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PCB Design Report : Door Buzzer

Contents

1 Introduction 2
1.1 Main functionality of the circuit 2
2 Circuit Analysis and Block Diagrams 2
2.1 Expected Behavior on Power-Up 2
2.2 Timer : NE555 3
2.2.1 Monostable Mode: Design choices and Computations 3
2.2.2 Experimental Verification of the NE555 Timer's Pulse Generation Capabilities 4
2.3 Tone Control : NPN Transistor 2N3904 4
2.3.1 Collector-Impedance Frequency response 4
2.3.2 Experimental verification of the Pulse Duration 5
2.4 Oscillator : LM380N audio power amplifier 6
2.4.1 Simulation Analysis of the LM380N Audio Amplifier 6
2.5 Personal Contributions : 7
2.5.1 Changing the notes frequency 7
2.5.2 Components 7
2.5.3 Alarm Detector using the Astable Mode 7
3 Sources and references (following APA norms) : 8

1 Introduction

1.1 Main functionality of the circuit

The Door Buzzer Circuit[1] is an electronic device designed to produce a two-tone sound, resembling a traditional doorbell. This circuit comprises various components, including an LM380N audio power amplifier, a loudspeaker, an 555 IC, and several resistors and capacitors. The two-tone sound is generated through a series of oscillations and feedback loop.

2 Circuit Analysis and Block Diagrams

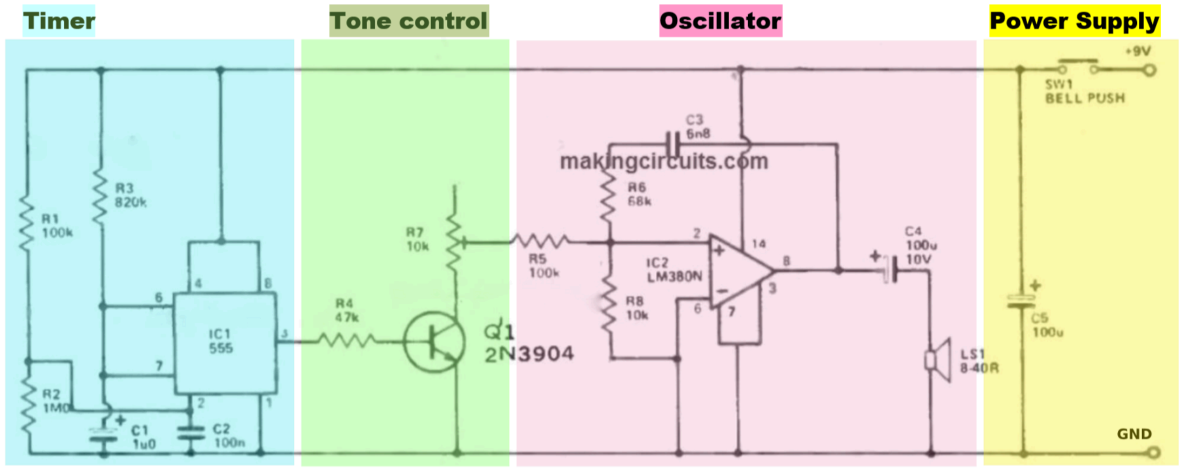

Figure 1: Door Buzzer schematic.

2.1 Expected Behavior on Power-Up

The NE555 timer, configured in monostable mode (a one-shot pulse generator) is activated at Power-Up, generating a **one-second pulse** on its Output (Pin 3), which in turn activates the NPN transistor Q1.

Concurrently, once the bell button is pressed, the audio amplifier is powered and starts to generate an oscillating output through its feedback loop.

The NPN transistor is activated for one second, during which the tone pitch of the oscillator gets higher (the NPN, then active, concurrently adds R_5 and R_7 to the circuit, effectively raising the frequency of the tone). After this one-second interval, the NPN deactivates (removing R_5 and R_7 from the circuit) and the oscillator part of the circuit reverts to its original lower-tone pitch.

This behavior ensures that when the doorbell button is pressed, the circuit produces a distinct higher tone for one second, followed by a lower-tone pitch, producing a ding-dong sound.

<u>Pitch Frequencies relative to the Potentiometer :</u>

- For the first pitch, assuming that :

$$R_{\text{eq}} = R_6 + (R_5 + R_7) // R_8$$

We'd obtain a frequency f_1 of about **305.3Hz to 303.62Hz**[2][3]

- Once the timer pulse ends, Q1 turns off. R_5 and R_7 are no longer in the circuit, and the oscillator returns to its lower frequency :

$$f_2 = \frac{1}{2\pi * RC} = \frac{1}{2\pi * 78k * 6n8} = \textbf{301.8 Hz}$$

[1] https://makingcircuits.com/blog/door-buzzer-circuit/

[2] frequency with and without the potentiometer $R_7 = 100k\Omega$.

[3] using my actual components values.

The frequency difference between f_1 and f_2 is not great but still **noticeable**. Refer to the Section 2.5 for discussions on improvements.

Notes :

- Since the monostable mode of the NE555 needs a rising edge to trigger, holding the doorbell (constant High) will not continuously keep the bell ringing. It will only trigger once for the determined duration for each button press (if the presses are sufficiently appart from each other).
- C_4 is a Decoupling capacitor (DC-stopping) which blocks the DC component and allows only the AC signal to get to the speaker.
- C_5 stabilizes the power supply voltage. The circuit awaits 9V of Vcc.

2.2 Timer : NE555

2.2.1 Monostable Mode: Design choices and Computations

The NE555 is in Monostable multivibrator mode (one-shot pulse generator) thus will only be triggered **once** upon pressed. Its datasheet[2] p.10 gives us the following equation for its output Pulse duration :

$$t_w = 1.1 * R_A * C$$

using Ra = 820k and C = 1 µF, one obtains :

$$t_w = 0.902s$$

We verify this computation by simulation (see Figure 2) and by experimentation (see Figure 4). Explanations of those results are included in Section 2.5.

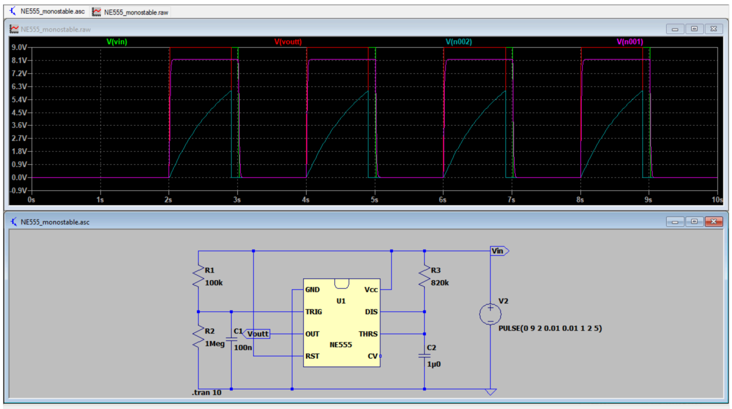

Figure 2: Monostable simulation of the NE555.

In monostable mode, the NE555 timer is configured to produce an output pulse of a fixed duration. Upon pressing the button, the trigger input (V_{trig}) goes low briefly (i.e. falls below 1/3 Vcc) and the TRIG comparator (see Figure 3) Sets the flipflop, making its output high and turns off the discharge transistor allowing C_1 (or C_2 in the simulated circuit, Figure 2) to charge through R_3 until the threshold voltage reaches 2/3 Vcc. Recall that this will take 1.1RC seconds (or approximately 0.9 seconds in our simulation Figure 2, which is consistent with the pulse duration we previously calculated).

When it gets to that point (i.e. the capacitor voltage V(n002) reaches 2/3 Vcc, here 6V), the THRES comparator Resets the flipflop, making the output low, and turns on the discharge transistor which grounds the discharge pin. Since this is connected directly to the point between the capacitor and resistor, the capacitor discharges essentially instantaneously. This also causes the threshold voltage to go to zero, and the flipflop's Reset input to go low. Now both the Set and Reset inputs to the flipflop are low and the circuit is again in a stable state with the output low. [4]

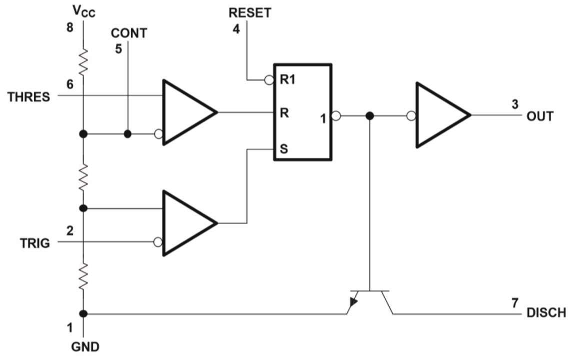

Figure 3: NE555 Functional Block Diagram.

2.2.2 Experimental Verification of the NE555 Timer's Pulse Generation Capabilities

To verify the pulse generation capabilities of the NE555 timer, we conducted an experiment using a signal generator with a pulse at 400mHz imitating a bell push. The resulting output pulse of the NE555 is 1.2 seconds, slightly deviating from our calculated value of 0.9 seconds. Possible reasons for this may include:

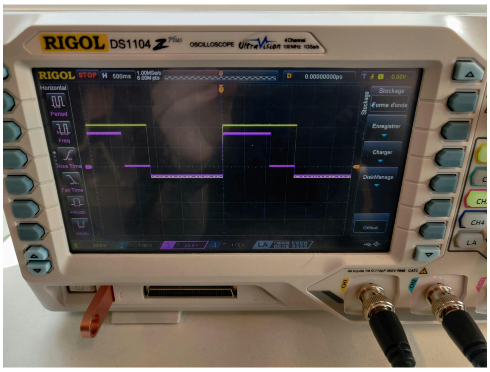

Figure 4: Monostable experimentation of the NE555.

1. Component tolerance: The actual resistance and capacitance may differ from their nominal values. Which could result in a longer output pulse duration. Which can be easily solved by manually checking them.
2. Triggering mechanism: The NE555 might be triggered again before the output pulse has fully decayed, resulting in a longer overall pulse duration. This can be solved by adding a debounce mechanism on the button, but the signal generator used for this experiment, voids any possible bouncing of the signal.
3. Leakage Current: Small leakage currents within the NE555 timer itself or on the PCB can cause the capacitor to discharge slowly, extending the pulse duration.
4. Stray Capacitance: Parasitic capacitance from wiring or components close together can add to the overall capacitance.

2.3 Tone Control : NPN Transistor 2N3904

2.3.1 Collector-Impedance Frequency response

The NPN transistor is used to switch resistances in and out of the circuit, which changes the value of the time constant and thus the frequency of the oscillations. Starting from the collector of the NPN, we compute its Impedance as following :

$$Z_{\text{eq}} = R_7 + R_5 + \left(R_6 + \frac{1}{sC_3}\right) \mathbin{//} R_8$$

$$Z_{\text{eq}} = R_7 + R_5 + \left(R_8 * \frac{R_6 + \frac{1}{sC_3}}{R_8 + R_6 + \frac{1}{sC_3}}\right)$$

$$Z_{\text{eq}} = R_7 + R_5 + \left(\frac{sC_3 * R_6 * R_8 + R_8}{sC_3(R_8 + R_6) + 1}\right) = \frac{(R_7 + R_5) * [sC_3(R_8 + R_6) + 1] + sC_3 R_8 R_6 + R_8}{sC_3(R_8 + R_6) + 1}$$

with $s = j\omega = j * 2\pi f$:

$$Z_{\text{eq}} = \frac{(R_7+R_5+R_8)+j\omega[(R_7+R_5)(R_6+R_8)*C_3+R_8R_6C_3]}{1+j\omega[C_3(R_6+R_8)]}$$

Plugging the numerator and denominator in the Pythagorean formula :

$$|Z| = \frac{\sqrt{(R_7+R_5+R_8)^2+(((R_7+R_5)(R_6+R_8)C_3+R_8R_6C_3)2\pi f)^2}}{\sqrt{1+((R_6+R_8)C_32\pi f)^2}}$$

This last expression and its graph Figure 5 represents the magnitude of the complex impedance as seen by the output of the amplifier looking into the rest of the circuit. This would be the magnitude part of a Bode plot. At frequencies above 1kHz the output impedance is around 110k.

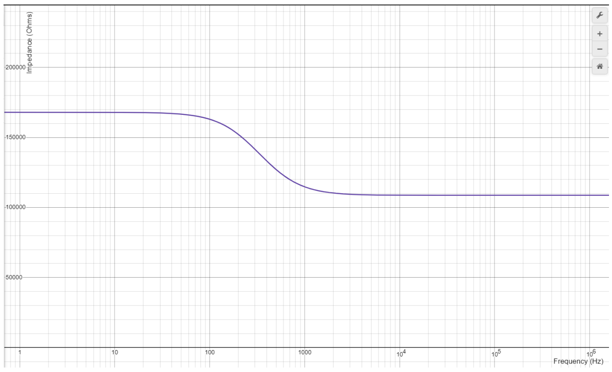

Figure 5: Impedance-Frequency **Bode** plot.

We are now able to compute the Collector current :

$$I_C = \frac{V_{\text{cc}}}{Z_{\text{eq}}} = \frac{9V}{110k} = 75 \text{ to } 82\mu A \text{ (with and without } R_7\text{)}$$

To ensure to be in saturation down to a Vc of about 1V, we choose hFe = 0.45 for $I_c < 0.1\text{mA}$ (which is the lowest possible value from Figure 15 called "Dc Current Gain" from 2N3904's datasheet [3]) :

$$I_B = \frac{I_C}{\text{hFe}} = 160 \text{ to } 180\mu A$$

and finally :

$$R_{\text{base}} = \frac{V_{\text{cc}} - V_{\text{BE}}}{I_B} = 46 \text{ to } 50k\Omega$$

The closest E12 value would be **47k.**

2.3.2 Experimental verification of the Pulse Duration

Measuring the voltage experimentally at the NPN gate, we observe it being open for the duration of the output pulse generated by the NE555, reaching 640mV (see Figure 6) as seen in the NPN-datasheet[3] ($V_{\text{BE}} = 0.65V$).

Why the transistor is conducting below the built-in voltage (0.65V) might be because of carrier injection from a Shockley boundry condition[9].

When testing the limits of this circuit, increasing the Voltage source above 9V resulted in a V_{BE} up to 0.75V.

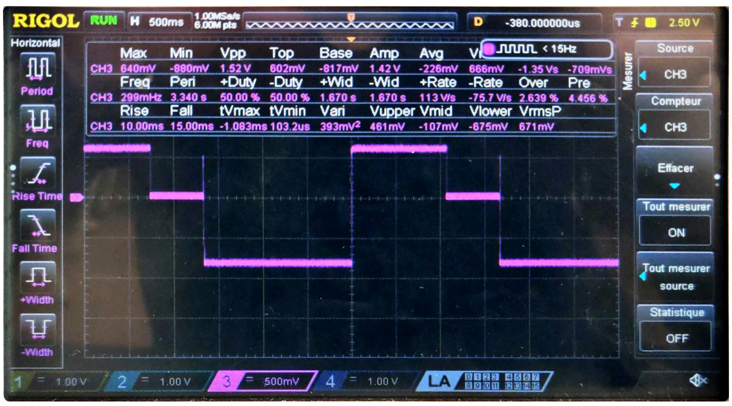

Figure 6: Voltage V_{BE} of the transistor.

2.4 Oscillator : LM380N audio power amplifier

Audio amplifiers, compared to general purposes Op-Amps, are optimized for minimizing distortion and preserving audio quality, for instance we can find out that the LM380 [6] :

- Vs power supply 10V - 22V
- General uses include : simple phonograph amplifiers, intercoms, line drivers, alarms, ultrasonic drivers, TV sound systems, AM-FM radio, small servo drivers, power converters, etc.
- Bandwidth up to 100kHz.

The audio amplifier seems to be in a sort of Schmitt Trigger installation with the main difference being the position of the capacitance (inside the feedback loop in our circuit compared to outside in a more classic Scmitt Trigger circuit, see Figure 7).

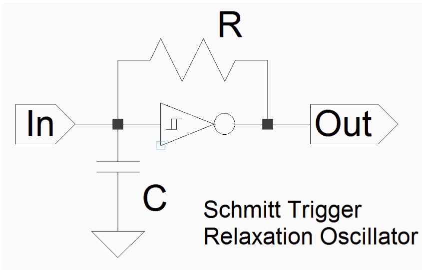

Figure 7: source : [7]

<u>So where does the oscillations originates from ?</u>

Some internal parasitic oscillations (due to Johnson's thermal noise[4][5]) start to affect the voltage on the feedback capacitor. This creates a small voltage difference between the inputs of the Opamp, which will be gradually amplified over and over again. This then taking as long as necessary to amplify until fully charging and discharging the capacitor C_3 leading to the full amplitude of the oscillations.

We should also take into account that the speaker connected to the op-amp's output acts as a non-linear load, it's vibration changes the resistance of the circuit, thus also affecting the feedback voltage.

2.4.1 Simulation Analysis of the LM380N Audio Amplifier

Since no model for the LM380N audio amplifier was found online, I simulated my circuit using another amplifier : the LT1006 Op-Amp [5].

Here we obtain a stable oscillation of about 77.5Hz, we do not expect this value to be representative for our circuit since the resistors value were adapted for the the 2.5million gain of the LT1006 Op-Amp. We would expect, however, that our LM380N audio amplifier would oscillate with more precision.

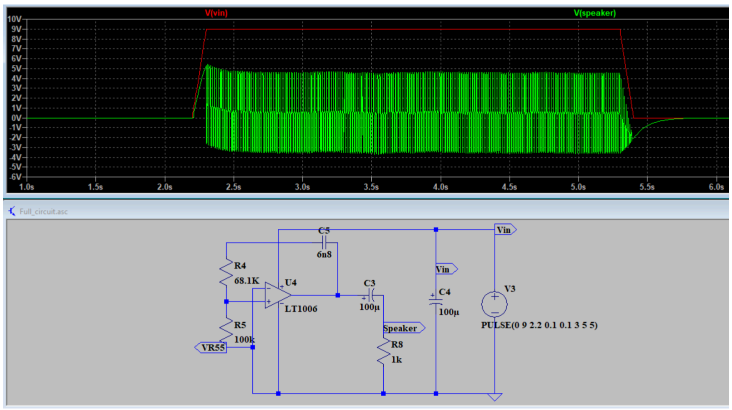

Figure 8: LT1006 amplifier oscillator.

[4]J. B. Johnson (1928) **"Thermal Agitation of Electricity in Conductors, Phys. Rev. 32, 97 "** https://journals.aps.org/pr/abstract/10.1103/PhysRev.32.97

[5]Texas Instrument **"Op Amp Noise Theory and Applications"** https://intranet.ee.ic.ac.uk/t.clarke/ee2lab/handouts/A/noise-3.pdf

2.5 Personal Contributions :

2.5.1 Changing the notes frequency

When designing a doorbell circuit, achieving a traditional "ding-dong" sound comprising of two distinct notes - Mi and Do - is crucial. According to [8], this classic sound is typically comprised of these two notes. The corresponding frequencies for these notes are:

- **C** (Do) : 261.63 Hz
- **E** (Mi) : 329.63 Hz

which we rounded to the nearest integer.

To produce these specific notes, a formula can be used to calculate the equivalent resistance:

$$R_{\text{eq}} = \frac{1}{2\pi \text{fC}}$$

When the circuit is activated, it initially emits a "Mi" pitch (NPN activated, see green path Figure 9). One second later, the second note, "Do", is emitted (see orange path).

To adjust the pitch, I picked R_7 to be at $50k\Omega$ for manual fine-tuning ($R_7 = 0k - 100k\Omega$).

Using these values for R_6, R_5, and R_8 :

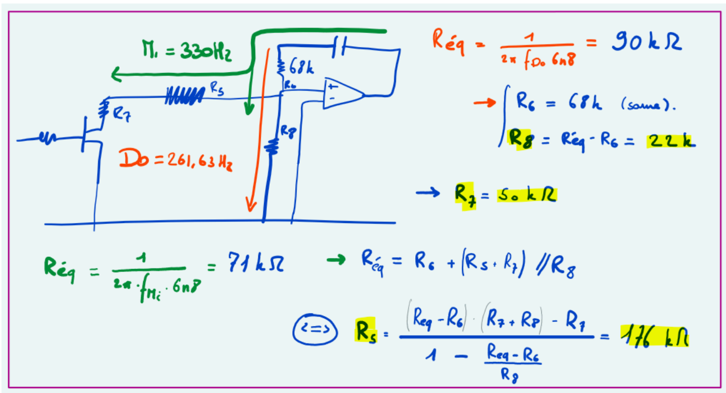

Figure 9: Computations to achieve a classic **"ding-dong"** sound on the circuit.

2.5.2 Components

In the case I'd re-design my circuit I would :

1. <u>Add a protection diode:</u> The circuit doesn't have any protection against voltage surges or spikes. Especially if we plan to power it using a house outlet.
2. <u>Using a more modern transistor:</u> The 2N3904 transistor is a bit old, we could use a transistor with better characteristics, such as the BC547 or BC557.
3. <u>Changing the Bell push :</u> we could choose another mechanism that makes sure the power is High for at least 2 seconds (1sec for each note).

2.5.3 Alarm Detector using the Astable Mode

For my final circuit, I opted for an **Astable mode** instead of a monostable mode. The two-tone buzzer achieved using the monostable mode was not audible enough and didn't really sound like a doorbell.

The Astable mode allows for a continuous ringing sound (dring-dring) as long as the button is pressed. Now instead of a one-shot pulse, the ne555 will output an oscillating signal to the NPN, changing the tone following the Astable frequency.

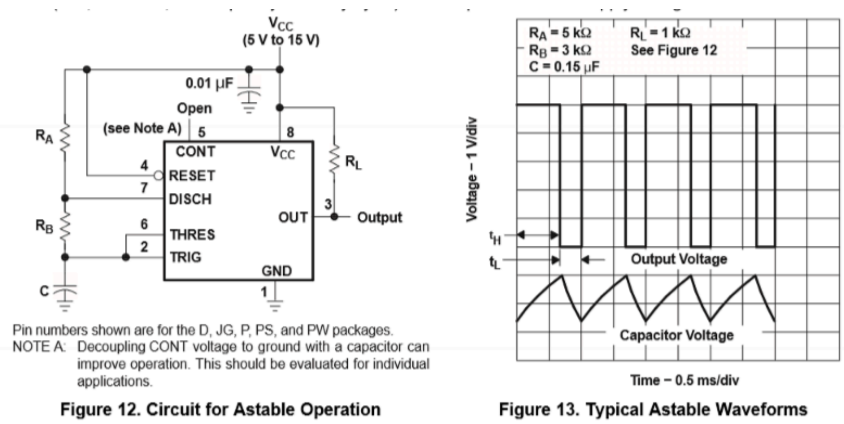

Figure 10: Astable Configuration [2].

Using
- $R_a = 100k$,
- $R_b = 1\text{M0}$ and,
- $C = 100$ nF

we obtain a switching frequency [2] of $f = \frac{1.44}{(R_a+2R_b)*C} = 6.85$ Hz

To go further, the Astable configuration for this circuit allows it to be adapted as an "Alarm detector". Inverting the bell button, the alarm will ring whenever a door in your house has been opened after placing the electrodes of contact to the door/wall which opens the circuit.

3 Sources and references (following APA norms) :

[1] : AspenCore (2024) **"555 Timer Tutorial"** consulted the 14/04/2024 on : https://www.electronics-tutorials.ws/waveforms/555_timer.html

[2] : Texas Instruments (2024) **"xx555 Precision Timers datasheet "** consulted the 14/03/2024 on : https://www.ti.com/product/NE555

[3] : ONSEMI [ON Semiconductor] (2024) **"2N3903 Datasheet (PDF) - ON Semiconductor"** consulted the 14/04/2024 on : https://www.alldatasheet.com/datasheet-pdf/pdf/11469/ONSEMI/2N3903.html

[4] : Dave Astel (2024) **"Getting to know the 555 : Monostable Operation"** consulted the 15/04/2024 on : https://learn.adafruit.com/getting-to-know-the-555/monostable

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[7] : Wikipedia (2024) **"Schmitt trigger"** consulted the 20/04/2024 on : https://en.wikipedia.org/wiki/Schmitt_trigger

[8] : Wiki user (2022) **"What is the frequency of Do-Re-Mi?"** consulted the 14/04/2024 on : https://qa.answers.com/music-and-radio/What_is_the_frequency_of_Do-Re-Mi

[9] CHU-Berkeley (2009) : **PN and Metal–Semiconductor Junctions :** https://www.chu.berkeley.edu/wp-content/uploads/2020/01/Chenming-Hu_ch4-1.pdf#page=17