Circuit Simulation of the Analog Computer and Proportional Controlled DC Motor Based on Op Amp

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Abstract. Operational amplifier(op-amp) is a building block of many analog circuits, nowadays it has been the most widely used device in various electronics instruments. In modern electronics design, op-amp has a special weightage due to its robust characteristics. In this paper, two applications of op amp are discussed. One is using op-amp to construct an analog computer for solving second order differential equation. Another is to build a proportional controlled DC motor which transfer input voltage into angle. By varying the proportional gain at 1, 5 and 15, different result is obtained by octave simulation using step response graph and pole-zero diagram.

Keywords: op-amp, DC motor, analog computer, proportional control, feedback circuit.

1. Introduction

The development of op amps can be track back in to 20th century, from the invention of Fleming diode by J.A.Fleming in 1904 and the invention of the three-element triode vacuumed tube by Lee De Forest in 1906. The first invention achieved on direction current passing through, the second invention was the first active device capable of signal amplification. [1] Afterwards, the first op amp using vacuum tube was invented in early 1940's, then, improved as solid-state op amp in the 1950's and 1960's, in the mid of 1960's an IC op amp was invented which is similar to nowadays op amp.

The usage of op-amps has been widely investigated in recent years, many studies such as Norbert Herenscar uses op amp as integrator of a fractional order controller [2] by connecting two op amps in inverted closed loop configuration and single op amp connected in non-inverted closed loop configuration. Blesson Easo Varghese studies the method of using single op amp to achieve PID control by using lead and lag circuits which build by capacitors and resistors[3]. Emmanuel A. Gonzalez studies the application of op amp as an active device of fractional PID control, and built a topology with extra degree of freedom using interconnected configured RC networks[4]. Kichan Kim presents an DC-DC converter for display driving system using op amp and pulse width modulation controller which fabricated with amorphous indium gallium zinc oxide thin film transistors[5]. Arturs Bogdanovs induced an indirect DC link current measurement technique for a multi-phase DC converter with coupled inductors, an op amp circuit is used in Arturs's approach as improve the DC link current waveform restoration quality[6].

This paper will discuss from the circuit construction to the numerical simulation about two uses: as an analogue computer, and as a proportional controlled DC motor having voltage to angle characteristic. The tools which were used in this paper was Falstad, Tinker Cad and Octave, and the circuit was constructed as digital circuit and analog circuit form.

2. Application of op amp

2.1 Analog computer

The application of op amps is firstly investigated in analog computing area. In the following section, an analog computer built by op amps for solving a specific second derivative equation is built and discussed from the respect of circuit construction, graph demonstration.

2.1.1 Methodology

Objective: building an analog computer using op-amps solving the second derivative equation.

$$x'' - 0.3\,x' + x = f(t) \tag{1}$$

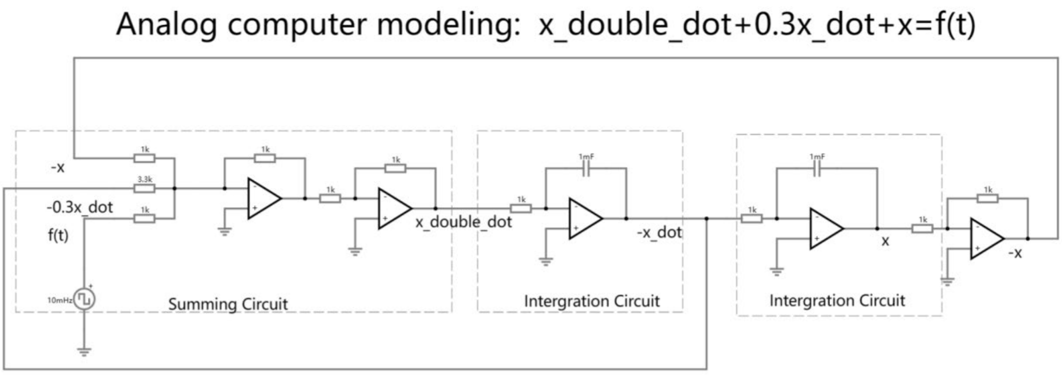

Figure 1: The analog computer circuit.

To construct the equation, four basic functional circuit is considered: the summing circuit, the integration circuit and the inverter circuit. To solve this equation, x'', $0.3\,x'$ and x should be denoted, and the value of x should be observed at the end. The value of x can be derived from an integration circuit of x' and the value of x' can be derived from an integration circuit of x''. Hence, the first step is to express x'' using the haven electronic components.

$$x'' = f(t) + 0.3\,x' - x \tag{2}$$

The first circuit is a summing circuit, to sum up the $f(t)$, $0.3\,x'$ and $-x$ which can be viewed as a simplified version shown in figure 2.

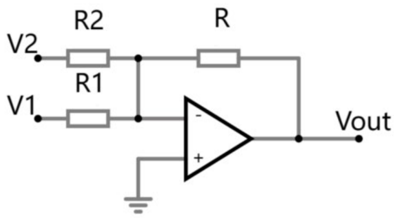

Figure 2: Simplified summing circuit.

The output of the summing circuit is followed:

$$V_{out} = -\left(\frac{V_1}{R_1} + \frac{V_2}{R_2}\right) R \tag{3}$$

Hence, the summing circuit needs another inverse circuit to output the value of x'', according to equation above, and the coefficient (0.3) of the derivative of x can be represented by changing the value of the resistance of R_1. Hence, a $3.3k\Omega$ resistor is used.

The value of x' is the integration of x'', according to equation 2, the summing circuit only needs the negative x' value for deriving the value of x'', hence, no inverse circuit needed in this part. The value of -x' then be fed back to the input of the summing circuit as a component of equation 2.

The value of x is the integral of $-x'$, which can also be denoted by circuit as the integral of $-x'$ connecting with an inverse circuit to inverse the negative sign to positive.

Hence, a circuit diagram shows in figure 1 is carried out. The input $f(t)$is set as a square wave input with $10mHz$ frequency and the amplitude are set to $500mV$, on the oscilloscope, the input square wave and the value of x is observed.

2.1.2 Circuit construction

The same circuit can be observed using Tinker Cad shown in figure 3. This circuit having two breadboards one on the left denotes the summing circuit of the figure 1. The second breadboard denotes the combination of the two integration circuit of figure 1. The Arduino is set high of 3 seconds then set low of 3 seconds to simulate the square wave.

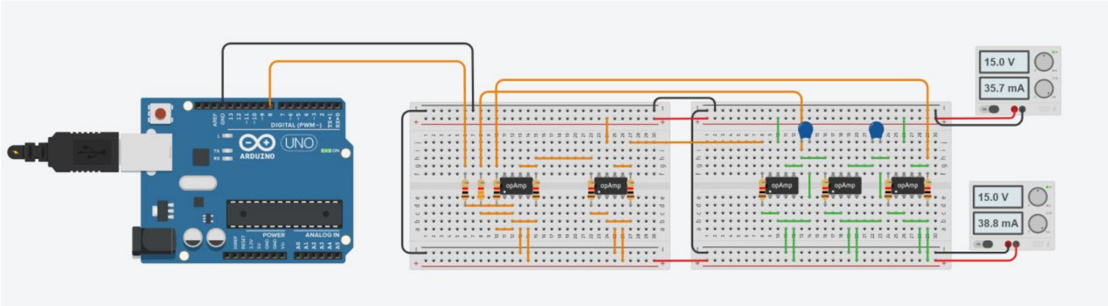

Figure 3: Tinker Cad circuit of the analog computer.

2.1.3 Result

The Falstad oscilloscope simulation is shown in figure 4 below, the red line is the step response of the output x, which oscillates at the beginning, then converge to zero steady state error at the end.

Figure 4: Falstad simulated step response of analog computer.

2.2 Proportional controlled DC motor

In this section, op amp is used as an important circuit construction of controlled DC motor, the proportion of the control can be modified by varying the proportional gain. The circuit construction, simulation and result are also discussed in the content.

2.2.1 Methodology

Objective: Building the circuit as a proportional control of the simulated motor (voltage to angle) using K=1,5, and 15

The proportional control of a DC motor controls the portion of the input voltage of the motor, the simplified circuit is shown in figure 5.

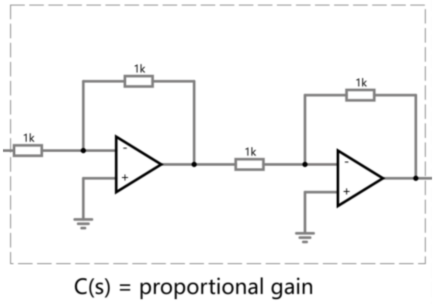

Figure 5: Proportional controlled circuit.

The relationship of the output voltage and the input voltage of the proportional controller can be denoted as the equation followed:

$$V_{out} = \frac{R_f}{R_{in}} V_{in} \tag{4}$$

The portion of the input voltage of the DC motor can be controlled by changing the ratio of the two resistances $\frac{R_f}{R_{in}}$.

This DC motor transfer the input voltage V_{in} into an angular speed ω having the gain of 3 and τ set to 0.1 seconds, to having the angle out, an inversed integration circuit is used, to integrate the angular speed ω into angle over a set of time.

The DC motor is built using Falstad shown in figure 6

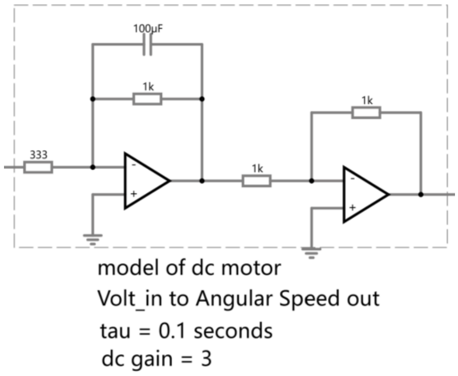

Figure 6: DC motor circuit.

Combining the two circuits using a summing circuit, the proportional controlled DC motor is shown in figure 7 below.

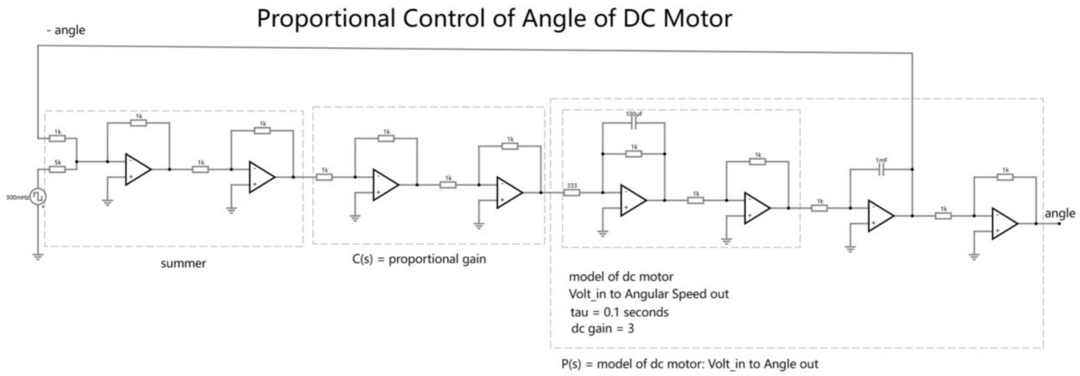

Figure 7: Proportional controlled DC motor circuit.

In this application, according to the data sheet, each op-amp having a maximum voltage of 15V, with the input voltage source having a 5V amplitude, the voltage exceeds the operation maximum voltage of each op-amp at K value is 5 and 15. Hence, the forcing voltage is reduced from 5V to 1V by using a $5k\Omega$ resistor instead of using an $1k\Omega$.

The value of the gain can be modified by varying the ratio of $\frac{R_f}{R_{in}}$, in this case, the gain is set to the value of 1,5 and 15. The performance of each will be compared lately.

2.2.2 Circuit Construction

The same circuit can be observed by Tinker Cad, the circuit is shown in figure 8 below. According to the schematic drawn in figure 7, the three components of the proportional control of DC motor is separated in three breadboards shown follows. The first breadboard using two op amp denotes the summing circuit, the second breadboard is the proportional control circuit, by varying the resistance of the first resistor, different gain (K) is set. The third breadboard is the DC motor, with gain of 3 and τ set to 0.1.

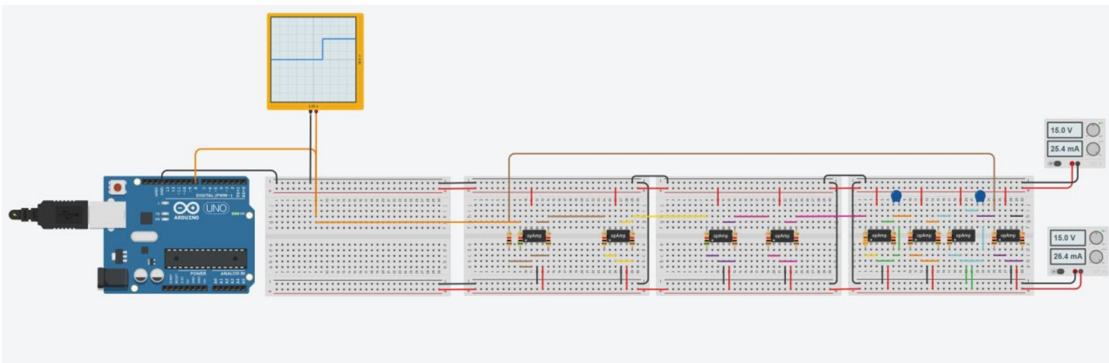

Figure 8: Tinker Cad proportional controlled DC motor circuit.

By using Octave, different value of K is simulated and plotted. The step follows figure 9 shown:

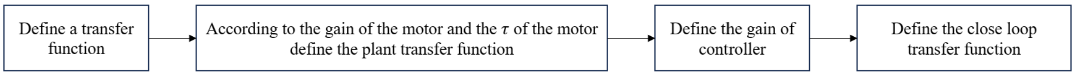

Figure 9: Simulation steps demonstration.

Using hold on command, two different step response can be plotted on the same graph for analyzing later on.

2.2.3. Result

Object 2: The oscilloscope waveform of different gain K is shown in figure 10, 11 and 12

Figure 10: Step response of K=1.

Figure 11: Step response of K=5.

Figure 12: Step response of K=15.

According to the waveform, as the gain increases, more oscillating shows at the beginning, however, gain of 1, 5 and gain of 15 shows a zero steady state error at the end.

Using Octave, the similar result is observed. For more straight forward representation and easier to compare, the three different gain is plotted on the same graph using hold on algorithm. The green curve is the step response of K=15, the blue curve is the step response of gain value K=5, and the red curve is the step response of K= 1.

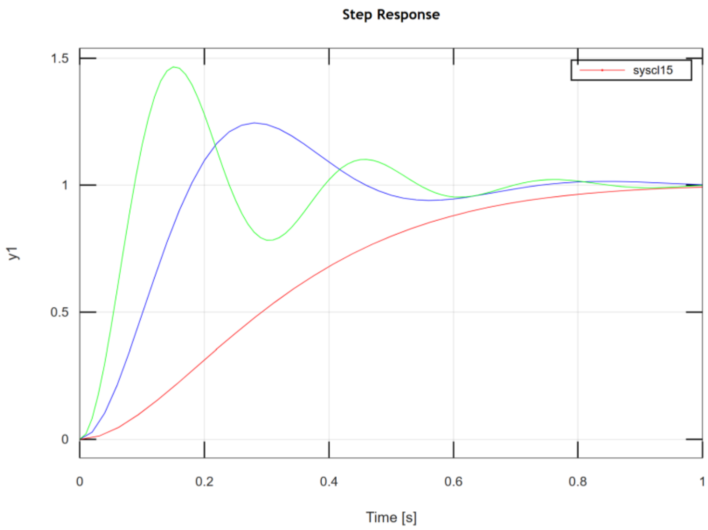

Figure 13: Step response of K=1, 5 and 15.

The graph shows below is the pole-zero map of three different gains. Having three sets of crossings, poles and zeros. Poles are the crossings at the imaginary axis denotes the frequency the values of the denominator become zero of the transfer function, and zeros are the crossings at the real axis, denotes the values of the nominator become zero of the transfer function.

The poles of different value of K can be plotted using the pzmap algorithm shown in figure 14, having green crosses is the poles and zeros of K=15, blue crosses is the poles and zeroes of K=5, red crosses is the poles and zeros of K=1, and in all three cases, same open loop poles are observed.

From the graph, it is easy to conclude that, as the value of K increasing, poles are more separated from each other, which has the phenomena of a more oscillating step response.

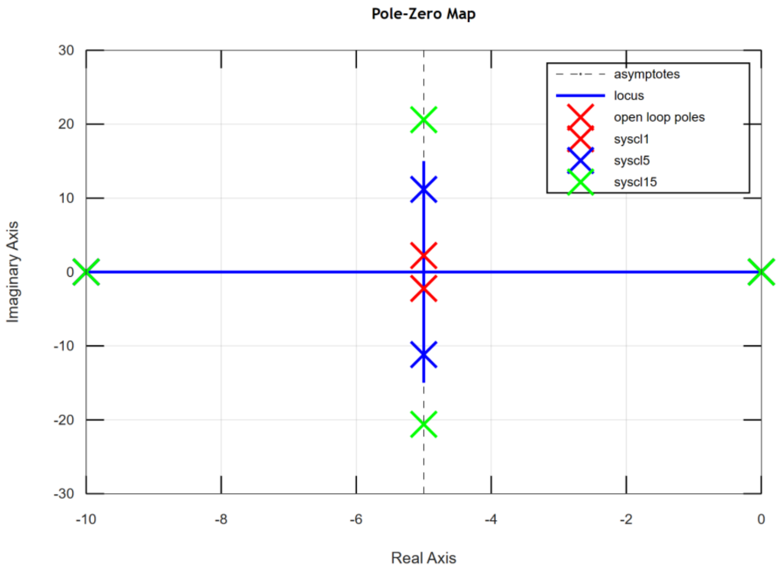

Figure 14: Pole-zero map of K=1, 5 and 15.

3. Conclusion

In this paper, two objectives are achieved, firstly, the analog computer circuit of solving the second order differential equation is build and analysed, secondly, the circuit of proportional controlled DC motor with different gain is constructed and discussed, additionally, the step response graph and the pole-zero map plotting to compare how the different proportional controlled gain value influence the stability of convergence at the input voltage changes is also discussed.

For realistic consideration, the op amp having a less maximum input voltage than the voltage source, hence, the forcing amplitude is reduced by a factor of 5 when inducing a resistor having a resistance five times than the ideal value at the summer.

For further study, the simulated circuit can be achieved in real electronic circuit and tested by oscilloscope, also, considering the circuit simulates a DC motor for real world application, safety consideration should be done, such as overload voltage.

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