Coil design simulation for Vibrating Sample Magnetometer

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In this experiment, suitable configuration of detecting coils have selected by analysing the geometric factor($\vec{g}_k$) of detecting coil around the vibrating sample in VSM. An important feature of the VSM is a stable the electrodynamic vibrator which is electronically controlled by feedback and error minimization circuit. The vibrator associated electronics have been made using locally available low-cost materials in a modest budget of a few thousand rupees. Sample vibrator is an important part of the VSM which is build to fulfill the principle requirements that is pure sinusoidal vibrations of constant frequency and stability of vibration amplitude of the signal. The VSM is suitable for the study of magnetic properties of materials in high magnetic fields. By using Multisim v.14.2 software the sine wave generator , error minimization circuit , preamplifier and power amplifier circuit prototypes have designed and verified.

OBJECTIVE

- To determine Coil configuration with different geometry factor (g_x, g_y, g_z) of detecting coils.
- To simulate the electronic circuit needed for vibrating the sample with desired frequency and amplitude.

THEORY AND WORKING FORMULA

VSM is used to measure the magnetic behavior of magnetic materials. The Vibrating Sample Magnetometer (VSM) is based upon Faraday's law, according to which an EMF is induced in a conductor by a time-varying magnetic flux. In VSM, a sample magnetized by a homogenous magnetic field is vibrated sinusoidally at small fixed amplitude with respect to stationary pick-up coils. The resulting field change inside the pick-up coils (detection coils), induces voltage and from measurement of this voltage the magnetic properties of sample deduced.

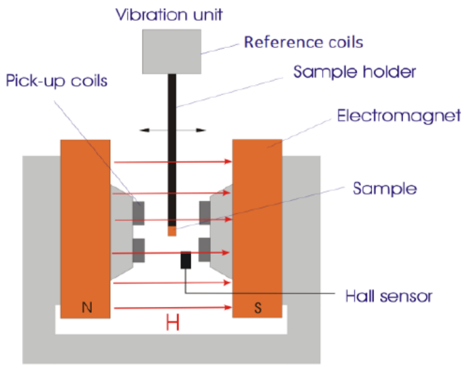

FIG. 1: Schematic diagram of a vibrating sample magnetometer

Geometric Factors of Coil

Suppose our magnetized sample is placed at the origin. If the position of this sample is varied in sinusoidal way over a small distance $\vec{\delta}(t)$ then a change of flux $\partial\vec{B}(t)$ that will be induced at a point $\vec{r}$ in space will be

$$\partial\vec{B}(t) = \mu_0\vec{\delta}(t).\nabla\vec{H}(\vec{r})$$

If we place a small coil at$\vec{r}$ then the voltage induced in it will be given by

$$V(t) = \sum_p\sum_n\int_A\left(\frac{\partial\vec{B}}{\partial t}\right).d\vec{A}$$

where n is the number of turns, A denotes the area vector of a single turn and p is the number of coils. The summation over n includes only those turns which contain elemental area $d\vec{A}$ and for which $\partial\vec{B}/\partial t$ is given by above equation.
Here we can approximate our magnetized sample with a magnetic dipole if the dimensions of our sample are small as compared to the distances between the sample and the detection coils. With this approximation we can assume the vibrating sample to be an oscillating dipole. The magnetic field of a dipole placed at origin is given by

$$\vec{H}(\vec{r}) = \frac{1}{4\pi}\left(\frac{\vec{m}}{r^3} - \frac{3(\vec{m}.\vec{r})\vec{r}}{r^5}\right)$$

where $\vec{r}$ is the position vector of a point in space and $\vec{m}$ is the magnetization of the sample. Suppose the sample is vibrated sinusoidally along the $\hat{z}$-axis and the external magnetic field is applied along the $\hat{x}$-axis as shown in $fig.2$. Then

$$\vec{\delta}(t) = \sin(\omega_0 t + \phi_0)\vec{d}$$

Furthermore, let the magnetic moment of the dipole, polarized along $\hat{x}$-axis, then the field induced by the sample at the position of a coil $\vec{r}$ will be

$$\vec{H}(\vec{r}) = -\frac{1}{4\pi}\left(\frac{-m}{r^3} + \frac{3mx^2}{r^5}, \frac{3mxy}{r^5}, \frac{3mxz}{r^5}\right)$$

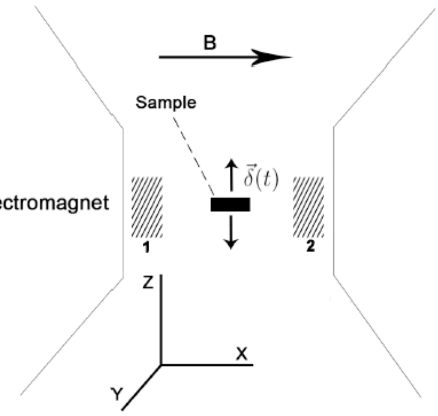

FIG. 2: A sample oscillated in a magnetic field and vibrated along the $\hat{z}$-axis.

So the gradient of $\vec{H}(\vec{r})$ at $\vec{r}$ will be given by

$$\nabla\vec{H}(\vec{r}) = \begin{pmatrix} \frac{\partial\vec{H}}{\partial x} \\ \frac{\partial\vec{H}}{\partial y} \\ \frac{\partial\vec{H}}{\partial z} \end{pmatrix}$$

After solving this equation we got

$$\nabla\vec{H}(\vec{r}) = \frac{-3m}{4\pi r^7}\begin{pmatrix} x(3r^2-5x^2) & y(r^2-5x^2) & z(r^2-5x^2) \\ y(r^2-5x^2) & x(r^2-5y^2) & -5xyz \\ z(r^2-5x^2) & -5xyz & x(r^2-5z^2) \end{pmatrix}$$

Then using the above equation, we got

$$\begin{aligned}\frac{\partial\vec{B}}{\partial t} &= \mu_0\omega_0 cos(\omega_0 t)\vec{d}.\nabla\vec{H}(\vec{r}) \\ &= -\frac{3m\mu_0\omega_0}{4\pi r^7}cos(\omega_0 t)d(z(r^2-5x^2)\hat{i}, -5xyz\hat{j}, x(r^2-5z^2)\hat{k})\end{aligned}$$

Which consequently gives

$$V = -\frac{3}{4\pi}m\mu_0\omega_0 cos(\omega_0 t)d\sum_n\int_A d\vec{A}.\vec{g}$$

where $\vec{g}_k = (g_x, g_y, g_z)$, these are the factors which sample space and contribute to the voltage. From the above equation the direction of the external magnetic field determines the direction of $\vec{m}$ and the orientation of the axis of the coil determines the direction of the area vector $d\vec{A}$.
In our project our coil is oriented along z-axis then $d\vec{A} = dA\hat{k}$, so the above equation will be

$$V = -\frac{3}{4\pi}m\mu_0\omega_0 cos(\omega_0 t)d\sum_n\int_A dA\frac{x(r^2-5z^2)}{r^7}$$

A closer look shows that the induced voltage crucially depends on the term in the integral. As it is a function of the coil geometry only, we will call it a geometric factor g_z.

$$g_z = \frac{x(r^2-5z^2)}{r^7}$$

Similarly other geometry factors are given by

$$g_x = \frac{z(r^2-5x^2)}{r^7} \quad and \quad g_y = \frac{-5xyz}{r^7}$$

dictate the induced voltages in coils oriented along $\hat{x}$ and $\hat{y}$ axis respectively. These geometric factors are to be integrated over the pick up area of the coils.

Electronic circuit for *VSM*

In *VSM* vibration unit or sample vibrator consists reference coil is used to provide vibration at constant frequency to the sample holder. Sample is fixed to the end of the sample holder. The sample vibrator is main subsystem of *VSM* which is built to fulfill the following principle requirements:

1. Pure sinusoidal vibrations of constant frequency
2. Stability of vibration amplitude under load variation and friction

So for controlling the vibrator an electronic circuit has been designed.

I. Sine-Wave Generator

It requires adjusting variable frequency range between $20-170Hz$. The output of sine wave generator is feed into the sine wave filters for phase shifting and to obtain desired shape. It can also done by function generator.

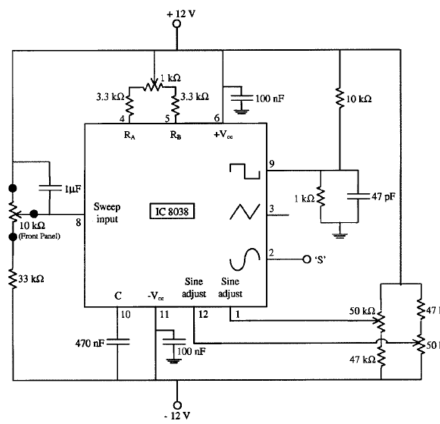

FIG. 3: Sine wave generator circuit

II. Error Minimization Circuit

The error minimization circuit is a variable voltage feed which can be applied directly to the power amplifier. This has an in-phase component and also a phase-lagging component with respect to the reference voltage.

In this way a substantial reduction in the difference (error) between the required velocity obtained through sensing coil(pick- up coil) and that obtained through the reference coil of the driver can be achieved.

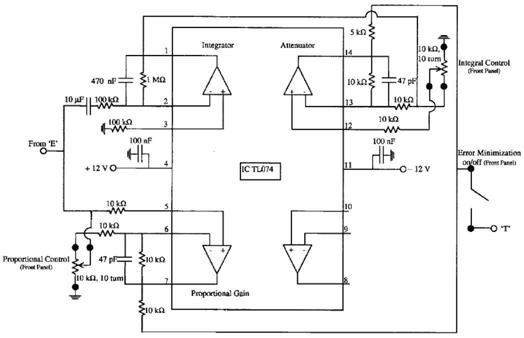

FIG. 4: Error minimization circuit using $ICTL074$

III. Preamplifier and Power Amplifier

A preamplifier is used as a high gain amplifier to prepare a small electrical signal for further amplification or processing and reduce the effects of noise and interference. It is used to boost the signal strength to drive the cable to the main instrument without significantly degrading the signal to noise ratio (SNR). The second amplifier is typically a power amplifier. The preamplifier provides voltage gain (e.g. from $10mV.$ to $1V.$) but no significant current gain. The power amplifier provides the higher current necessary to drive loudspeakers attach through reference coil or driver coil which is connected to sample vibrator to provide vibration.

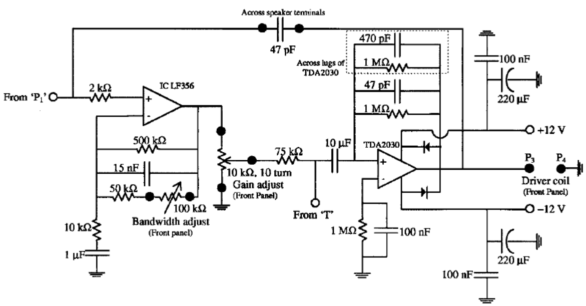

FIG. 5: Preamplifier and power amplifier circuit

PROCEDURE

Selecting Coil configuration

For selecting the suitable coil configuration it is important to understand the behavior of geometric factors$(\vec{g}_k)$ in the region surrounding the vibrating sample. Particularly we are interested in the contours of these factors (g_x, g_y, g_z). The contours indicate that suitable dimensions for a detection coil are one in which the sign of the geometric factor stays the same because otherwise the flux change from regions with opposite signs will cancel each other out. Therefore we need to have a closer look at the behavior of $\vec{g}_k$. After selecting required coil configuration then we have calculated EMF generated in the coil for applied magnetic field.

SPICE simulation(Multisim v.14.2)

SPICE is an acronym for Simulation Program with Integrated Circuit Emphasis. It is a general purpose software that simulates different circuits and can perform various analysis of electrical and electronic circuits including time domain response, small signal frequency response, total power dissipation, determination of nodal voltages and branch current in a circuit, transient analysis, determination of operating point of transistors, determinations of transfer functions etc.

By using $Multisim \;\; v.14.2$ software , we have designed and verified the sine wave generator , error minimization circuit , preamplifier and power amplifier circuit prototypes.

OBSERVATION

- The contours of g_x, g_y and g_z indicate the suitable dimension for a detection coil in which the sign of the geometric factor stays the same because otherwise the flux change from regions with opposite signs will cancel each other out.
- Furthermore the coils oriented along $\hat{x}-$axis will also detect some perturbations in the external magnetic field which is an undesired and will unnecessarily complicate the analysis.
- However, coils along $\hat{y}$ and $\hat{z}$ axis do not suffer this complication as their cross-sectional area vectors are perpendicular to the external magnetic field. By taking these factors into account, I have selected a coil configuration with two detection coils.
- So these coils will be placed along $\hat{x}-$axis, one on each side of the sample and their cross-sectional areas will be oriented along the $\hat{z}-$ axis. Therefore we need to have a closer look at the behavior of g_k.
- $Fig.9$ shows a complete volume contour for g_k at two values, other values show similar structure. This indicates that if a positive voltage is induced in the coil placed at $+x$ axis then an equal negative voltage is produced in an identical coil placed at $-x$.
- Winding one of the coils clockwise and the other anti clock wise will result in generation of the same signed

voltage in both coils. We can then connect them in electrical series to get a stronger signal.

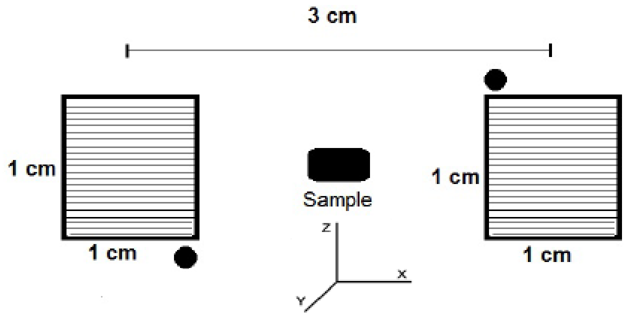

FIG. 6: Schematic diagram of detection coils.

So the voltage induced across this coil for the arrangement will be

$$V = -\frac{3}{2\pi} m\mu_0 \omega_0 cos(\omega_0 t) d\alpha$$

$$where, \ \ \alpha = \sum_n \int_A dA \frac{x(r^2 - 5z^2)}{r^7}$$

CONTOUR PLOTS

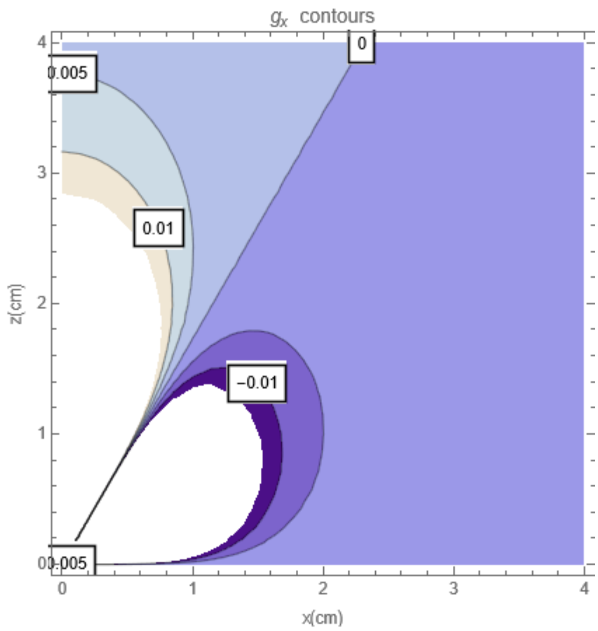

FIG. 7: Equi-signal contours of g_x for $\phi = 45°$ and $0 \leq \theta \leq 90°$.

We have calculated value of α using *Mathematica*12.3. In our setup for this project which is having 91 turns each with diameter 1cm gives α = 15.91

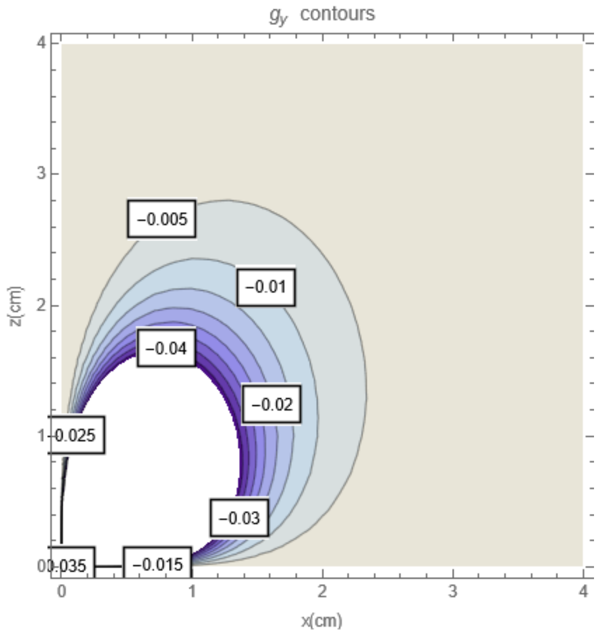

FIG. 8: Equi-signal contours of g_y for $\phi = 45°$ and $0 \leq \theta \leq 90°$.

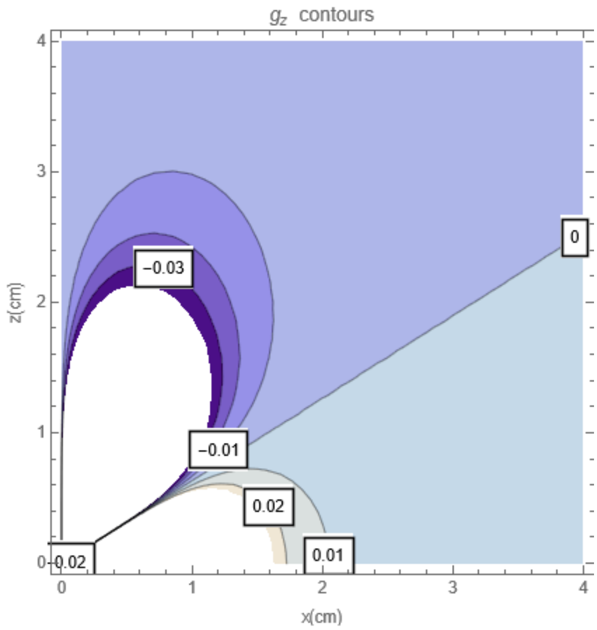

FIG. 9: Contours for g_z for $\phi = 0°$ and $0 \leq \theta \leq 90°$

From value of α, we could calculate the magnitude of induced voltage as

$$|V| = \frac{3}{2\pi} m\mu_0 \omega_0 \alpha d$$

which upon rearrangement gives,

$$m = \frac{2\pi V}{3\mu_0 \omega_0 \alpha d}$$

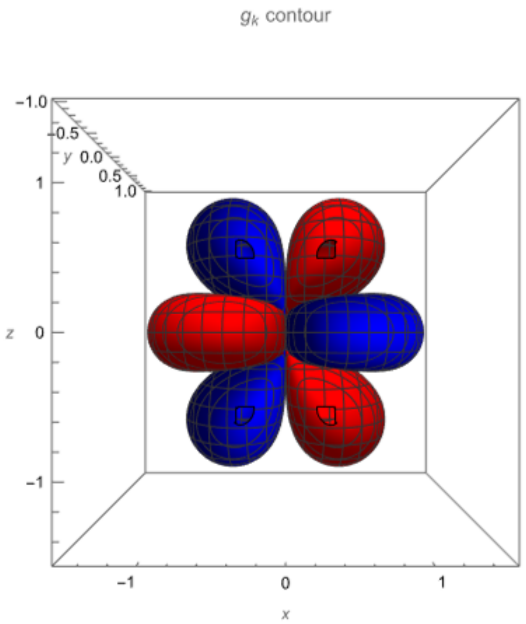

FIG. 10: Contour for g_k presenting surfaces with $g_k = 0.5$ in blue and $g_k = -0.5$ in red.

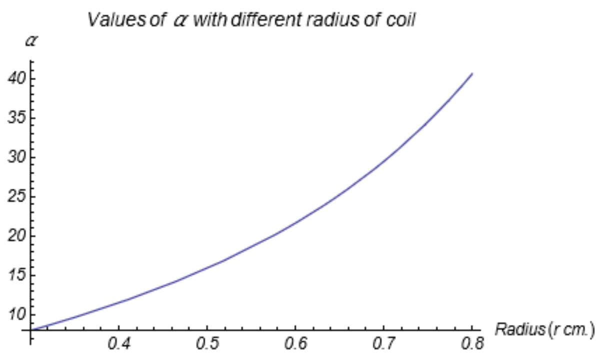

FIG. 11: Value of α with different r

From the above equation, one can investigate the magnetization m of the sample by measuring the induced voltage in the coil.

CIRCUIT SIMULATION

To control the vibratory frequency and amplitude, we have design an electronic circuit in which various IC's is used to generate sine wave of desired frequency and amplitude. For this various stages of experimental results are shown below.

Stage 1: Output of Sine wave Generator shown in $fig.13$ which shows the sine wave signal of $100Hz$. It is generated from the sine wave generator 555 timer IC. For getting desired shape it feed to the next stage.

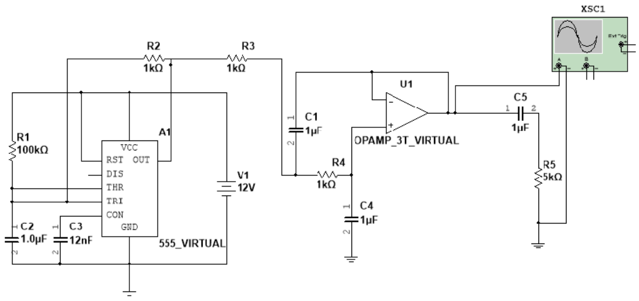

FIG. 12: Schematic Design of sine wave filter

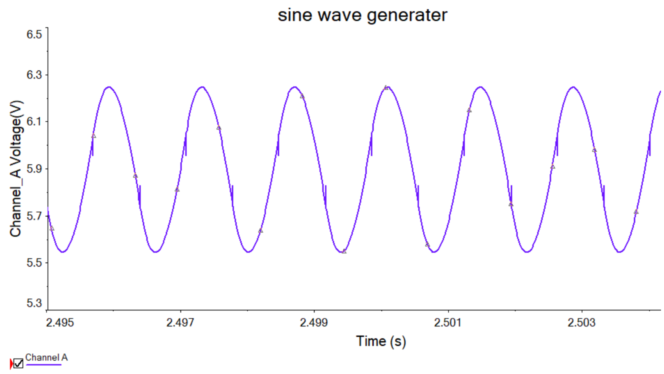

FIG. 13: Simulated waveform of sine wave filter

Stage 2: $Fig.15$ shows the output of Error minimization circuit of $TL074$. Here we get sine wave of $100Hz$ frequency with proper shape with maximum noise reduction.

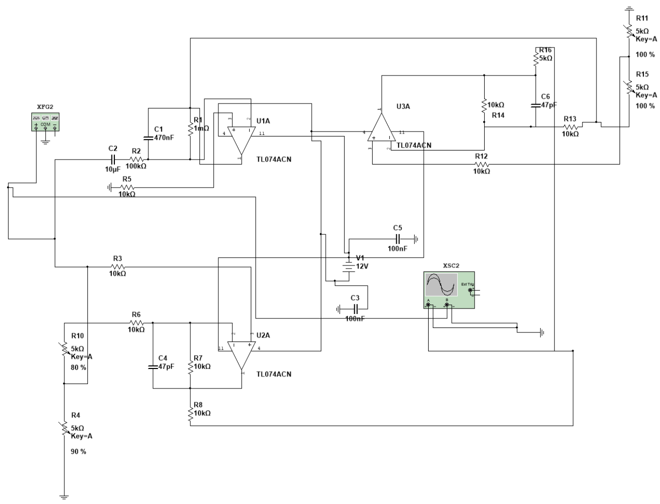

FIG. 14: Schematic design of Error Minimization Circuit

Stage 3: $Fig.17$ shows the output of $ICTDA2030$. Power amplifier generates sine wave with higher amplitude to drive loudspeakers which is connected to the terminal in the circuit.

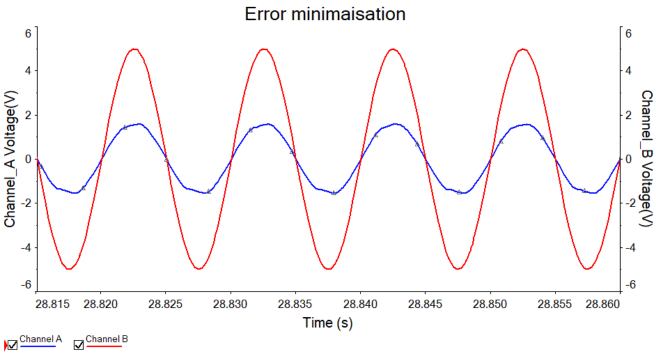

FIG. 15: Simulated waveform of Error Minimization Circuit

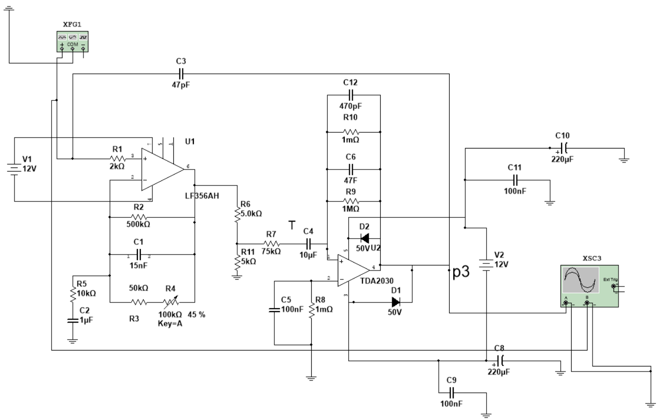

FIG. 16: Schematic design of prepower amplifier

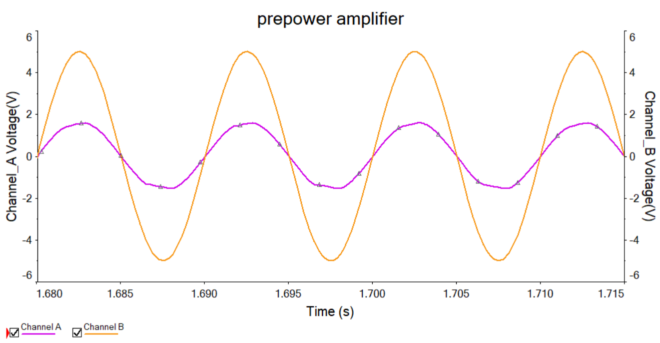

FIG. 17: Simulated Waveform of prepower amplifier

RESULT

- The contours of g_x, g_y and g_z indicate the suitable dimension for a detection coil in which the sign of the geometric factor stays the same.
- By taking these factor into account, the detection coils will be placed along $\hat{x}-axis$, one on each side of the sample and their cross sectional areas will be oriented along the $\hat{z}-axis$.
- The sign of g_x changes at $\theta = 62.5°$
- The sign of g_z changes at $\theta = 39.2°$
- For g_y, the sign remains unchanged.
- For our detection coil setup , we have got the value of $\alpha = 15.91$
- To control the vibratory frequency and amplitude we have design an electronic circuit in which various IC's is used to generate sine wave of desired frequency and amplitude.

CONCLUSION

In the first part of experiment we have selected the suitable coil configuration by understanding the behavior of geometric factor $\vec{g}_k$ surrounding the vibrating sample. From contours of different geometric factor we have chosen the suitable dimension in which sign of geometric factor remains same. Then we have simulated setup for the design of electronic circuit to control the sample vibrator used in VSM. The environment is built around a Vibrating Sample Magnetometer and includes the *Multisim* simulation for the circuit analysis.

It provides the user the possibility to include various design specifications, including fast and intuitive schematic design entry for simulation and also non electrical ones, such as costs, size etc. Experimental observational testing of various modules such as electronic circuitry, induced voltage, actuator frequency and amplitude are found to close agreement with our theoretical value with some percentage variation. The error detection and correction circuit is incorporated to reduce the error due to the reference signal.

ACKNOWLEDGMENT

I would like to thank Dr. Pratap kumar sahoo and Dr. Santosh Gunda Babu for their guidance in this project. I would also like to thank my batchmate Ritesh for disscusion which helped me in fulfilment of this project.

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Appendixes: Mathematica Code

Github file link : `https://github.com/pradyotpsahoo/P441-P442`