Digital Measurement of voltages

rev 1

Purpose: Digital measurement of voltages using a voltage-to-frequency converter, using the frequency-to-voltage converter, making a comparator with hysteresis.

Summary of theory

A simple way to digitally measure a voltage is to obtain a signal (usually rectangular) whose period or frequency is linear with the voltage measured. Then, using a digital method to measure the time intervals and the frequencies, a value proportional to the one of the measured voltage, is obtained (the proportionality factor is, usually, a power of 10).

The operating principle of the voltage-to-frequency converter

The purpose of the converter is to generate a signal whose frequency is linear with its input voltage. A block diagram is given in Figure 1, where a controlled pulse generator is used. It generates a negative pulse, with period T_1 and amplitude U_i, when a rising slope is inputted to it. *The time reference in the block diagram periodically generates pulses with period T_r.* The schematic allows the measurement of the positive voltages.

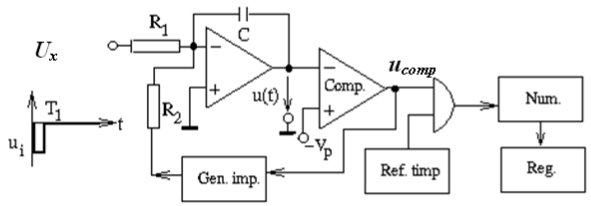


Fig. 1 Block diagram of the voltage-to-frequency converter

Suppose $u(t)$ is initially 0, and U_x>0V. The voltage $u(t)$ drops as shown by the relation:

$$u(t)=\frac{U_x\,t}{R_1C} \qquad (1)$$

until $u(t)=-V_p$ (Fig.2). Now, u_{comp} = "logical" 1, and the pulse generator generates a pulse with inverse polarity than the one of the measured voltage. If high enough, $u(t)$ linearly increases during period T_1. After this pulse, $u(t)$ decreases with the same slope, as initially, until $u(t)=-V_p$ (a period T_2). A new pulse is generated and the process is repeated. Therefore, at the integrator output, a periodic sequence of triangular pulses, and, at the output of the comparator, a sequence of very short pulses, appear. The purpose is to determine their frequency of occurrence.

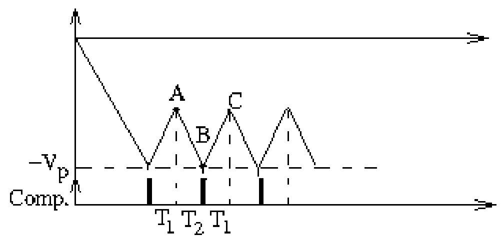


Fig.2. The waveforms for a $V-f$ converter

On the segment A-B (Figure 2), suppose that t_A=0 is the time origin, the voltage can be written as follows:

$$u(t)=u(0)-\frac{U_x}{R_1C}t\Rightarrow u(T_2)=u(0)-\frac{U_x}{R_1C}T_2=-V_p \qquad (2)$$

for the B-C segment:

$$u(t)=u(T_2)-\left(\frac{U_x}{R_1}-\frac{U_i}{R_2}\right)\frac{1}{C}(t-T_2)\Rightarrow u(T_1+T_2)=u(0) \qquad (2`)$$

$$u(0)-\frac{U_x}{R_1C}T_2-\left(\frac{U_x}{R_1}-\frac{U_i}{R_2}\right)\frac{1}{C}T_1=u(0)\Rightarrow\frac{U_x}{R_1C}(T_1+T_2)=\frac{U_i}{R_2C}T_1 \qquad (2``)$$

It results that the period $T=T_1+T_2$ is given by the relation (3)

$$T=\frac{U_i}{U_x}\frac{R_1}{R_2}T_1 \quad \text{and} \quad f=\frac{1}{T_1}\frac{R_2U_x}{R_1U_i}=K_1U_x \qquad (3)$$

At the output of the comparator, a sequence of very short pulses with the frequency of occurrence proportional to the measured voltage U_x, appears. Therefore, the voltage measurement is equivalent to the digital measurement of this frequency.
This operation is done by means of the gate, time reference generator, counter (universal counter). The number of pulses counted during the gate open time (T_r) is:

$$N=\frac{T_r}{T}=\frac{R_2T_rU_x}{R_1T_1U_i}=K_2U_x \qquad (4)$$

The precision of the number N is determined by:

- the pulse area, U_iT_1,
- the precision of the ratio of the resistances, R_1/R_2,
- inaccuracies of the Operational Amplifier and of the comparator,
- the precision of the time reference.

In addition, at the precision of the digital measurement of the voltage U_X (seen as a relative error) an error of the type ***1/N***, which is specific to digital measurement of the frequencies and time intervals, appear.

The operating principle of the frequency-to- voltage converter

The purpose of the converter is to generate a DC voltage whose value is linear with the frequency of its input signal. A block diagram is given in Figure 3, where a controlled pulse generator is used. It generates a negative pulse, with period T_1 and amplitude U_1 (fixed values), when a rising slope is inputted to it. The resulted waveform is applied to a mean value detector (a LPF with the frequency f_{3dB} lower than the frequency of the input signal).

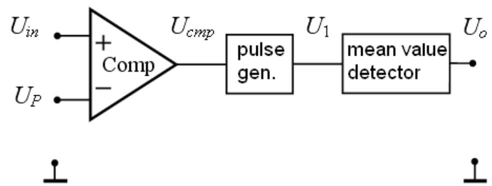


Fig.3. Block diagram of the frequency-to-voltage converter

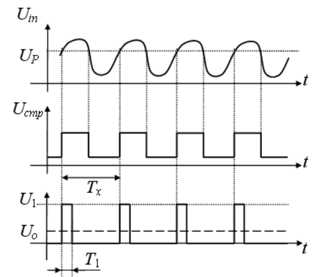


Fig.4. The waveforms for the $f-V$ converter

If $U_P\in\left[U_{in\_\min},U_{in\_\max}\right]$ and $T_1<T_x$ relation (5) is obtained for U_o:

$$U_o=\frac{T_1}{T_x}U_1=K\cdot f_x \qquad (5)$$

The precision is determined by:

- the pulse area, $U_i T_1$,
- inaccuracies of the mean value detector (frequency f_{3dB} to high for the input signal),
- the noise superimposed on the input signal,
- inaccuracies of the comparator.

The comparator with hysteresis

The comparator generates a voltage that can only have two values, U_{oH} or U_{oL}, depending on the value of the input voltage (if its higher or lower than a threshold voltage, U_P). The comparator with hysteresis is characterized by the fact it has two threshold voltages (as observed also from the example given in Figure 3), depending on the increasing or decreasing evolution of U_{in}.

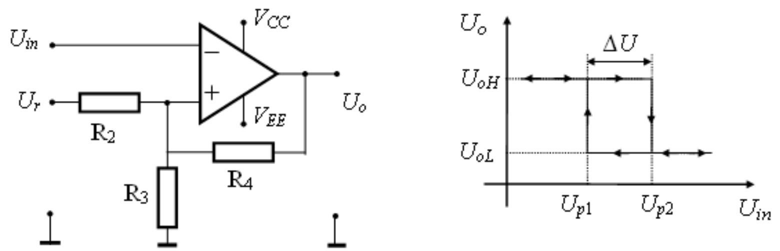


Fig. 5. Schematic of a comparator with hysteresis and its input-output characteristic

For the circuit in Figure 5 :

$U_{in}<U_{p1}\Rightarrow U_o=U_{oH}$ (the maximum value of the output voltage)

$U_{in}>U_{p2}\Rightarrow U_o=U_{oL}$ (the minimum value of the output voltage) (6)

where $$U_p=\frac{\frac{U_r}{R_2}+\frac{U_o}{R_4}}{\frac{1}{R_2}+\frac{1}{R_3}+\frac{1}{R_4}} \Rightarrow \begin{cases} U_{p1}=\frac{1}{2+K}U_r+\frac{K}{2+K}U_{oL} \\ U_{p2}=\frac{1}{2+K}U_r+\frac{K}{2+K}U_{oH}\end{cases} \text{ if } \begin{cases} R_2=R_3 \\ K=\frac{R_2}{R_4}\end{cases} \qquad (7)$$

The threshold voltage, U_p, and the trigger window, ΔU, can be defined :

$$\begin{cases} U_p=\frac{U_{p1}+U_{p2}}{2}=\frac{1}{2+K}U_r+\frac{K}{2\cdot(2+K)}\cdot(U_{oH}+U_{oL}) \\ \Delta U=U_{p2}-U_{p1}=\frac{K}{2+K}(U_{oH}-U_{oL})\end{cases} \text{ so that } \begin{cases} U_{p2}=U_p+\Delta U/2 \\ U_{p1}=U_p-\Delta U/2\end{cases} \qquad (8)$$

Another important parameter of a comparator is *Slew Rate* (SR), which indicates the maximum speed of the variation of the output voltage of the comparator, for all the possible values of the input signal :

$$SR=\max\left\{\frac{dU_o(t)}{dt}\right\} \qquad (9)$$

Measurements

Attention ! 1. the supply must be set at 9V, in order to have the system operating.

2. to measure voltages from the protoboard, use "green" and "black" (the electrical ground) plugs, wires connected to the **crocodiles** of the meters or wires connected to the PCB. **Do not connect the crocodiles of the measurement devices directly to the terminals of the components !!**

3. after doing the measurements, leave the circuit as it was when starting the measurements (both functionally and in terms of equipping), with all the components received in the box.

4. for all the drawings on the worksheets, write down, under the figure, the values for the used deflection coefficients

The main circuit of the voltage-to-frequency converter, and of the frequency-to-voltage converter, is the integrated circuit LM 331. Its internal block diagram and the description of its pins, are given in Fig.6 and Fig.7. According to the datasheet, to operate as a voltage-to-frequency converter, the maximum range of its input voltages must be between [$V_{GND} \div V_{CC}$ - 2V]. To operate as a frequency-to-voltage converter, the minimum range of the values of its input signal must be between approximately [0V- 1V]. For the comparator with hysteresis, one of the operational amplifiers from the integrated circuit LM 358, is used.

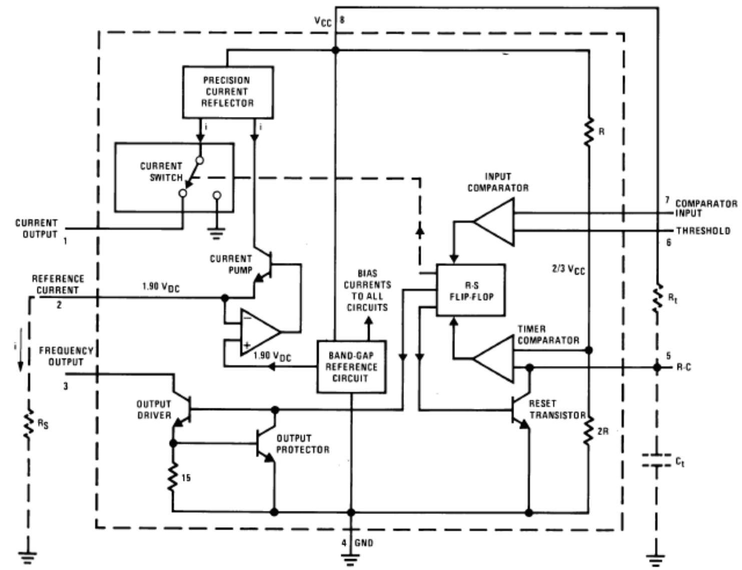


Fig. 6. LM331 internal block diagram

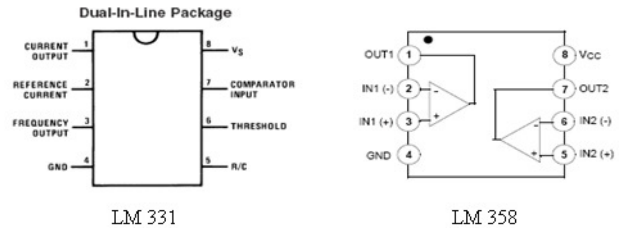


Fig.7. LM 331 and LM 358 ICs

1. ***Analysis of the voltage-to-frequency converter***

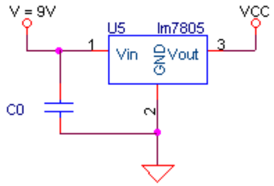


Fig.8a. Schematic of the supply V_{CC}

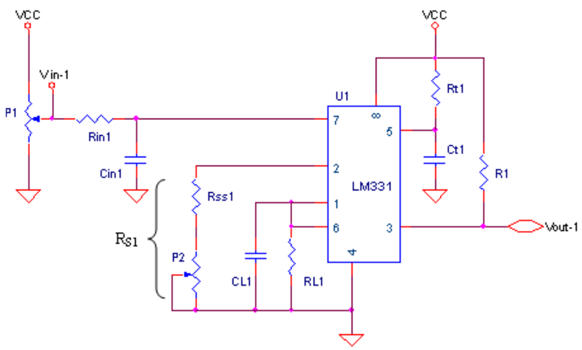


Fig. 8b. Schematic of the voltage-to-frequency converter

a) **Turn off the supply of the circuit** (remove the cable from the orange power supply)**,** if the circuit is supplied. Identify the circuit (Fig.11 and Fig.12), which corresponds to the schematic from Fig. 8b, the input ($V_{in\text{-}1}$) and the output ($V_{out\text{-}1}$) of the voltage-to-frequency converter. Check the correspondence between the schematic and the circuit on the board.

Turn on the supply of the circuit and check (using the scope) that the voltage from the power source is approximately 9V, without oscillations, and that the voltage V_{CC} is 5V. (Use CH1 of the scope, coupling DC, and the menu **MEASURE->Type=Mean**). In Fig. 4a, the schematic to obtain the voltage V_{CC}, using *the 3 terminals stabilizer* U5 (LM7805), is given.

Connect the voltmeter to measure the DC voltage V_{in1}, and the scope (CH2, coupling DC) and the frequency meter at $V_{out\text{-}1}$, to view the waveform of the signal and to measure its frequency.

Measure the two values of the output signal, $U_{oH\text{-}1}$ and $U_{oL\text{-}1}$, (adjusting the scope optimally, and using cursors, if needed). (**V_{in1} must be lower than 3V**)

Remark 1: The setting on the scope should be done so that the image is synchronized, it occupies approximately ½ of the space on the vertical axis of the screen, and, so that, on the display, 2 to 5 periods of the signal can be viewed. **Use the same parameters, for the image, unless otherwise specified.**

Remark 2: For ease of viewing the signals on the display of the scope, when 2 signals are viewed, connect the input to CH1, coupling DC, and the output to CH2, coupling DC.

b) "Calibrate" the conversion characteristic: input the voltage $V_{in\text{-}1}$ = 2,50V (adjusting the potentiometer P_1) and adjust the potentiometer P_2 so that the frequency of the output signal is 2,50KHz. (To measure the frequency with reasonable precision, over a short time interval, set the measurement period, on the frequency meter, at 1s. The frequency can also be measured using the scope).

Pay attention: The value 2,,50 means the respective measure must by adjusted with a precision better than 0,01 m.u. (the corresponding measuring unit).

c) Obtain the conversion characteristic of the voltage-to-frequency converter. **Turn off the supply of the circuit**, and measure R_{S1}, R_{L1}, R_{t1}, C_{t1} (using the multimeter). The resistance R_{S1} is the series-equivalent resistance obtained with R_{SS1} and P_2. **The capacitor C_{t1} and the resistance P_2 must be removed from the circuit, prior to measurement !!!!**

Remark: Although, under normal conditions, the components must be removed from the PCB when measuring them, because of the particularities of the circuit (very high resistances in parallel with the respective components), some of them can be measured directly in the circuit, **but, disconnect the supply.**

Connect the removed components, power on the circuit, and input the voltages $V_{in\text{-}1}$ = { 500mV, 1V, 1,5V, 2V, 2,5V, 3V}, obtained by adjusting the potentiometer P_1. Fill in Table 1 with the measured values, $f_{measured}$, and with the calculated ones (f_{calc}), using the relation (10). Using the values

from Table 1, determine the relative errors $\varepsilon_{U\text{-}f}$ for the measured frequencies comparing to the calculated ones.

$$f_{calc} = \frac{1}{2{,}09} \cdot \frac{R_{S1}}{R_{L1}} \cdot \frac{1}{R_{t1} C_{t1}} \cdot V_{in-1} \qquad (10)$$

2. ***Analysis of the frequency-to-voltage converter***

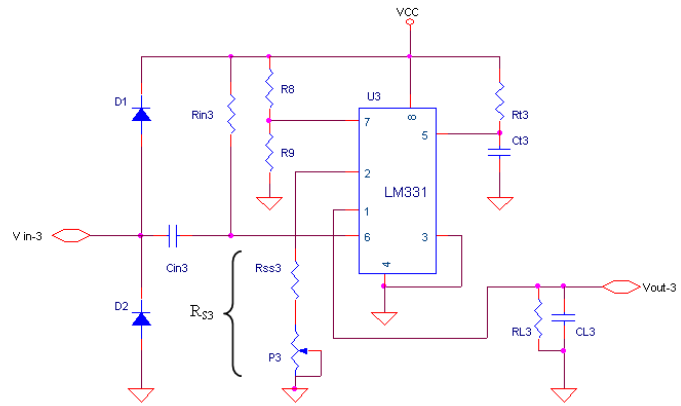


Fig. 9. Schematic of the frequency-to-voltage converter

a) **Power off the circuit** and identify the parts (Fig.11 and Fig.12) which corresponds to the schematic in Fig.9, and the input ($V_{in\text{-}3}$) and the output (V_{out3}) of the frequency-to-voltage converter, also. Check the correspondence between the schematic and the circuit. Connect the scope (CH2), and the proper voltmeter, to measure the DC voltage $V_{out\text{-}3}$, and the scope (CH1) and the frequency meter at $V_{in\text{-}3}$ to view the input waveform and to measure its frequency. Input TTL signal from the corresponding output of the generator (press **SHIFT+9**) and **power on the circuit**.

b) "Calibrate" the conversion characteristic: set the frequency of the input signal at 2,50kHz and adjust the potentiometer P_3 so that the DC voltage $V_{out\text{-}3}$= 2,50V.

c) Obtain the conversion characteristic of the frequency-to-voltage converter. Power off **the circuit**, and measure R_{S3} , R_{L3} , R_{t3} , C_{t3} (using the multimeter). The resistance R_{S3} is the series-equivalent resistance obtained with R_{SS3} and P_3 . **The capacitor C_{t1} and the resistance P_2 must be removed from the circuit, prior to measurement !!!!**

Remark: **The components C_{t3} and P_3 must be removed from the circuit, to measure them !!!**

Power on the circuit and input a signal with the frequency $f_{in\text{-}3}$ = {500Hz , 1KHz , 1,5KHz , 2KHz , 2,5KHz , 3KHz}. Fill in Table 2 with the measured value $V_{measured}$ and with the calculated values (V_{calc}), using the relation (11). Using the values from Table 2, determine the relative errors $\varepsilon_{f\text{-}U}$ of the measured values compared to the calculated ones.

$$V_{calc} = 2{,}09 \cdot \frac{R_{L3}}{R_{S3}} \cdot R_{t3} C_{t3} \cdot f_{in-3} \qquad (11)$$

3. ***Analysis of the conversion U-f and f-U***

Power off the circuit and connect the output of the *U-f* converter, $V_{out\text{-}1}$, with the input of the *f-U*, $V_{in\text{-}3}$. Connect the scope and the proper voltmeter to the input of the circuit (V_{in1}), and the scope to the output (V_{out3}). **Power on the circuit** and input the voltages $V_{in\text{-}1}$ = { 500mV, 1V, 1,5V, 2V, 2,5V, 3V}, obtained by adjusting the potentiometer P_1. To measure the output voltage, use the menu **Measure** of the scope, set on the mean value for CH2 (**MEASURE -> Source =CH2, Type=Mean**). Write it down in Table 3 and compute the relative error, ε_1, between $V_{out\text{-}3}$ and $V_{in\text{-}1}$.

How do you expect these two voltages to be ? Which are the causes for the differences between the measured values and the *theoretical* relation between them ?

4. *The hysteresis comparator*

a) **Power off the circuit**, measure and identify the resistances R_2, R_3, R_4, R_5 (R_2 ≈68KΩ, R_3 ≈27KΩ, R_4 ≈68KΩ, R_5 ≈68KΩ). Make the circuit in Fig.10, on the test board (solderless). Connect the scope, CH1 at $V_{in\text{-}2}$ and CH2 at $V_{out\text{-}2}$. At the input $V_{in\text{-}2}$, apply, from the generator, a triangular signal with the frequency of 1kHz, the amplitude A=2V and DC bias A_{mean}=2V (Adjust DC bias from the ***OFFSET*** knob, from the generator, "pulled"). **Power on the circuit**, set C_y = 1V/div, for CH1 and CH2, and the 0V level at one division above the bottom of the screen (for both channels). Draw the two waveforms, superimposed.

b) Using the voltage cursors, measure the levels of the output voltage, $V_{out\text{-}2\ H}$, $V_{out\text{-}2\ L}$, and the input voltages, corresponding to the two thresholds (U_{p1} and U_{p2}), $V_{in\text{-}2\ p1}$ and $V_{in\text{-}2\ p2}$. Compute the threshold voltages, U_{p1} and U_{p2}, using the relations (7).

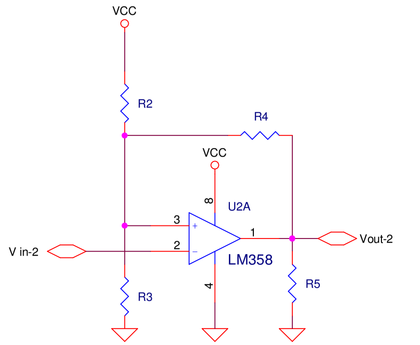


Fig. 10. Schematic of the comparator with hysteresis

c) Set the scope in XY mode (**Display-> XY**) and adjust the image so that it is as big as possible, and it can entirely be displayed on the screen. Draw the image.

d) Return in the time domain, in Yt mode of the scope (**Display-> Yt**) and determine the slope of the signal $V_{out\text{-}2}$ (t) on positive and on negative slope: SR_+, SR_-, respectively. To do that, measure the time interval needed for the signal to reach 2V, starting from 1V, on positive slope, Δt_1, and from 2V to 1V, on negative slope, Δt_2 and compute SR, using relations (11):

$$SR_+ = \frac{1}{\Delta t_1}\ [V/s] \text{ and } SR_- = -\frac{1}{\Delta t_2}\ [V/s] \qquad (11)$$

Measure the rising / the falling time of the signal $V_{out\text{-}2}$ (t) (t_{rise} / t_{fall}) and compare it to the rising / the falling time computed with SR_+, SR_-. What do you observe ? Explain.

e) modify the hysteresis thresholds, by modifying R_3 at a value between 2K and 3.7K. Return in XY mode (**Display-> XY**); observe that both thresholds become close to the 0V value (left of the screen). Measure the new values of the thresholds, U_{p10}, U_{p20}. Return in Yt mode.

5. *Simulation of transmitting the value of a voltage on long distances*

a) **Power off the circuit**, disconnect the function generator and make the assembly from Fig.12 (without C_2), where R_2 ≈68KΩ, R_6 ≈27KΩ, R_7 ≈5.6KΩ. Use the same settings for the U-f and the f-U converters (at points 1 and 2), as well as the circuit for the comparator (from point 4).

Remark: The resistances R_6=27K and R_7=5.6K simulate the effect of using some "long" cables between the voltage to measure and the measurement "device" (attenuation of about 1/6).

Connect the voltmeter to the input of the circuit ($V_{in\text{-}1}$), CH1 of the scope to the output of the comparator ($V_{out\text{-}2}$), and CH2 of the scope to the output of the circuit ($V_{out\text{-}3}$). **Power on the circuit** and input the voltages $V_{in\text{-}1}$ = {500mV, 1V, 1,5V, 2V, 2,5V, 3V}, obtained by adjusting the potentiometer P_1. To measure the output voltage, use the **Measure** menu of the scope set on the mean value of CH2 (**MEASURE -> Source =CH2, Type=Mean**). Fill in Table 4 and compute the relative error, ε_2, between $V_{out\text{-}3}$ and $V_{in\text{-}1}$, and, ε_3, the relative error comparing to $V_{out\text{-}3}$ obtained at point 3.

Remark: If $V_{out\text{-}3}$ is zero, no matter the value of $V_{in\text{-}1}$, and at $V_{in\text{-}3}$ the rectangular signal has V_H > 1.5V, connect C_2 (220pF) in the circuit.

b) **Power off the circuit** and modify the previous circuit so that at the input of the f-U converter ($V_{in\text{-}3}$) is the same as the voltage at he input of the comparator ($V_{in\text{-}2}$), without using the comparator any more. **Power on the circuit** and measure the voltage $V_{out\text{-}3}$ depending on $V_{in\text{-}1}$ = {500mV, 1V, 1,5V, 2V, 2,5V, 3V}. What can be observed ? View, on CH1, the signal $V_{in\text{-}3}$, measure $V_{in\text{-}3\ H}$, and the voltage on pin 7 of LM 331 (the f-U converter). Explain what happens.

c) The analysis of the circuit formed by the *U-f converter, the attenuator, the comparator with hysteresis, the f-U convertor, in dynamical regime.* **Power off the supply and make again the circuit from point (5.a), without the potentiometer P_1, not to input DC voltage, anymore**. Set the signal generator to obtain a triangular signal with the amplitude U_0 = 1V, DC bias U_C = 1.5V and frequency of 5Hz, so that it varies between 0.5V – 2.5V (measured with the scope). Input the signal at $V_{in\text{-}1}$, and display on the scope (coupling DC) the signals $V_{in\text{-}1}$ on CH1, and $V_{out\text{-}3}$ on CH 2. Measure the peak-to-peak value (A_{PP}) of the signal $V_{out\text{-}3}$ (*measure* menu) and compare it with the one corresponding to the signal $V_{in\text{-}1}$. Increase the value of the frequency (with step of 1Hz) until the relative error between the two peak-to-peak values is of 20%. Which is the cause of this phenomenon ?

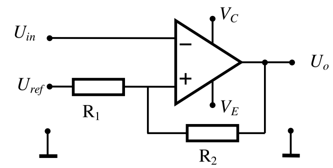
Measure the delay introduced by this circuit. To do that, apply, at $V_{in\text{-}1}$, a rectangular signal with the frequency 2Hz and the variation range 0.5V – 2.5V. Measure the rising time of the signal from $V_{in\text{-}1}$ (t_{c1}) and the time needed for the signal to reach the 95% level, starting from 0%, for $V_{out\text{-}3}$ (Δt_3). Determine the delay of the circuit with the relation (12):

$$\Delta t_{\text{circuit}} \approx \Delta t_3 - t_{c1} \qquad (12)$$

Comment upon the result.

Preparatory questions

1. Which are the main error sources of the $V - f$?

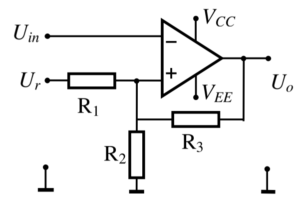


2. Determine U_{P1} and U_{P2}, the two thresholds of the comparator from the figure, if U_{oH} = 4V , U_{oL} = 0,6V and U_{ref} = 0V, R_1 =2R_2.

3. For the circuit in the figure, U_{oH} = 4,4V, U_{oL} = 0,6V, SR=50V/μs, U_{ref} = 0V and R_1 =2R_2, determine the maximum frequency of the signal from the output of the comparator.

4. For the circuit in the figure, U_{oH} = 4,7V, U_{oL} = 0,3V, SR=100V/μs, U_{ref} = 0V and R_1 =2R_2, determine the rising time t_{rising}, the maximum frequency and the duty cycle of the rectangular signal from the output of the comparator. Suppose that t_c < 1/10 of the minimum period of the pulse width.

5. If the conversion precision of a *U-f* converter is ε_1=1%, and the precision of the inverse converter, *f-U*, is ε_2=2% , determine the relative error between the output voltage of the *f-U* converter and the input voltage of the U-*f* converter (if the two are connected in cascade). Suppose the two converters are "calibrated" identically.



6. Determine U_{P1} and U_{P2}, the two thresholds of the comparator from the figure, if U_{oH} = 3.6V , U_{oL} = 0,6V and U_r = 5V, R_1 = =2R_3

7. Determine U_P, the threshold voltage of the comparator, and ΔU_P, the trigger window, if U_{oH} = 4,2V , U_{oL} = 0,35V and U_r = 4.9V, R_1 =R_2 =3R_3.

8. Give an example where the conversion *U-f, f-U* is a necessary solution. Explain.

9. Determine the optimal threshold voltage and the window of the trigger, for a hysteresis comparator, which has a sinusoidal signal (voltage) input with the amplitude A=2V, and RSZ=20dB, if at the output a rectangular signal at the same frequency is intended.

Hint: $U_{ef\_zg} = U_{\max\_zg} / \sqrt{3}$

10. Determine the SNR min of a triangular symmetrical signal, with the peak-to-peak value of U_{PP}=2V, no bias voltage, which can be input to a comparator with hysteresis, with $U_{Threshold}$ = 10mV and ΔU = 40mV so that its output is a rectangular signal of the same frequency. *Hint:* $U_{ef\_zg} = U_{\max\_zg}/\sqrt{3}$.

11. Which is the role of a comparator ? Which is the difference between a comparator and a comparator with hysteresis ?

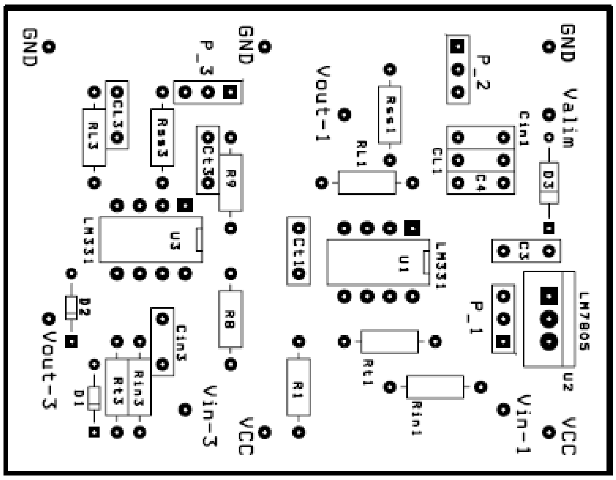


Fig.11. The assembly of the system of the $U-f$ converter and the $f-U$ converter, on the electronic board

Attention: The electrical voltages GND, V_{supply}, V_{CC}, $V_{out\text{-}1}$ and $V_{in\text{-}3}$ can be obtained on corresponding wires: black, red, orange, green and yellow. Voltages $V_{in\text{-}1}$ and $V_{out\text{-}3}$ can be read at the corresponding test points (individual pins).

Remark: After the measurement of the values of the potentiometers P2, P3, and of the capacitors Ct1, Ct3, (by removing them from the socket) reconnecting them back to the circuit will be carefully done, not to bend and / or broke the pins of the components.

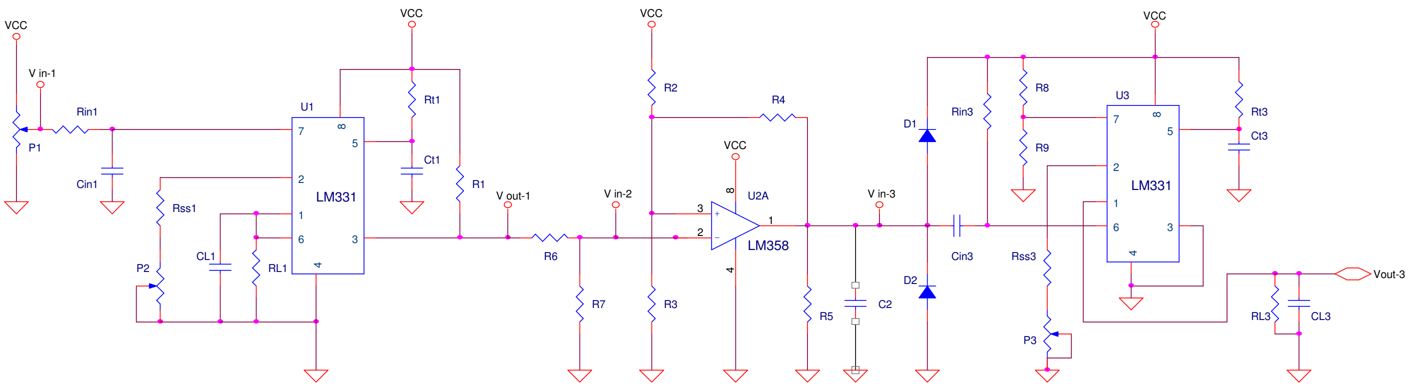


Figure 12: Assembly of the system with $U-f$ converter, voltage divider, hysteresis comparator and $f-U$ converter