An Audio Integrator Box: Indication of Spill at the Fermilab Test Beam

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Abstract

A schematic design for an audio integrator box is created and implemented, resulting in two working models to be sent to the MESON Test Facility at Fermilab. Each circuit is designed to drive a speaker and a light-emitting diode (LED) for the time any group at the MTEST experimental area receives spill from the beamline. The circuit integrates NIM signals ranging from 10kHz to 100kHz and emits audio frequencies that increase with increasing input rates fom the test beam. The schematic diagram for the audio integrator box is given below in Figures 1 and 2.

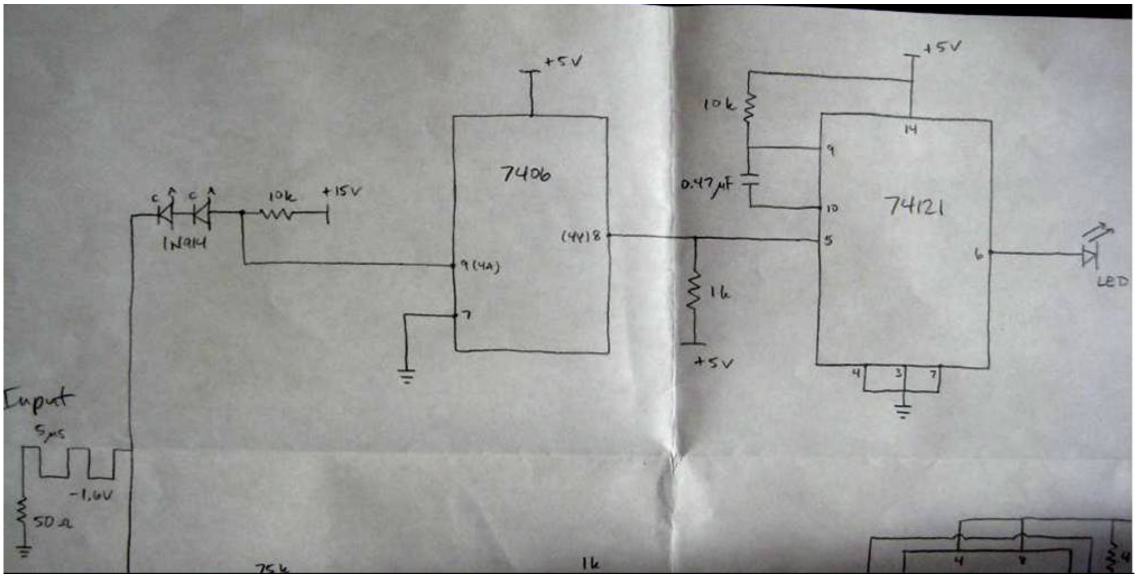

Figure 1: LED Schematic

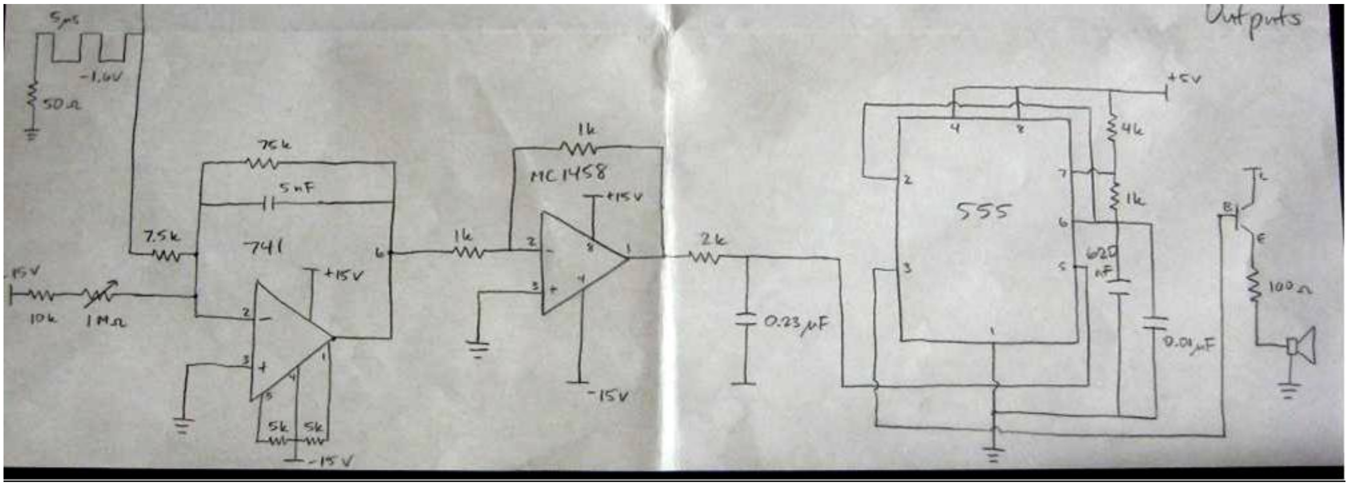

Figure 2: Speaker Schematic

1 Motivation and Goals

At Fermi National Accelerator Laboratory (FNAL) and other particle accelerators, physicists collide particles at energies reaching up to the TeV scale in order to investigate fundamental interactions amongst particles such as leptons, quarks, and photons. At the MTEST Facility at FNAL, spill from the test beam is divided amongst the various groups performing experiments there. The test beam, or beamline, is simply a line at Fermilab along which the colliding protons travel, and spill refers to the outflow of these protons to their target. The beamline is characterized by proton pulses that are each 1μs long at a voltage level of -1.6V with input frequencies ranging from 10kHz up to 100kHz. The task at hand is to design and build a NIM module that takes these proton pulses and converts them into audio frequencies output by a speaker. The average human can hear frequencies ranging from 20Hz up to 20kHz, so input frequencies from the test beam cannot simply be fed through to drive the speaker. Output frequencies are to depend on the input pulse rate – the higher the pulse frequency, the higher the pitch output by the speaker. In addition, there is to be a visual signal in the form of an LED that will light up for the duration any group at MTEST receives spill.

2 Design for Producing a Visual Signal When Receiving Beam

The method which is taken to drive a light-emitting diode begins with two silicon 1N914 diodes used to step up the input voltage, followed by a 7406 logic inverter triggering a 74121 monostable multivibrator. The 74121 integrated circuit outputs timed pulses of chosen length which drive the LED.

2.1 Silicon Diodes, 1N914

Since the input current is not sufficient to light up the LED, diodes are first used to raise the input voltage up to a level accepted by the next piece of circuitry, the inverter. The current versus voltage characteristic for the diodes used in the circuit is given in Figure 3.

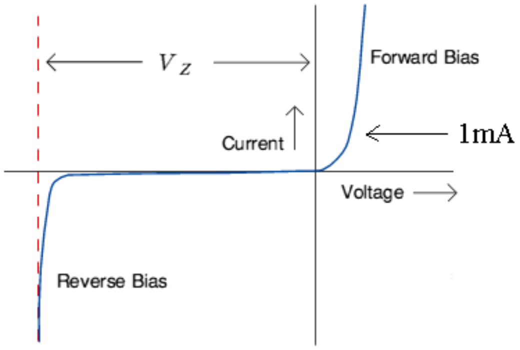

Figure 3: Silicon Diode Current vs. Voltage Curve

In the forward-biased region, the region defined by application of positive voltage to the anode, or the p-type semiconductor material of the diode and negative voltage application to the cathode, or the n-type material, it can be seen that there is a maximum voltage drop attained across one of the diodes. This maximum is accomplished at a current of about 1mA and produces a 0.6V drop. In reference to the schematic diagram of the circuit in Figure 1, two 1N914 diodes are placed in series with a 10kΩ resistor, which is tied to +15V from an external DC power supply. With these values of voltage and resistance, applying Ohm's Law,

$$V = IR \qquad (1)$$

gives a current of 1.5mA injected through the diodes. This current is sufficient to set the 0.6V drop across each of the two diodes that was seen in Figure 3. Considering then the voltage drop across the two Si diodes, it is clear that the input voltage, varying from -1.6V up to 0, will be shifted up to voltage levels of -0.4V and 1.2V, respectively.

2.2 Logic Inverter, 7406

The purpose of the 7406 logic inverter is to raise the voltage levels again and invert the input pulses since the next piece of circuitry is rising edge triggered. The 7406 inverter is characterized for use in driving TTL inputs [1], so its threshold voltage is 1.5V [2]. Therefore, an issue arises in that out of the diodes, a voltage level of 1.2V should not be enough to trigger the inverter. Nevertheless, it is found that the box functions properly. This problem and others that arise later in the schematics will be addressed further on in this paper. A schematic for the internal circuitry of a single gate for the 7406 is given in Figure 4 [1].

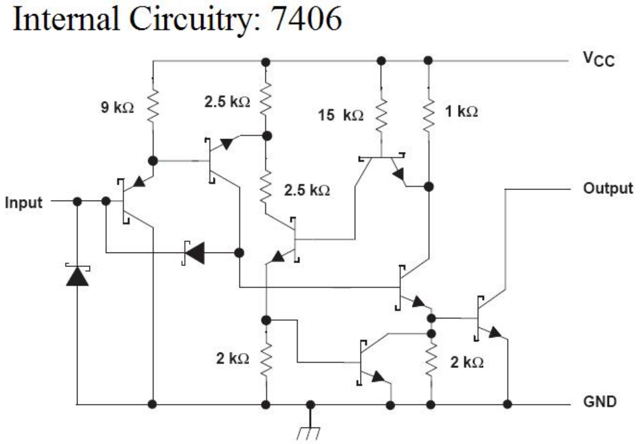

Figure 4: Internal Circuitry of Inverter 7406

The transistor on the far right in which its emitter is tied to ground and the collector is the output can be thought of as a switch to be open or closed. If the transistor is in the so-called closed, or "on" state, it will conduct, and current will flow through the transistor. The transistor's resistance in this case is labeled R_{closed} and is on the order of 10Ω-100Ω. The loop in which current will flow in the schematic is given below in Figure 5. The point of interest which is marked is simply the output that runs to the monostable multivibrator.

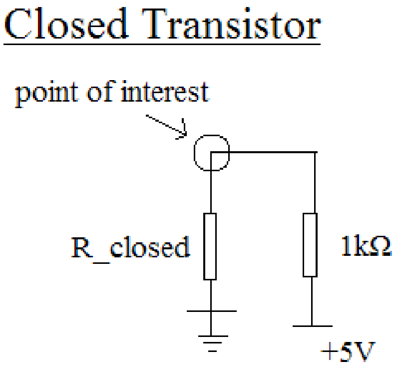

Figure 5: Output of the 7406

The inverter outputs current, but the multivibrator is sensitive to a voltage level; therefore, a 1kΩ resistor tied to +5V has been placed at the output of the 7406 to create this voltage. The particular values for the resistor and the voltage supply were selected by making calculations of the produced voltage level at the marked point of interest. Ohm's Law in (1) can be used first to find the current flowing through the loop in Figure 5. Since there are two resistors in series, the total resistance is found by a simple addition. Therefore, the current through the loop is given by:

$$I = \frac{V}{R} = \frac{5}{1k + R_{closed}} \sim 5mA \qquad (2)$$

At the point of interest then, the voltage level seen is simply the drop across the 1kΩ resistor, or equivalently, R$_{closed}$:

$$V = (5mA)\,(R_{closed}) \qquad (3)$$

which will range between about 0.05V and 0.5V. Now, if the transistor is open, or in the "off" state, it will be non-conducting, and current will not flow through the transistor as its resistance will be very large, on the order of 10^5-$10^6\Omega$. Very simply then, the voltage level seen at the point of interest in Figure 5 will be the +5V provided by the DC power supply. The 7406 is a logic inverter in that it may be thought of as being composed of two cross-coupled NAND gates as shown in Figure 6 below [3].

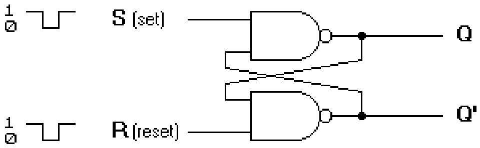

Figure 6: Set-Reset (S-R) latch composed of two NAND gates

This is a known as an S-R latch, or S-R flip flop; its logic table is given here:

S	R	Q	Q'	
1	0	0	1	
1	1	0	1	(after S=1, R=0)
0	1	1	0	
1	1	1	0	(after S=0, R=1)
0	0	1	1	

Figure 7: S-R latch logic

The flip-flop generally operates with a 1 at both inputs, but with a momentary application of 0 to the set input, Q will go to 1 and Q' outputs a 0 thereby inverting the pulse.

2.3 One-Shot, 74121

The one-shot is the critical component involved in driving the LED and is used to produce determined timed output pulses that are fed to the diode. The time width of the output pulses is determined by an external resistor and capacitor. A multivibrator is a circuit that is useful in manipulating a two-state system, in this instance, a timing mechanism. There are three basic types of multivibrator, the first called an astable multivibrator in which the two available states of the system are unstable. This free-running circuit exhibits oscillation between the two states and requires no external trigger to flip from one state to the next. The second type of multivibrator is a bistable, otherwise known as a flip-flop. This circuit is one in which both available states are stable, and an external event must exist to cause a flip from one stable state to the next and back again. The third kind is called a monostable, which is often called a one-shot. This type of circuit involves one stable state and one unstable state; an external trigger is necessary to flip the circuit to the unstable state for a specified period of time before reverting to the stable state [4]. To drive the LED, the one-shot integrated circuit (IC) is the most desirable since the input pulses from the test beam act as the trigger to activate the one-shot and induce it to output pulses sufficiently long to light up the LED. When spill from the beamline ceases, there is no input into the one-shot, and the circuit returns to its stable state in which the LED is not lit up. Moreover, in designing the box, retriggerability of the one-shot was considered. This concept is more easily understood by taking a look at Figure 8 below [5].

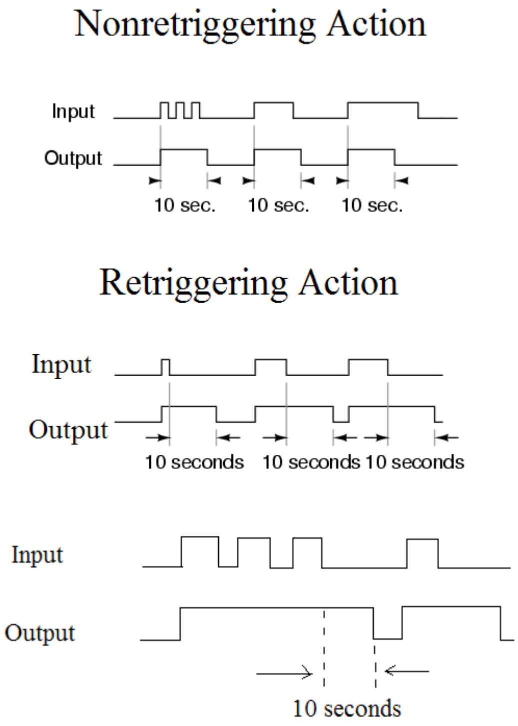

Figure 8: Timing for Retriggerable and Non-Retriggerable One-Shots

As is seen here, a retriggerable one-shot begins the timing interval after a transition from HIGH to LOW occurs. Moreover, the most important difference between the two is that retriggerability allows for a new timing interval to begin should another input pulse be fed to the one-shot within the duration of an output pulse. This can result in output pulses of varied length; however, for the constant input pulse rate dealt with here, output pulses of different lengths need not be considered. In contrast, non-retriggerable one-shots will show no response to any subsequent input pulses introduced during the length of an output pulse; hence, output pulses are in all cases of a fixed time width. Although it is seen that the LED remains lit for the duration pulses are received with the 74121 nonretriggerable one-shot, a retriggerable one-shot would have been more applicable. With a steady spill input frequency as is provided at the test beam, retriggerability would ensure an output pulse that would never fall LOW assuming a chosen delay time that is at least as wide as the maximum distance between any two pulses. This is due to the property just mentioned above- each pulse seen within the duration of the output pulse will force a new time interval to begin. In this case then, one long output pulse would be sent to the LED that begins when the first input pulse triggers the one-shot and ends shortly after the very last input pulse transitions to LOW. The 74121 that was used for the two modules is TTL compatible and therefore has the same 1.5V threshold as the inverter, so the +5V from the 7406 is a sufficient trigger. For this particular IC, the output pulse width is given by the equation:

$$t_w = kR_{ext}C_{ext} \tag{4}$$

where k for the 74121 is ~0.7 with R_{ext} in kΩ, C_{ext} in pF, and t_w in ns [6]. As in the case of the retriggerable one-shot previously mentioned, choosing the width of the output pulse to be wider than the greatest possible distance between two input pulses should be considered. Choosing values for the external resistor and capacitor so that t_w is shorter than this distance would guarantee time gaps where the 74121's output would transition from HIGH to LOW causing the LED to flicker. This consideration provided the motivation to choose the values for R_{ext} and C_{ext} seen on the schematic giving $t_w = 0.00329$s, since the maximum distance between two pulses is simply $\frac{1}{10kHz}$. However, as can be seen from Figure 8, this does not ensure that the output remains HIGH for the entire time beam is received. Regardless, no flickering of the LED is observed.

2.4 Design Alternatives

As stated, the threshold voltage of the inverter is 1.5V; however, only 1.2V is output from the two Si diodes. The low level threshold voltage for the 7406 is 0.8V, so one cannot be sure of the region between 0.8V and 1.5V; the 7406 may or may not work within this range, and therefore the box seems to work on luck. This issue may be resolved by simply placing a third diode in series with the other two, thereby creating an output voltage level of 1.8V, which would surely suffice to trigger the 74121. The only purpose the 7406 then serves is to invert the pulses to account for the one-shot being rising edge triggered. So, bypassing the inverter and thereby sending negative pulses to the 74121 would prevent the leading edge of the input pulse from triggering the one-shot. The one-shot would not output pulses until after the input rises from LOW to HIGH causing a 1µs delay before the LED would light up. This delay is not significantly long, and so the circuitry was modified on one of the integrator boxes and subsequently shown to work in the NIM crate.

3 Production of Audio Output

The method by which the speaker is driven involves integration over the input voltage producing output voltages dependent on the input frequency. This output is fed to an inverting amplifier MC1458 and subsequently to an RC filter that flattens the integrator's output, making it acceptable to the NE555 voltage control oscillator.

3.1 Operational Amplifiers

The functionality of an operational amplifier (op-amp) is crucial to understanding how the integrator 741 works. Referring to the schematic in Figure 2, the op-amp is a very high gain differential amplifier characterized by having two inputs, an inverting (-) and a non-inverting (+) input, and a single output. Gain is simply defined as being the ratio of output voltage to input voltage and is on the order of 10^5-10^6 for op-amps. If an increasingly positive voltage is applied at the non-inverting input, the output will tend to become more positive, and if applied at the inverting input, output will tend to become more negative. Moreover, an increasingly negative voltage applied at the non-inverting input will drive the output more negative, and if applied at the inverting input, will tend to make the output more positive [4]. There are two important properties of op-amps which govern how they function. First, the output does what is required to maintain a negligible voltage difference between the two inputs. This point will be discussed further in the next section within the context of negative feedback loops. Second, the inputs draw no current, so in Figure 2 the only path for current to take is to pass through the capacitor or the parallel resistor [4].

3.2 Integrator, 741

As drawn in the schematic, the integrator 741 contains an op-amp placed in a negative feedback loop, in which the op-amp's output is coupled to the inverting input. In Figure 9 below, if the input voltage is increased, the output voltage will increase as dictated by the gain of the op-amp. However, as the output voltage increases, output is fed back into the (-) input, which will lower the voltage differential between the two inputs and tend to drive the output down [7].

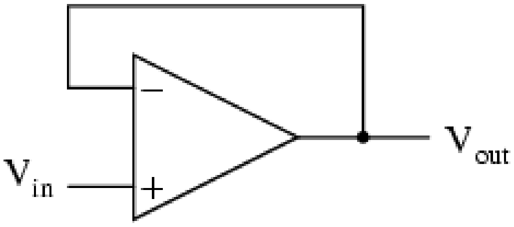

Figure 9: Schematic Diagram for a Negative Feedback Loop

With the 741 in the schematic, the non-inverting input has been tied to ground, which by negative feedback will ensure that the inverting input is held at 0V, otherwise known as a virtual ground. Analyzing the flow of current through the integrator, the following set of equations is obtained:

$$I_{in} = \frac{V_{in}}{R_1} \qquad (5)$$

$$I_{in} = I_1 + I_2 \qquad (6)$$

$$V_{out} = -I_1 R_2 \qquad (7)$$

$$I_2 = -C\frac{dV_{out}}{dt} \qquad (8)$$

where I_{in} is the current flowing into the integrator, I_1 is the current flowing through the parallel resistor, and I_2 is the current flowing through the integrator's capacitor. R_1 in the case here is a 7.5kΩ resistor, and R_2 is a 75kΩ resistor. These equations result in the following differential equation for the circuit:

$$\frac{dV_{out}}{dt} = -\frac{V_{in}}{R_1 C} - \frac{V_{out}}{R_2 C} \qquad (9)$$

with the initial condition that V_{out} $(t = 0) = 0$. The solution to this differential equation is obtained by using the method of integrating factors and is given by:

$$V_{out} = \frac{1}{R_1 C}\exp\left(\frac{-t}{R_2 C}\right)\int\limits_0^T \exp\left(\frac{\tau}{R_2 C}\right) V_{in} d\tau \qquad (10)$$

which is a solution for each input pulse, and can be separated into two time regimes, depending on whether t is shorter or longer than T, the width of an input pulse. The two solutions are given below for these cases, the first where $t < T$ and the second where $t > T$ until the next pulse hits.

$$V_{out} = \frac{V_{in} R_2}{R_1}\exp\left(\frac{-t}{R_2 C}\right)\left[\exp\left(\frac{-t}{R_2 C}\right) - 1\right] \qquad (11)$$

$$V_{out} = \frac{V_{in} R_2}{R_1} \exp\left(\frac{-t}{R_2 C}\right) \left[\exp\left(\frac{T}{R_2 C}\right) - 1\right] \qquad (12)$$

Graphing these two behaviors in Matlab produces the output voltage versus time plot seen in Figure 10.

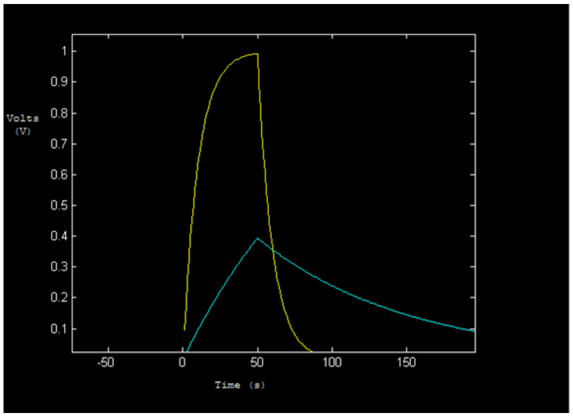

Figure 10: Theoretical Integrator Output, Voltage vs. Time

The curve with a lower peak voltage differs from the other in that the value of R$_2$ is ten times greater, producing a smaller range of output voltages from the integrator. This characteristic allows for a greater control of this output since the difference between the minimum and maximum voltage level is small causing less movement of the output within the range of input frequencies. The actual output of the integrator seen on the oscilloscope is shown below in Figure 11.

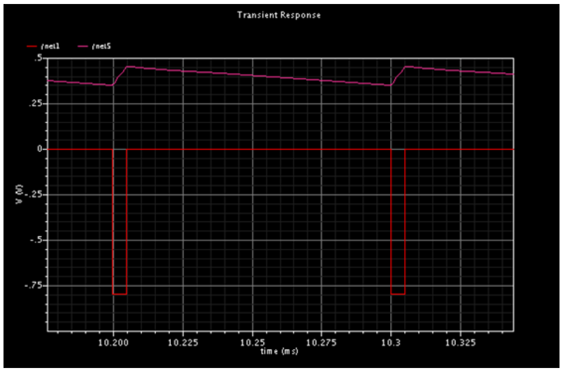

Figure 11: Integrator Output, Voltage vs. Time

The ramps resulting from the integration of the input pulses as the capacitor charges as well as the exponential decay due to the discharging of the capacitor between pulses can be seen. Moreover, the higher the frequency of the input pulses, the more voltage per unit time there is to integrate over; hence, the output voltage will be larger for higher input frequencies than for lower.

3.3 Inverting Amplifier, MC1458

The next component in the circuit is an inverting amplifier that inverts the output from the integrator to produce the desired frequency response from the NE555 voltage-to-frequency converter. In reference to Figure 12 below, an op-amp is seen in which the non-inverting input is again grounded creating a virtual ground before the inverting input [8]. Because of this virtual ground, the voltage across R$_f$ will simply be V$_{out}$, and the voltage across R$_{in}$ is just V$_{in}$.

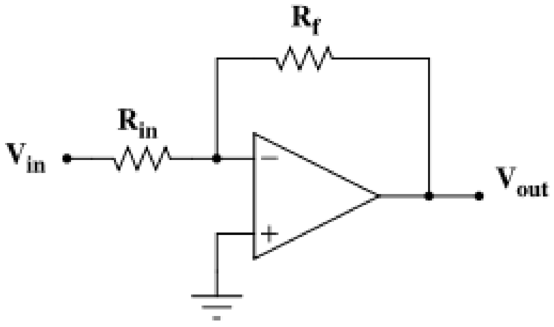

Figure 12: Schematic Diagram for an Inverting Amplifier

As previously stated, the inputs of an op-amp draw no current, so solving the circuit yields the following equations:

$$I_{R_{in}} = \frac{V_{in}}{R_{in}} \qquad (13)$$

$$I_{R_f} = \frac{V_{out}}{R_f} \qquad (14)$$

$$\frac{V_{out}}{R_f} = \frac{-V_{in}}{R_{in}} \qquad (15)$$

$$\frac{V_{out}}{V_{in}} = \frac{-R_f}{R_{in}} \qquad (16)$$

Therefore, choosing R$_f$ = R$_{in}$ as is done in the schematic will give:

$$V_{out} = -V_{in} \qquad (17)$$

as desired. The consequence of this inverting amplifier will be discussed later when the voltage-to-frequency converter is addressed.

3.4 Low-pass RC filter

A low-pass RC filter is placed after the output of the inverter after it was seen that the voltage-to-frequency converter did not respond well to high-frequency output from the integrator. The output voltage from a low-pass filter is given by the following relation [4]:

$$V_{out} = \frac{V_{in}}{\sqrt{1+\omega^2 R^2 C^2}} \qquad (18)$$

where $\omega = 2\pi f$, with f varying from 10kHz to 100kHz. As this angular frequency increases, V_{out} will decrease eventually reaching zero. In this way, the waviness of the integrator's output is averaged, and the output from the filter is a flat line voltage acceptable to the voltage-to-frequency converter.

3.5 Voltage Control Oscillator, NE555

The voltage control oscillator (VCO) is the crucial component involved in driving the speaker. Wiring the NE555 integrated circuit as a pulse position modulator as seen in the schematic, the behavior shown in Figure 13 is observed [9].

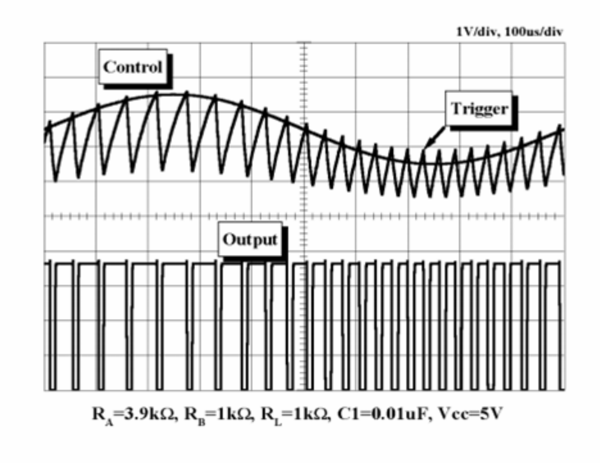

Figure 13: Pulse Position Modulation, NE555 Output

The voltage level at the low point of the modulation signal is 1.5V and the voltage level at the peak of this signal is 5V. It is important to note that the larger the voltage level of the modulation signal, the less frequent the output pulses, and the lower this voltage, the higher the output frequency. However, the opposite behavior is desired in that the more frequent the input pulses from the test beam, the larger the output voltage from the integrator, and ideally the higher the frequency of pulses out of the NE555. Because the NE555 was found to behave in this manner, the inverting amplifier discussed earlier became necessary. To find the ideal voltage levels at which the NE555 functions, a plot was made of the frequency versus voltage output from the isolated VCO by applying a DC voltage from an external power supply to its input.

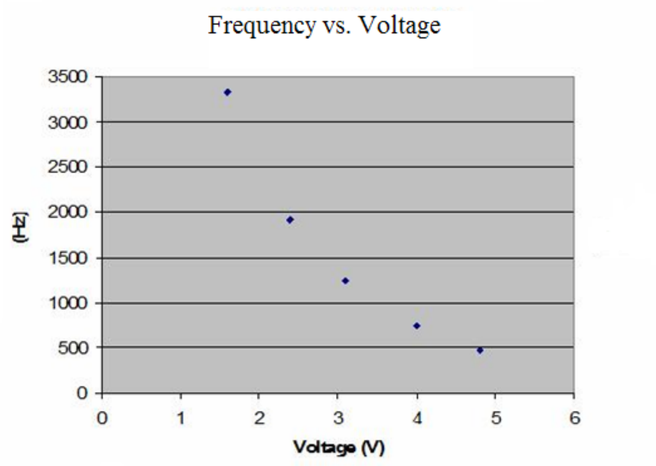

Figure 14: Frequency vs. Voltage for isolated VCO supplied with +5V

A range from 2-4V was found to be the optimal input voltage range as the behavior appears monotonic within those bounds. Since the output of the inverting amplifier negates the input, the input voltage range to the NE555 varied from -4V up to -2V, now associating the higher frequency output from the NE555 with the higher input voltage. Referencing the schematic in Figure 2, the 1MΩ potentiometer placed before the inverting input of the 741 acts as a variable resistor that allows for controlled injection of current into the circuit and hence enables tuning of the integrator's output. The potentiometer was tuned to raise the voltage level up again to 2-4V and covers the entire range of input frequencies from 10kHz to 100kHz.

3.6 NPN Transistor

The transistor is the final component necessary to drive the speaker and serves to amplify the output current from the NE555 so that the speaker may be heard. A transistor has three terminals- a base, collector, and emitter, as shown in the schematic [4]. There are two flavors of transistor, npn and pnp. There are three defining properties for the npn transistor; the pnp follows the same rules but with reversed polarities. First, the collector must be more positive than the emitter. Second, the base-emitter junction is forward-biased so that if positive voltage is applied to the junction, current will flow easily from the emitter to the base. Oppositely, the base-collector junction is reverse-biased, so that hardly any current is injected from the collector to the base. Last, maximum values of collector current I_C, base current I_B, and collector-to-emitter voltage drop V_{CE} must not be exceeded or else the transistor will fail. Provided these three rules are obeyed, the collector current is proportional to the base current as following:

$$I_C = \beta I_B \tag{19}$$

with β the current gain, and β ~ 100. The collector current flowing to the emitter and finally to the speaker will therefore be on the order of 100 times more than the base current, or the output current from the VCO, and the speaker will be heard.

4 Conclusions

Both audio integrator boxes have been constructed and shown to work on the NIM crate in the electronics shop at UChicago and are ready to be taken to Fermilab to work at the MTEST Facility. The front panel on each box was machined to have a trigger input, an enable/disable switch allowing users control of the speaker output, and the LED. If the project was to be repeated, it would be worthwhile to drive the LED using a retriggerable one-shot and wire the circuitry so that the 7406 is not required as was done with one of the modules. Also, it would have saved some time to have entered the schematic diagram into a simulation program such as SPICE to see first if the design would work as desired before beginning the building process.

Acknowledgements

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