Audio Engineering Society

Convention Paper 10212

Presented at the 158th Convention

2025 May 22-24, Warsaw, Poland

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Analog Pseudo Leslie Effect with High Grade of Repeatability

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ABSTRACT

This paper describes the design of an Analog Stomp Box capable of reproducing the effect observed when a loudspeaker is rotated during operation, the so-called Leslie effect. When the loudspeaker is rotating two physical effects can be observed: The first is a variation of the amplitude because sometimes the speaker is aimed at the observer and then, after 180 degrees of rotation, the loudspeaker is aimed opposite to the observer. To recreate this variation in amplitude, a circuit called Tremolo was designed to achieve this effect. The second is the Doppler effect, which was obtained with a circuit designed to vary the phase of the signal (Vibrato). The phase variation simulates a frequency variation for the ears. Assembling these two circuits in cascade, it is obtained the Pseudo Leslie Effect. These Vibrato and Tremolo circuits receive the control signal from a Low Frequency Oscillator (LFO) which controls the effect frequency. To get a high degree of repeatability, which is not simple in analog circuits employing photocouplers, those photocoupler devices were replaced with VCAs. The photocouplers have a great variation of your optical characteristics, so it is hard to obtain the same result in a large-scale production. However, using VCAs is easily achievable. The THAT2180 IC is a VCCS, Voltage-Controlled Current Source with an exponential gain control and low signal distortion. The term Pseudo was used because, in the Leslie Effect, the rotation of the loudspeaker gives a lag of 90º between the frequency and amplitude variations. This lag has not been implemented, but the sonic result left nothing to be desired.

1 Introduction

Digital and analog audio effects [1] are often compared by musicians and the two types naturally have advantages and disadvantages. Hobbyists usually prefer to use analog devices because of their good sound and to avoid using DSPs, FPGAs, Arduino [2] [3] and others. An example of an analog Leslie Effect is presented in [4]. However, analog circuits in general, often found in the literature, present a major problem in terms of repeatability. The devices normally used to control characteristics such as magnitude, phase and spectral content are JFETs operating in the ohmic region, photocouplers made up

of LEDs and LDRs, among others, which have different characteristics from one to another. This is not the case with a Voltage-Controlled Current Sources (VCCS), the THAT 2180 [5], which has high performance and a high degree of repeatability. These ICs, used with the aid of opamps, resistors and capacitors, give a very good sound, compared to digital circuits.

2 Low Frequency Oscillator - LFO

To create signals that vary the Tremolo and Vibrato parameters [1], it is necessary to use a low frequency generator in the 1 Hz to 10 Hz range, which can be altered to the musician's taste. It should have two controls: RATE (frequency control) and DEPTH (effect magnitude control).

One of the most robust LFO's [6] widely used is formed by the loop of a Bistable and an Integrator (see Figures 1 and 2). The bistable is responsible for generating a square wave, through positive feedback, whenever the signal is a few millivolts above the positive input reference the output is transferred to upper saturation. When the signal is a few millivolts below the reference voltage, the output is taken into lower saturation. As a result, a square wave is produced. This wave is applied to the integrator, from which a triangular wave is obtained.

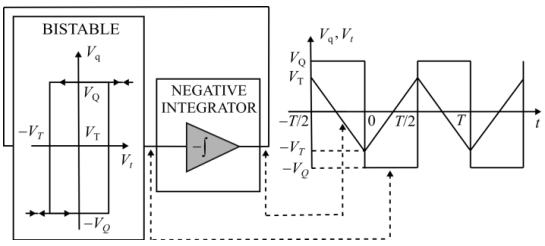


Figure 1. LFO Block Diagram.

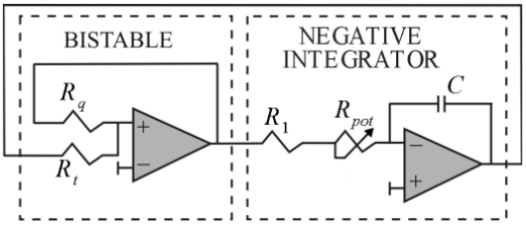


Figure 2. Simplified LFO circuit.

The circuit shows that when the bistable changes state there is:

$$\frac{V_Q}{R_Q} = -\frac{V_T}{R_T} \tag{1}$$

Then,

$$\frac{|V_Q|}{|V_T|} = \frac{R_Q}{R_T} \tag{2}$$

Considering $\sigma_0 = 1/RC$, it can be shown that [5]:

$$f_0 = \frac{1}{T} = \frac{V_Q \sigma_0}{4V_T} = \frac{V_Q}{V_T} \cdot \frac{1}{4RC} = \frac{R_Q}{R_T} \cdot \frac{1}{4RC} \tag{3}$$

To obtain low frequencies, in order of a few Hz, it is necessary to use relatively high values for the integrator's resistor and capacitor. Therefore, the short-circuit resistor strategy is used through an association of resistors (see figure 3a).

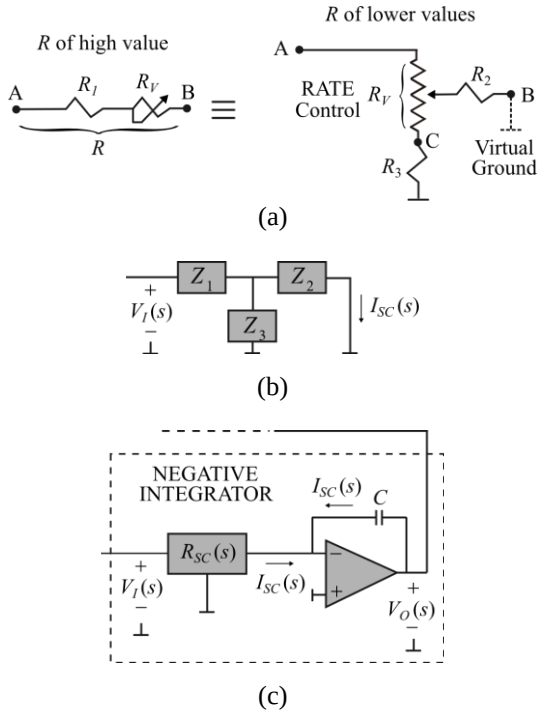


Figure 3. (a) Strategy to use an association of resistors. (b) Circuit to calculate short-circuit resistor. (c) Negative integrator with short-circuit resistor.

2.1 Design of the LFO for a 1 Hz to 10 Hz Range

The short-circuit resistance, as shown in Figure 3, is:

$$R_{SC} = \frac{R_V R_2 + R_V R_3 + R_2 R_3}{R_3} \tag{4}$$

Then, from (3):

$$f_0 = \frac{R_Q}{R_T} \cdot \frac{1}{4R_{SC}C} \tag{5}$$

To ensure oscillation, the value of the R_Q resistor must be greater than the value of the R_T resistor. This prevents the different saturation voltages of the opamps, preventing the Bistable from changing state.

So, it was adopted $R_Q = 100\ k\Omega$ and $R_T = 47\ k\Omega$. The value adopted for the capacitor was $C = 200\ nF$. The circuit in Figure 3 shows that the two extreme points (A and C), where the potentiometer cursor is positioned, define the R_{SC} minimum (R_{SCmin}) and R_{SC} maximum (R_{SCmax}) values.

$$R_{SCmin} = R_2 \tag{6}$$

$$R_{SCmax} = \frac{R_V R_2 + R_2 R_3 + R_V R_3}{R_3} \tag{7}$$

When the potentiometer responsible for RATE is at its minimum value $R_V = 0$, the value of $R_{SC} = R_2$. Thus, the maximum and minimum frequencies are given by

$$f_{0max} = \frac{R_Q}{R_T}\frac{1}{4R_{SCmin}} = \frac{R_Q}{R_T}\frac{1}{4R_2C} \tag{8}$$

$$f_{0min} = \frac{R_Q}{R_T}\cdot\frac{1}{4R_{SCmax}C} \tag{9}$$

Then, it is possible to calculate, from (5), the minimum and maximum frequency of the oscillator by applying the maximum and minimum values of the R_V potentiometer.

The minimum and maximum frequency values are $f_{min} = 1\ Hz$ and $f_{max} = 10\ Hz$, respectively. Then is:

$$R_2 = \frac{R_Q}{R_T}\cdot\frac{1}{f_{0max}4C} = 275.027\ k\Omega \tag{10}$$

$$R_{SC} = \frac{R_Q}{R_T}\cdot\frac{1}{f_{0min}} = 2750.275\ k\Omega \tag{11}$$

The commercial value used will be $R_2 = 274\ k\Omega$. Adopting $R_V = 100\ k\Omega$. Using (4), you can find the value of $R_3 = 11.578\ k\Omega$. The commercial value used was $R_3 = 11.5\ k\Omega$.

To meet the absolute maximum working conditions of the THAT 2180 [5], the maximum variation of the voltage control ΔVc must be ± 1 V.

As commercial Stomp Boxes are usually powered by a 9 V DC battery, the reference voltage will be 4.5 V. To obtain this reference voltage was implemented a Voltage Divider (see Figure 4). So, considering the maximum voltage control variation ΔVc and reference voltage, the value ΔVc must vary from 4.8 V ≤ V ≤ 4.2 V.

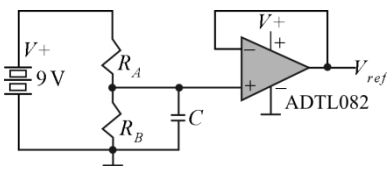


Figure 4. Voltage divider topology. $R_A = R_B = 100\ k\Omega$ and $C_A = 100\ uF$.

The result at the output of the LFO is a triangular voltage wave 3.0 V < V < 6.0 V. As mentioned earlier, the maximum variation of ΔVc should be a maximum of ± 1 V in relation to 4.5 V. So, a resistor R_X resistor (Figure 5) was inserted to obtain the desired levels

From Figure 5, when the R_D potentiometer's wiper is at point D, the following equation can be written

$$\frac{V_0 - V_D}{R_X} = \frac{V_D - V_{REF}}{R_D} \tag{12}$$

$$\frac{6\ V - 5.5\ V}{R_X} = \frac{5.5\ V - 4.5\ V}{10\ k\Omega} \tag{13}$$

The value of this resistor can be calculated considering the maximum value of the DEPTH potentiometer $R_D = 10\ k\Omega$, the reference voltage $V_{REF} = 4.5\ V$, the output voltage of the LFO $V_{maxTriang} = 6.0\ V$ or $V_{minTriang} = 3.0\ V$ and respectively the adjusted output voltage of the LFO $V_C = 5.5\ V$ or $V_C = 3.5\ V$. Therefore, $R_X = 5\ k\Omega$.

As the value found is at the limit of the THAT 2180's conditions, the resistance value should be higher than the calculated one. Experimentally, it was found that a good effect result was obtained making $R_X = 200\ k\Omega$.

3 The Tremolo Project

In the tremolo circuit shown in Figure 5, the THAT 2180 output current signal is applied to the input of the ADTL082 opamp and transformed into the output voltage. The triangular wave output from the LFO is conditioned to provide the levels needed to control the VCA.

4 The Vibrato Project

Vibrato is the block responsible for generating a phase variation. This phase variation sounds to the ear like a variation in frequency. It simulates the Doppler effect, which appears when the speaker is rotated during the Leslie effect.

The All-Pass circuit was based on the THAT 2180 integrated circuit, and it was only necessary to adapt certain aspects of the circuit to make it a vibrato and combine it with an integrator and a differential amplifier, making the output signal identical to the input signal and presenting a 90° phase-shift. For example, 90º phase-shift is obtained when the input frequency is equal to 530Hz and Voltage Control in the THAT 2180 is equal to 0 V (see Table 1). The Vibrato circuit uses two All-Pass filters that make the effect of frequency variation more significant as can be seen in Figure 6.

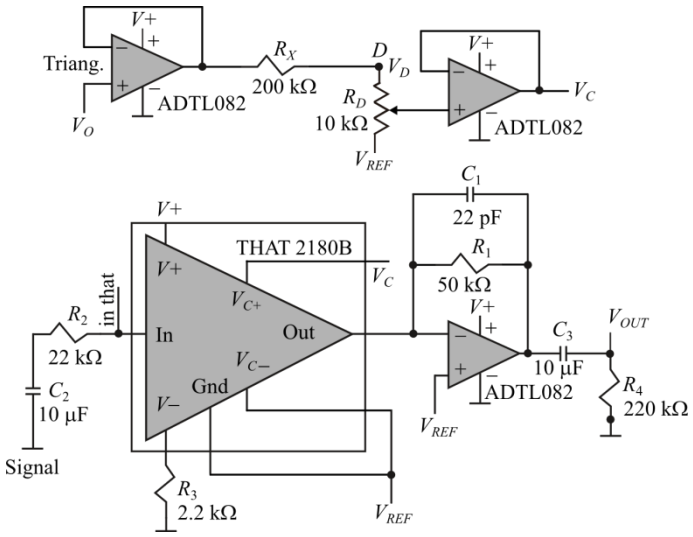


Figure 5. Tremolo topology.

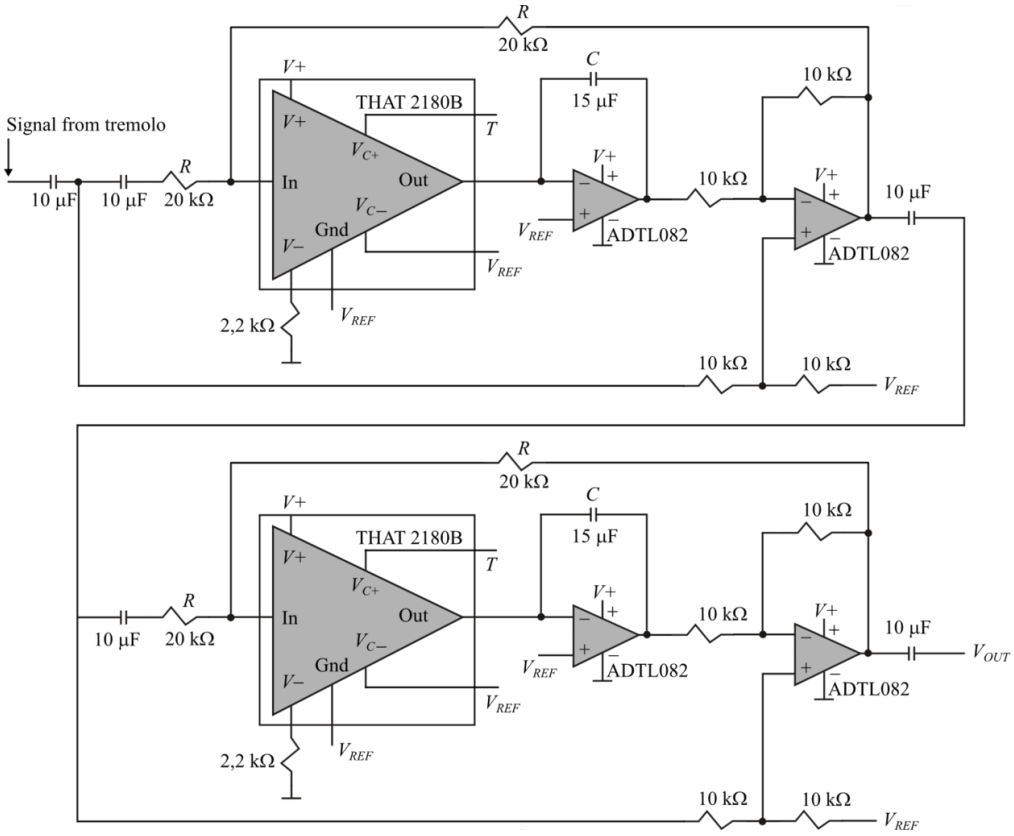


Figure 6. Vibrato topology.

One of Vibrato's main controls is the RATE, which alters the oscillation frequency of the LFO and, consequently, the speed with which the semitones occur.

The other control is the DEPTH, which alters the amplitude of the LFO output and, consequently, how much the delay provided by the All-Pass filters varies, causing variations in the semitone. These controls can

be adjusted to suit the musician's taste. As with the Tremolo, interesting vibrato effects can be achieved with LFO frequencies ranging from 1 Hz to 10 Hz.

4.1 All-Pass (AP) Project

At frequency σ_0 the phase rotates 90°. Then in the second-order All-Pass filter at frequency σ_0 the phase rotates 180° (see Figure 7).

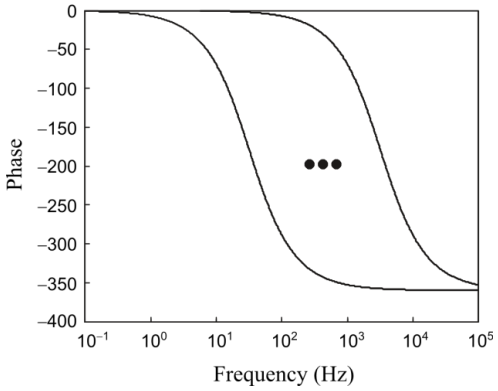


Figure 7. Normalized phase curve of a second-order AP.

The following is an algebraic representation of a first-order All-Pass circuit which is one of the stages in Figure 7:

$$V_O(s) = V_{IN}(s) - V_2(s) \tag{14}$$

where the voltages refer to the first stage circuit

$$V_{O1}(s) = V_{IN1}(s) - V_{21}(s) \tag{15}$$

$$I_I(s) = \frac{V_{IN}(s)}{R} + \frac{V_O(s)}{R} = \frac{V_{IN}(s)}{R} + \frac{V_{IN}(s) - V_2(s)}{R} \tag{16}$$

$$I_I(s) = \frac{V_{IN}(s)}{R} + \frac{V_O(s)}{R} = \frac{V_{IN}(s)}{R} + \frac{V_{IN}(s) - V_2(s)}{R} \tag{17}$$

where $I_I(s)$ refers to the input current of the first stage and $R = 20\ k\Omega$

$$I_I(s) = \frac{2V_{IN}(s) - V_2(s)}{R} \tag{18}$$

$$V_2(s) = \frac{I_O(s)}{SC} = \frac{GI_I(s)}{SC} \tag{19}$$

$$V_2(s) = \frac{GI_I(s)}{SC} = \frac{G[2V_{IN} - V_2]}{RCS} \tag{20}$$

$$V_{IN}(s) = \frac{G}{RCS}[2V_{IN} - V_{IN} + V_O] + V_O \tag{21}$$

$$V_{IN}(s) = \frac{G}{RCS}[V_{IN} + V_O] + V_O \tag{22}$$

$$V_{IN}(s) - \frac{G}{RCS}V_{IN} = \frac{G}{RCS}V_O + V_O \tag{23}$$

$$V_{IN}(s)\left[1 - \frac{G}{RCS}\right] = V_O(s)\left[1 + \frac{G}{RCS}\right] \tag{24}$$

$$V_{IN}(s)[RCS - G] = V_O(s)[RCS + G] \tag{25}$$

So, the transfer function of a first-order All-Pass filter is given by:

$$T_{AP}(s) = \frac{V_O(s)}{V_{IN}(s)} = \frac{[s - G/RC]}{[s + G/RC]} = \frac{[s - \sigma_0]}{[s + \sigma_0]} \tag{26}$$

The current gain of the THAT 2180 that is altered by the LFO signal is given by:

$$G = \frac{I_O(s)}{I_I(s)} \tag{27}$$

where

$$G = 10^{\frac{V_C/0.0061}{20}} \tag{28}$$

where V_C is the gain control voltage. From the THAT 2180 Datasheet [5], it is given by:

$$G = 10^{\frac{G_{dB}}{20}} \quad G = 10^{\frac{V_C/0.0061}{20}} \therefore G_{dB} = \frac{V_C}{0.0061} \tag{29}$$

Table 1 shows G values for various values of the control voltage. Note that Vc is referenced to Reference Voltage equal to 4.5 V.

$V_C\ (mV)$	$G = = 10^{(\frac{V_C}{0.0062})/20}$	$\frac{G}{RC}$	$f_0 = = \frac{G}{(2\pi RC)}$
0	1	3333.33	530.785
50	2.56942	8564.7	1363.81
100	6.60194	22006.4	3504.21
150	16.9632	56544.0	9003.83
200	43.5857	145285	23134.6
250	111.990	373300	59442.8
300	287.750	959169	152733
-50	0.389192	1297.30	206.577
-100	0.151470	504.901	80.3983
-150	0.0589510	196.503	31.2903
-200	0.0229432	76.4776	12.177
-250	0.00892934	29.7644	4.73956
-300	0.00347523	11.5841	1.8446

Table 1. Gain and frequency values as a function of control voltage.

5 Conclusions

This paper presents the design of a Stomp Box whose effect is similar to the Leslie effect. It's called a pseudo-Leslie effect because in the original effect, the amplitude variation is offset by 90^{O} from the frequency variation (Doppler effect). In the circuit presented, the frequency variation is obtained with an All-Pass circuit whose varying phase sounds to the ear like a frequency variation. The result is very similar to the original Leslie effect. The hobbyist can also opt for the separate design of a Tremolo and a Vibrato, both with a high degree of repeatability due to the use of a higher performance analog component VCA. This was proven by exchanging different THAT 2180 ICs after the circuit had been assembled. The performance results were as expected. It is hard to explain a sonic result through graphs and tables but in a live performance it is easy to hear. [7]

6 Acknowledgements

The authors would like to thank THAT Corporation for providing the THAT2180 VCA and Rosalfonso Bortoni for the assistance.

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