1] has presented analysis and measurement of timing jitter induced by radiated EMI from the switch operation of DC-DC converters. To model the radiated EMI onto the timing jitter, an external H-field is applied around the phase-locked loop on the board. [1] used a ferrite core solenoid and a LC resonant circuit driven by a function generator. However, the H-field it generates is not large enough compared with the real magnitude of the H-field induced by the on-board and adjacent-board DC-DC noise. It also shows saturation problem due to the magnetic material saturation [5]. Its high inductance makes it vulnerable to the environment noise such as a PC board with ground plane [4], and the inductance changes with the H-field. All these will induce impedance error that may be dominant in the resonance circuit. Therefore, the current driving the solenoid and the generated H-field are not predictable.

In this paper, a single layer air core solenoid and a digital switch solenoid driver are proposed for the novel H-field generator. In contrast to analog drivers, there is no bias current for the digital switch. Theoretically, it can drive up to 16A current with more than 3 MHz power bandwidth.

2. Solenoid as an Electromagnetic Device

2.1. Inductance of a Solenoid

The inductance of a solenoid shown in Fig. 1 can be calculated by [9]

$$\begin{aligned} L &= \frac{\mu N^2 A}{l} \\ &= k\mu_0 N N' \pi R^2 \end{aligned} \qquad (1)$$

, where

μ_0 – Permeability of the free space
k – Relative permeability of the magnetic material to the free space
N – Number of turns
N' – Turns per meter

For a solenoid to generate a strong H-field, large inductance is not desirable. In such case, small input frequency fluctuation will vary very much its impedance, which may make conducting current unpredictable. For example, for a 4-layer, 100-turn, ferrite core solenoid, the inductance L is about 285 μH for a certain size and wire. If the real frequency is ω, then the impedance error induced by the input frequency fluctuation for a LC resonant circuit is:

$$\begin{aligned} Z &= \left| L\omega - \frac{1}{C\omega} \right| \\ &= \left| \frac{\omega^2 - \omega_0^2}{C\omega\omega_0^2} \right| \end{aligned} \qquad (2)$$

, where $\omega_0 = 1/\sqrt{LC}$ is the resonant frequency. When ω_0 is $2\pi \times 500$ kHz, the resonant capacitance C is 355 pF. If ω is $2\pi \times 502$ kHz, Z will approximately be 7.2 Ω. It can be even larger when the resonant frequency changes. Therefore, the impedance error can not be ignored. However, if inductance is reduced, C has to be bigger. Therefore, from Eq. (2), we can see the impedance error can be reduced by using a larger resonant capacitor, i.e. a lower inductance of the solenoid.

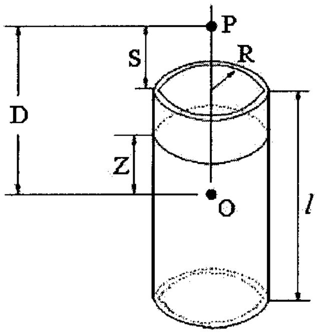

Figure 1. Dimension of a Solenoid

2.2. Magnetic Field Strength H

For an air core solenoid, the magnetic field B at a point P shown in Fig. 1 is given by [2]

$$B = \int_{-\frac{l}{2}}^{\frac{l}{2}} \frac{\mu_0 I R^2 N}{2l\left[R^2 + (D-z)^2\right]^{\frac{3}{2}}}\, dz$$

$$= \frac{\mu_0 I N'}{2}\left[\frac{-(2D-l)}{(4R^2+4D^2+l^2-4Dl)^{\frac{1}{2}}}+\frac{(2D+l)}{(4R^2+4D^2+l^2+4Dl)^{\frac{1}{2}}}\right] \quad (3)$$

, where I is the current through the coil.

If there is a magnetic material in the core of the coil, μ_0 has to be changed to μ [9] [3], which is permeability of the magnetic material and equal to $k\mu_0$. Therefore, the magnetic field strength H at the point P, which is in the air, can be calculated by $H = B/\mu_0$. If D is replaced with $S + l/2$, then H becomes

$$H = k\frac{IN'}{2}\left[\frac{-S}{(R^2+S^2)^{\frac{1}{2}}}+\frac{S+l}{[R^2+(S+l)^2]^{\frac{1}{2}}}\right] \quad (4)$$

The partial derivatives of H with respects to l and S are

$$\frac{\partial H}{\partial l} = k\frac{IN'}{2}\frac{R^2}{[R^2+(S+l)^2]^{3/2}} > 0 \quad (5)$$

$$\frac{\partial H}{\partial S} = k\frac{IN'}{2}\left[\frac{-R^2}{(R^2+S^2)^{3/2}}+\frac{R^2}{[R^2+(S+l)^2]^{3/2}}\right] < 0 \quad (6)$$

From Eq. (4), (5) and (6), it can be seen that increasing k, I, N', l, and decreasing R and S can increase H at the point P.

k can be increased by choosing different magnetic materials. For example, for a ferrite core, k can be 8 and 1000000 for a Ferrite U60 and a supermalloy, respectively. Very big k can dramatically increase the magnetic field of the coil, but make it very easy to saturate and very unstable to the variations of temperature and voltage etc. N' can be increased by using multiple layers. R and S are determined by the application, which typically requires S as small as possible and R to satisfy the area requirement for H-field coverage. Increasing k, N', l, however, can increase inductance as well. As shown in Eq. (4), inductance does not help increase H-field but make it vulnerable to the input frequency error and environment noise. Therefore, inductance of the solenoid should be as small as possible.

Alternatively, an air core and single layer solenoid is proposed and very high current I is used to drive the coil. l and I are carefully chosen so that a reasonable high H-field is generated. It has an inductance of only several μHs, such that very high noise immunity is accomplished. Compared with a multiple-layer solenoid, a single layer solenoid has the advantage of low self-capacitance and thus high self-resonant frequency [8]. In conclusion, an air core and single layer solenoid becomes the choice of design.

3. Solenoid Driver

3.1. Analog Drivers

In order to see the efficiency of analog drivers, a source follower using an N-channel power FET transistor was designed as shown in Fig. 2. But it has problems of stability and low current driving capability due to its big bias current. Then a power operational amplifier circuit shown in Fig. 3 was tested. However, the power bandwidth is limited. In our application, although it works up to 60 kHz, it is still not big enough for the research of radiated EMI noise from DC-DC converters on timing jitter. Although there exist commercial operational power amplifiers working more than 1 MHz frequency power bandwidth, they are not cost effective.

3.2. Digital Switch Driver

A digital power switch using both N and P-channel power FET transistors is proposed as an alternative. The proposed digital driver circuit is shown in Fig. 4. Instead of using an analog sine wave, which will have dead zone for the digital switch driver, as in the cases for analog drivers, a square wave is used as the input signal overdriving to the supply voltage. The transistors have very low channel resistance and very high switch

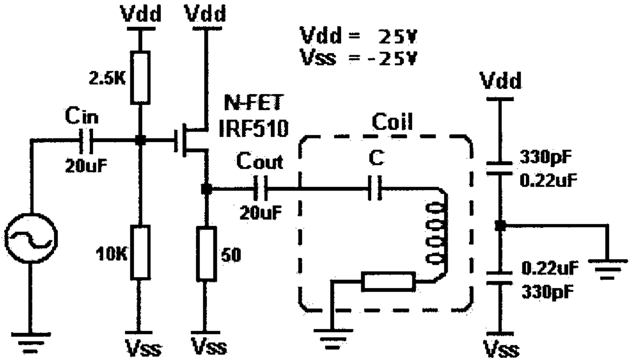

Figure 2. Solenoid Driver by a N-channel Power FET Transistor

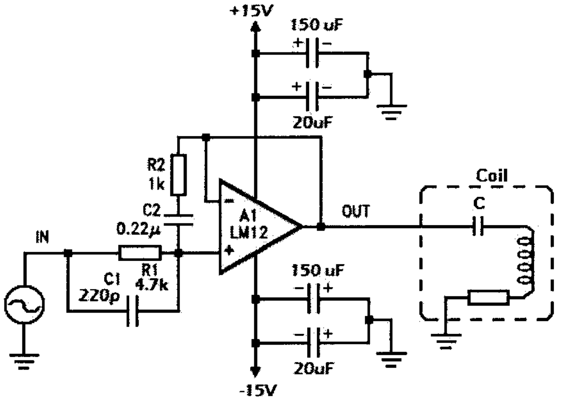

Figure 3. Solenoid Driver by a power Operational Amplifier

speed [7] [6]. Theoretically, it can drive up to 16A current and more than 3 MHz frequency. It satisfies both frequency and current driving capability requirements. It has several advantages:

1. Rail-to-rail output voltage.
2. Low power consumption because of no static current from V_{dd} to V_{ss}.
3. High stability due to the digital operation.
4. Higher noise immunity.
5. Much less cost than a linear power operational amplifier.

The circuit uses multiple carbon resistors to reduce the parasitic inductance. If one wire resistor is used, even though it shows high power rating, it suffers from the parasitic inductance from the wire resistor. A small sense resister R_3 is used, as shown in Fig. 4, to measure the voltage so that current through the coil can be calculated by just dividing the value of the sense resistance. Fig. 5, 6, 7, and 8 show the voltage waveforms of the sense resister under different frequencies.

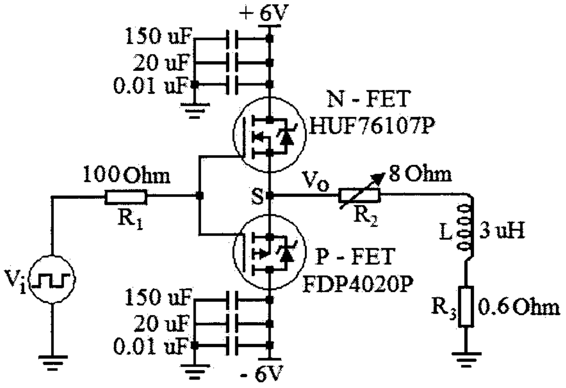

Figure 4. Solenoid Driver by a Power Switch Pair

4. Measured H-field and Calculated H-field

4.1. Measured H-field

A Hewlett-Packard close-field probe 11941A is used to measure the generated H-field. If the resonant circuit is used, the capacitance has to be tuned whenever the frequency is changed. In order to simplify the measurement process, the resonant capacitor was not used. Even though there is impedance due to inductance, it is predictable. As shown in Fig. 9, the H-field is not flat, otherwise the curves in Fig. 9 will be almost flat. The final measured H is calculated by

$$H = V_{SA} + AF + K \tag{7}$$

, where

V_{SA} – Voltage in $dB\mu V$ measured on spectrum analyzer

AF – HP 11941A Antenna Factor in $dB\left(\frac{\mu A/m}{\mu V}\right)$

K – Loss or gain in dB between HP 11941A and spectrum analyzer.

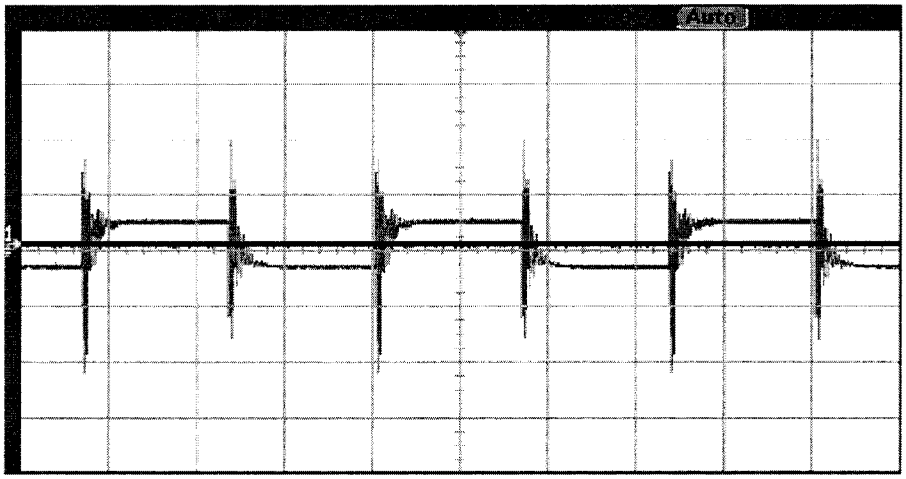

Figure 5. Voltage Waveform of the Sensor Resister for 100 kHz Input Frequency

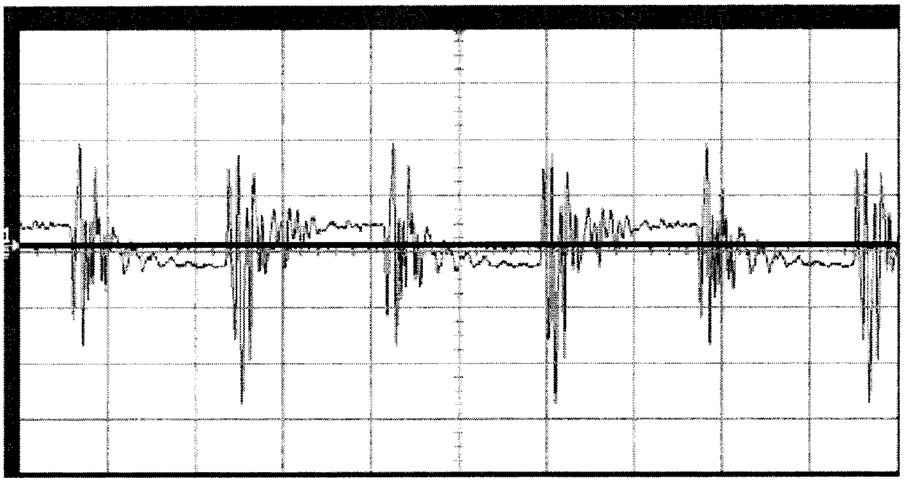

Figure 6. Voltage Waveform of the Sensor Resister for 400 kHz Input Frequency

In our case, there is no extra gain or loss, so K is zero. Also for frequency lower than 1 MHz, we assume the Antenna Factor is linearly distributed. The measured H-field is shown in Table 1.

Frequency [kHz]	Measured Voltage V_{SA} [dBμV]	Antenna Compensation AF [dB($\mu A/m/\mu V$)]	H-field [dBμV/m]
100	79.8	71.00	150.80
200	86.6	68.78	155.28
300	89.5	66.56	156.06
400	91.1	64.33	155.43
500	92.0	62.11	154.11
600	92.5	59.89	152.39
700	92.9	57.67	150.57
800	93.1	55.44	148.54
900	93.1	53.22	146.32
1000	93.2	51.00	144.20

Table 1. Measured H-field

5. Comparison of Measured H-field and Calculated H-field

As in Fig. 4, since we didn't use the resonant capacitor, the current can be calculated by

$$I = \frac{V_{dd}}{R_2 + 2\pi f L + R_3} \tag{8}$$

, where R_2 is the current limiting resistor.

From Fig. 9, we can see the error between calculated and measured H-field is quite small. If a resonant capacitor is used to cancel the impedance of the solenoid, R_2 becomes 0 Ω, and R_3 is reduced to 0.375 Ω, the maximum 16A current can be reached. Therefore, the constant and highest H-field, theoretically more than 190 $dB\mu V/m$, can be achieved. Comparing this current-driving solenoid driver with the voltage-driving driver using a function generator in [1] which cannot output more than 1A current, the advantage of using this novel digital current driver is quite obvious.

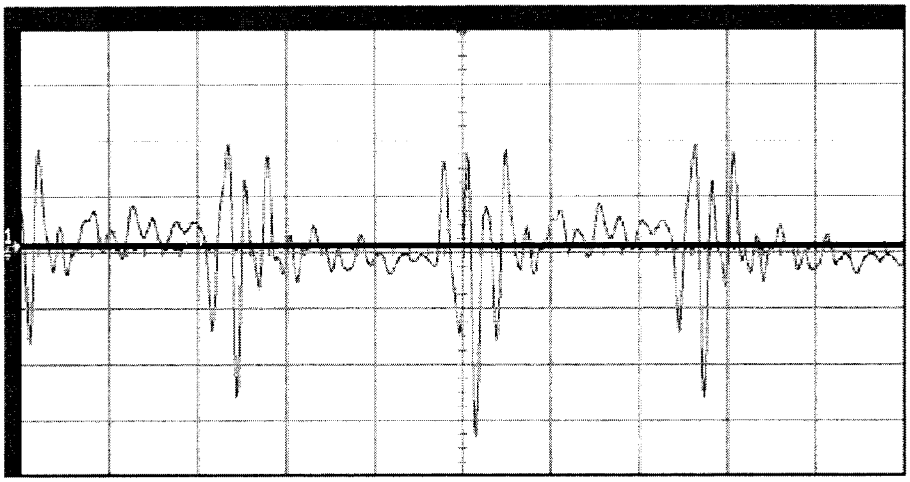

Figure 7. Voltage Waveform of the Sensor Resister for 700 kHz Input Frequency

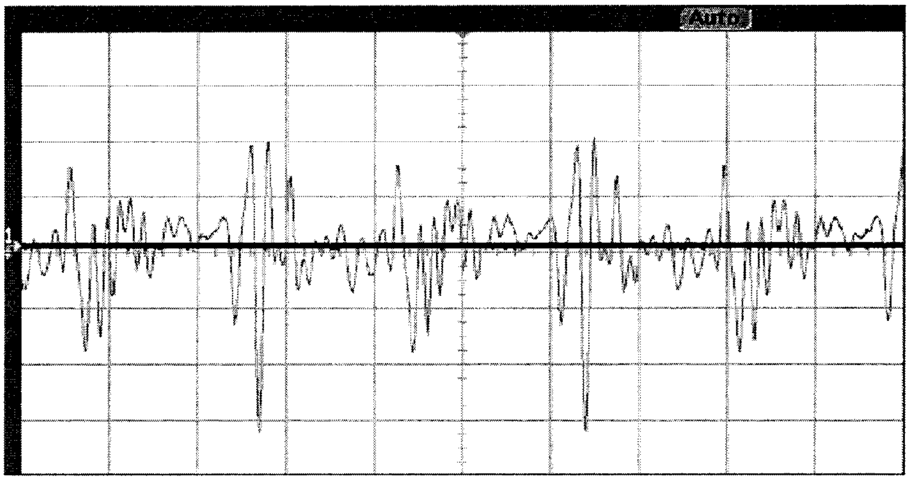

Figure 8. Voltage Waveform of the Sensor Resister for 1 MHz Input Frequency

6. Conclusion

In this paper, an analysis on inductance, H-field, and choosing a solenoid as the source of the H-field generator is given. A digital solenoid driver is proposed and tested. Compared with analog drivers, the digital driver has advantage of low power, stable, and powerful current-driven capability. The novel H-field generator is used for further research on modeling timing jitter.

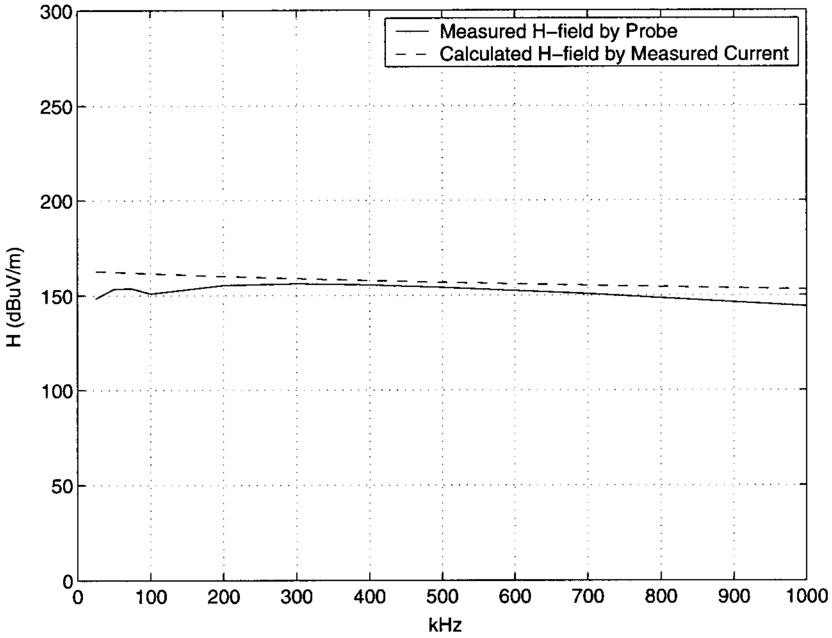

Figure 9. Comparison of Measured H-field and Calculated H-field

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