Indian Journal of Science and Technology, *Vol 8(12), DOI: 10.17485/ijst/2015/v8i12/65739, June 2015*

ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645

Design and Analysis of Current Mode Amplifier as Drive Electronics for Linear Voice Coil Motor

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Abstract

Voice Coil Motor is a precise positioning and motion control device, the drive electronics must be of utmost accuracy such that it accounts for the exact requirements of the motor load. This work mainly focuses on the design and analysis of a current mode based operational amplifier, which is expected to generate the precise magnitudes of current. An improved Howland current pump, current drive based amplifier is theoretically analyzed and the analog simulation is performed. A novel hardware scheme is proposed which is suitable for VCM testing and the methodology to develop the hardware is also emphasized.

Keywords: Analog Simulation, Current Drive Amplifier, Current Pump, Drive Electronics, Improved Howland Voice Coil Motor (VCM)

1. Introduction

Voice coil motors are the prime mover extensively suitable for the direct drive valve mechanism like hydraulic[1] and precise positioning applications[2]. The magnetic field interaction of permanent magnet with the moving coil assembly generates the necessary mechanical thrust. The mechanical force developed by the VCM is given by Lorentz force which is mathematically given by,

$$F = B_g, I_C, L \tag{1}$$

Where,

F is the mechanical force exerted by the motor, B_g is the air gap flux density and L refers to the length of the conductor under the influence of the magnetic field.

Design of voice coil motor involves the[3] magnetic circuit analysis based on the finite element analysis technique to compute the flux density orientations such that the air gap flux density can be computed to contribute to the force generated by the VCM.

Constant current drive based operational amplifier approach has been used in[4] generalized impedance converters, improved Howland current source finds prominent importance in bio-medical circuits where the precise magnitude of currents and the stable output impedance is achieved[5] with accurate precision. Precise current generation is also possible with the Howland current generator as the drive/readout circuit in case of MEMS ma gnetometers[6]. In [7] high power CMOS drivers are developed with a differential architecture. The drive electronics for development can also find its applications in power electronics domain like DC-DC inverters[8] and multi-level inverters[9]. Finite element method[10] is a prominent technique to analyses the behaviour of the VCM. A novel controller can also developed using the FPGA[11].

This work aims at the development of a control electronics which helps in generating precise currents to the coil assembly using a high power amplifier configuration capable of generating up to 10A with satisfactory power consumption limits. Voltage type amplifiers have very low output impedance, such that the load of the VCM in return generates back EMF effects which oppose the main drive voltage. Such back EMF effects are minimized by

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the current drive amplifier mode, which has a high output resistance which restricts the EMF effects from the load side.

2. System Description

This section represents the process flow of the implementation represented pictorially by means of a flowchart. Figure 1 represents the process flow diagram which identifies the methodology for the design and development of drive electronics.

Mathematical analysis of current mode based amplifier using improved Howland current pump configuration is done. The design requirements of the drive board are identified based on the mathematical analysis and the analog simulations are carried out. Validation is carried out on the accuracy of the obtained simulated parameters with the theoretical analysis. Until, the theoretical and simulation results coincide, the analysis continues. Similar results yields to the next step, the hardware design of the current mode based drive board for VCM design.

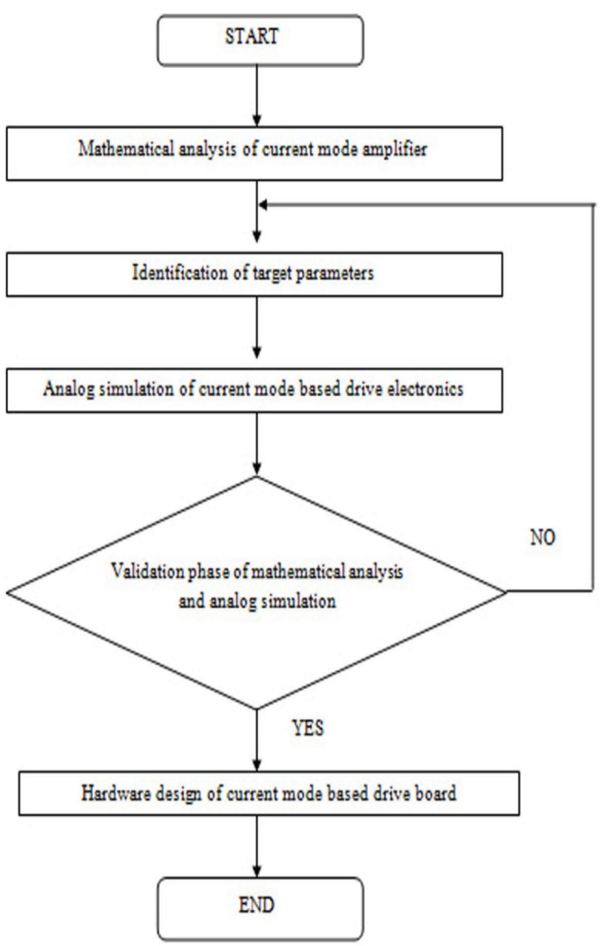

Figure 1. Process flow diagram.

3. Mathematical Analysis of Improved Howland Current Pump

The control electronics is designed purely based on supplying the necessary coil current which is one of the key parameters which influences the mechanical force of the VCM. Figure 2 represents the improved Howland current pump configuration which provides the accurate magnitude of current at the VCM load. The use of an improved Howland current pump in this work is that it acts as a V-I converter to generate the current based on the obtained transconductance.

The merit of using the Howland current pump is, both sourcing and sinking of current is possible. Sourcing and sinking signifies the direction of the current flow through the load. Sinking refers to the grounding of the load and sourcing refers to providing the voltage source to the load. Hence bidirectional operation of VCM is possible with this drive.

Rm1, Rm2, Rm3 and Rm4 refers to the matching resistors, R5 refers to the output impedance of the circuit. Va is the reference potential at the input and non-inverting terminal which are assumed to be equal.

Mathematical analysis of the Howland current source is as follows:

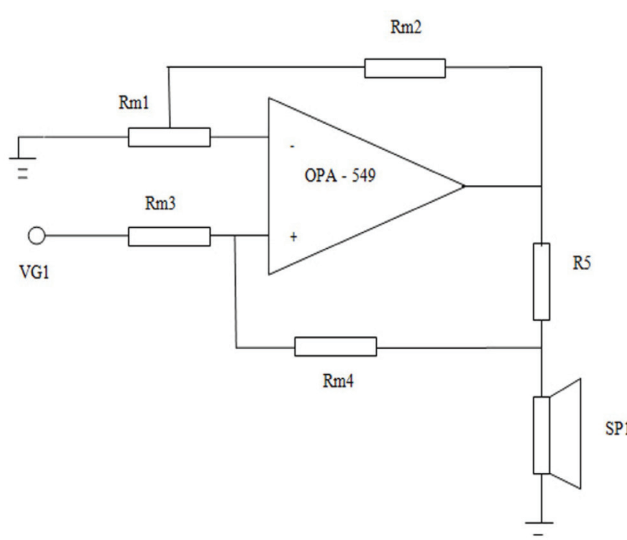

Figure 2. Improved Howland current pump circuit.

The condition of resistance matching in case of Howland current pump is given by,

$$\frac{R_{m2}}{R_{m1}} = \frac{R_{m4} + R_{m5}}{R_{m3}} \quad (2)$$

Equation (2) refers to the resistance matching condition which affects the value of larger value of output impedance. The resistors must be matched precisely such that tolerance should be of the order of 0.001%. The matching resistors' value is taken as equal for analysis and the output resistance of the schematic ultimately determines the tolerance.

From Kirchhoff's current law,

$$I_{m1} = I_{m2} \quad (3)$$

$$I_{m3} = I_{m4} \quad (4)$$

$$I_{m4} + I_5 = I_{Load} \quad (5)$$

By nodal analysis method, the current equations are re-written as,

$$\frac{V^{F3} - V_{F4}}{R_{m1}} = \frac{V_a - V_{out}}{R_{m2}} \quad (6)$$

$$\frac{V^{+} - V_a}{R_{m3}} = \frac{V_a - V_{load}}{R_{m4}} \quad (7)$$

$$\frac{V_a - V_L}{R_{m4}} + \frac{V_O - V_{load}}{R_{m5}} = I_{Load} \quad (8)$$

The transconductance of the circuit is computed as ratio of the output current to the input voltage which is computed to be,

$$\frac{I_{Load}}{V^{+}} = \frac{R_{m2}.R_{m5}}{R_{m1}} \quad (9)$$

Since the matching resistors are equal in magnitude, the LHS of equation (9) is the ratio of the output load current to the input voltage which is given by,

$$g_m = \frac{1}{R_5} \quad (10)$$

Equation (10) clearly signifies that the transconductance is independent of the matching resistors and its magnitude is affected by the output impedance.

Based on the transconductance expression obtained in equation (10), the Table 1 signifies the range of output impedance values taken into consideration for the desired value of transconductance.

Table 1. Range of output impedance values – Comparison

Output impedance(Ω)	Transconductance
0.5	2
1	1
1.5	0.67
2	0.5

4. System Analysis and Simulation

The previous section gives a clear inference that the output impedance is the critical component which affects the system transconductance. This section deals with the simulations of the transconductance amplifier configuration based on the following load requirements.

The operational amplifier used for the control electronics is the OPA-549, from Texas Instruments which has the following features.

Voltage ratings - 8V to 60V
Current Ratings - up to 10A
Slew Rate - 9V/μs

TINA-TI from Texas Instruments, is the simulation tool based on which the analog simulation is performed which supports DC, AC and transient analysis.

DC analysis signifies the circuit behavior in practical scenario, with respect to the biasing conditions. Frequency response of the circuit is evaluated by AC analysis and transient analysis is done at noisy or harsh environments. Selection of the output impedance is the most prior task, which ultimately decides the voltage levels. The Table 2, indicates the values of the simulation parameters which are simulated for the output impedance of 2Ω. Simulations are carried on varying the output impedance in the range of 0.5Ω to 2Ω.

The Table 3 indicates the electrical parameters which satisfy the load requirements of VCM based on the analog simulation. The DC analysis plots are generated which signifies the amount of the input voltage to be

Table 2. Design requirements for VCM

Parameter (Unit)	Value
Coil current (A)	3
Output voltage (V)	7.214
Load impedance(Ω)	2.416
Total power rating (W)	21.735

supplied to generate the fixed output current. Figure 3 shows the DC analysis of the transconductance amplifier.

In the context of VCM with 2.406 ohm resistance and 18.8 N/A force constant, the input voltage to be applied is 6.13V to obtain 3A of load current in order to get force of about 54N.

Table 3. Simulation results based on the chosen output impedance value

Parameter	Value(unit)
Output impedance(R5)	2(Ω)
Input voltage (VG1)	6.13 V
Output current (AM1)	3A
Power amplifier output (VF1)	13.69 V
VCM Load potential (VF2)	7.23 V

5. System Block Diagram and Hardware Design

This section is organized into 2 parts, namely the system block diagram and the hardware design respectively.

5.1 Block Diagram of System Operation

Figure 5 symbolizes the conceptual block diagram regarding the implementation of drive electronics.

The working operation is described as follows.

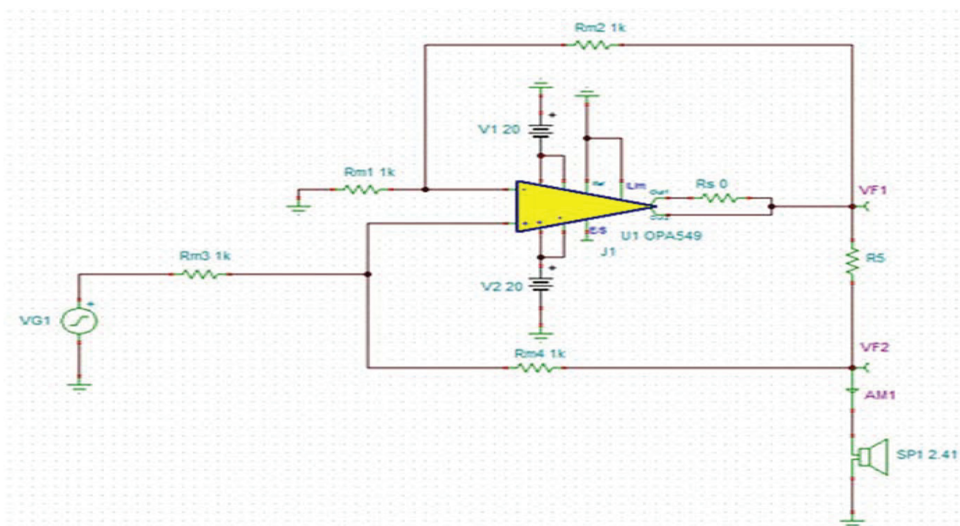

Figure 3. Circuit schematic for analog simulation.

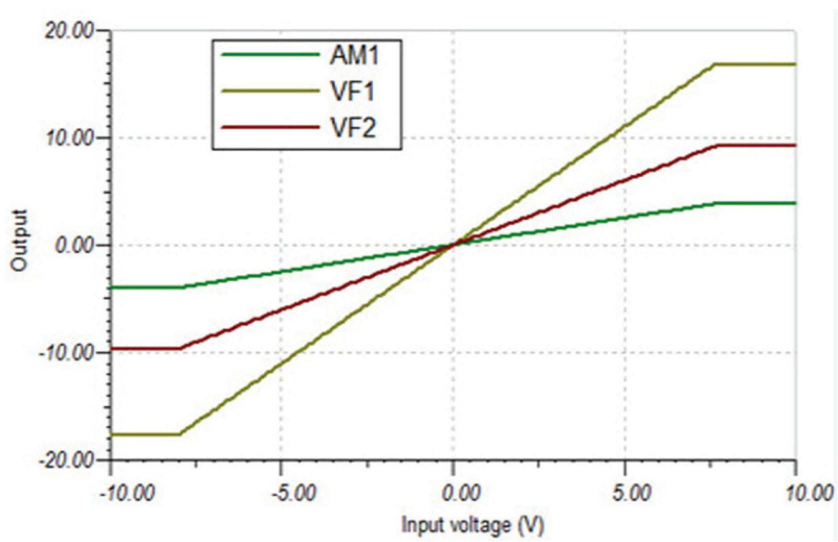

Figure 4. Characteristic plot – DC analysis.

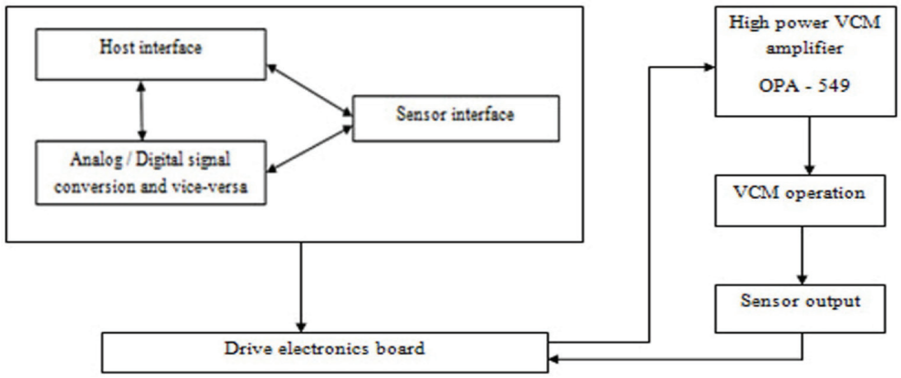

Figure 5. System Block Diagram.

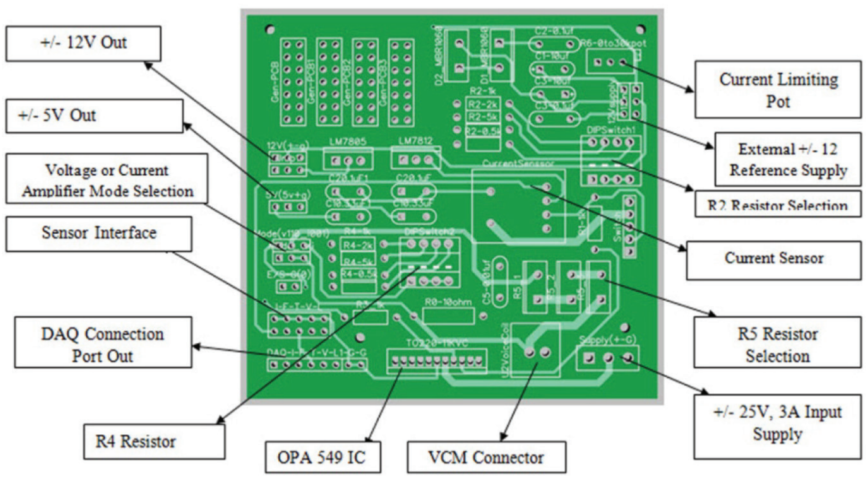

Figure 6. Customized PCB layout design.

The Data Acquisition system (DAQ) comprises of a set of sub-modules. The host interface helps in system – user interaction also having an analog to digital conversion and vice-versa. The sensor interface is used to obtain the data of various real-time parameters.

The drive board accepts the input voltage in digital form, this voltage is converted to current using the high power VCM transconductance amplifier. This current is supplied to the VCM, the various sensors which are interfaced provide the respective readings.

Figure 6 has a current drive based electronics which comprises of the improved Howland current pump. This hardware scheme is designed to supply the accurate value of known magnitude of coil current, the voltage can be varied so that the required power level can be achieved which is proportional the value of g_m.

The PCB design of drive board which incorporates the improved Howland current pump along with the general purpose slots as sensor interfaces is shown in the Figure 4. Since this PCB is supposed to drive high power VCM enough care is taken to keep the track width on PCB to support high current flow.

The drive board consists of the high power VCM amplifier OPA-549. It is an 11-pin package amongst which the pin numbers 6 and 8 are shorted internally; the current limiting resistor of 0-30 k pot is connected to limit the output current through the VCM to a desired value (3A in case of VCM). The input voltage to the amplifier is supplied by external data acquisition (DAQ) card's analog output (16 bit ADC). This card also supports analog input channels for feedback and sensor interface. On the drive board general purpose slots are provided on the left top corner, which can be used to connect additional sensors. DIP Switches 1 and 2 are connected to resistances R2 and R4 respectively, to tune the appropriate resistances as 0.5 k, 1 k, 2 k, 5 k etc., which in turn selects the gain of the amplifier.

Voltage regulators of 5V and 12V are used to obtain the constant DC voltage forms the main supply input

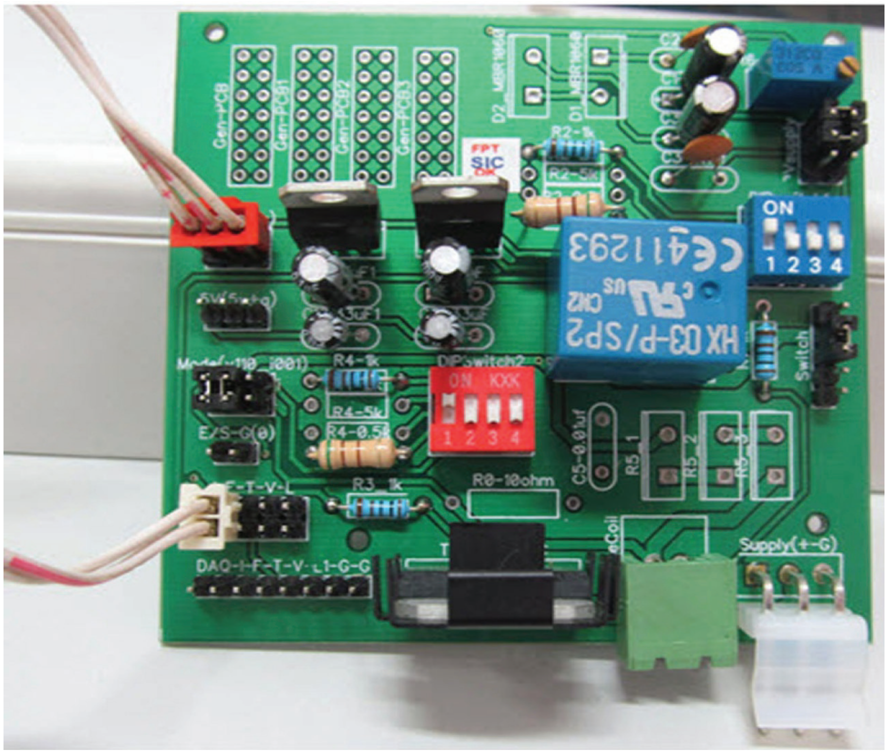

Figure 7. Drive electronics hardware.

which acts as a reference supply for other subsystem on the board. Current sensor is placed in series with the VCM which measures the value of the current through VCM. This will be used to calculate the experimental value of transconductance.

5.2 Hardware Snapshot

The following images indicate the hardware setup of the current drive based control electronics to be tested for the VCM operation.

As per Figure 7, the drive board will be subjected to provide excitation to the VCM; the drive board is very cost effective and reliable.

6. Results

A current mode based operational amplifier is developed to account for the load requirements of the VCM. The theoretical analysis is validated by the analog simulation which yields the same results. The proposed hardware scheme is advantageous in the way not only to serve as drive electronics but can also be used to carry out VCM related tests. This work also overcomes the back EMF problem, which proves to be an advantage over voltage drive amplifiers.

7. Conclusion and Future Work

In this work, identification on the necessity of using the current based drive system in order to avoid back EMF problem in voltage drives is done. A current drive scheme based on Howland Current pump is studied analytically and corresponding equation of transconductance is obtained. Further in order to validate this analysis and concept a circuit simulation is conducted in TINA TI, analog simulator using OPA 549 IC as main element. Parameter selection is done based on the load requirements of the motor. The theoretical analysis provides similar results with the simulations and the proposed hardware scheme is verified and looks to be cost effective.

The extension of this work is also to design a GUI which will help in conducting various VCM related tests for measurement of parameters like force constant, linearity over extension, etc.

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