Analog Circuits and Systems
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Lecture 34: Regenerative Comparators and Non-Sinusoidal Oscillators
Review

- Negative feedback amplifiers
- Negative feedback systems
- Filters
- Oscillators
- All of these can be considered best as second order differential equations forming second order filters.
- In the case of feedback amplifiers and negative feedback systems the transient response can be optimized when $Q=1$
Review (contd.,)

- The steady state response can be optimized when $Q = 1 / \sqrt{2}$
- Filters are designed for a variety of Qs and pole frequencies for frequency shaping
- Oscillators have $Q = \square$; they require frequency and amplitude stability
- Frequency compensation methodology is common to all the above
- The topic that is going to be covered in the present lecture focuses on Positive Regenerative Feedback
Comparators v/s opamp ICs

- Comparators as an element has already been introduced in Lecture 9.
- Comparator is an interface component
- Its input is analog and its output is digital (1/0 or high/low).
- It is a one-bit Analog-to-Digital Converter (ADC)
- The output changes its state when the input voltage crosses a reference value.
Comparator (contd.,)

Voltage Comparator

Current Comparator
Ideal Comparator

- Ideal comparator has infinite gain in the active region while transiting from one state to the other.
- LM311 comparator (made available by most IC manufacturers & costs $0.2 in >1k quantities).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Total Supply Voltage</td>
<td>3.5 to 30 V</td>
</tr>
<tr>
<td>2 Rise Time</td>
<td>115 ns</td>
</tr>
<tr>
<td>3 Common Mode Input Voltage</td>
<td>0.5 to 28 V</td>
</tr>
<tr>
<td>4 Input Offset Voltage</td>
<td>7.5 mV (max)</td>
</tr>
<tr>
<td>5 Input Offset Current</td>
<td>70 nA (max)</td>
</tr>
<tr>
<td>6 Input Bias Current</td>
<td>300 nA (max)</td>
</tr>
</tbody>
</table>
Offset Voltage

Input offset voltage (7.5 mV in case of 311)
Commercial Comparators

- are designed to have a forward gain of the order of 100
- Active transition region will be
  \[
  \left( \frac{V_u - V_L}{A_0} \right)
  \]
  instead of zero in case of infinite gain

\[
|V_{\text{offset}}| + \left| \frac{V_u - V_L}{A_0} \right|
\]

⇒ input referred offset
Commercial comparators (contd.,)
Regenerative Positive Feedback (Schmidt Trigger)

\[ \beta = \frac{R_1}{R_1 + R_2} \]

\[ (\beta V_o - V_i) A = V_o \]

\[ \frac{V_o}{V_i} = -\frac{A}{1 - A\beta} \]
Unlike the negative feedback non-inverting amplifier designed as a VCVS \( \frac{A}{1 - A\beta} \) of gain 1 + \( \frac{R_2}{R_1} \left( \frac{1}{\beta} \right) \)

This positive feedback circuit gives

\[
\frac{V_o}{V_i} = - \frac{A}{1 - A\beta} ; 0 < A\beta < 1
\]

\( A\beta \) results in a highly sensitive amplifier (sensitivity to \( A\beta \))
Regenerative Positive Feedback (contd.,)

- Rarely used in amplifier topologies.
- Used in comparator design when active region is only a transition region.
- $A_b > 1$, regenerative comparator or Schmitt trigger.
- Most important mixed mode or digital circuit which is used to convert analog to digital or cleanup distorted (due to transmission line and noise) digital signal.
Regenerative Positive Feedback (contd.,)

- For $Ab \gg 1$, it develops hysteresis in its input output characteristic.
- This hysteresis is an integral part of all ON-OFF control systems:
  - Class-D power amplifiers
  - Switched mode power suppliers
  - A to D converters
  - Function generators
  - Astable multivibrators
  - Timers

![Diagram of Regenerative Positive Feedback](image-url)
Simulation 1

- $R_1 = R_2 = 1k; V_s = 10; \text{opamp}=\text{TL082}$
Simulation 2

- $V_i$ is a triangular waveform with $V_p = 10V; f = 1000Hz$
Regenerative Comparator

Output = \( V_{n_{\text{noise}}} \left[ 1 + A\beta + (A\beta)^2 + L \right] \)

an infinite series.
If \( A\beta < 1 \) it is convergent and appears as
\[
V_o = -AV_{n} \left[ 1 + A\beta + L \right] = \frac{-AV_{n}}{1 - A\beta}
\]
If \( A\beta > 1 \) it is divergent series, it goes to infinity and in this case it goes to \( \pm V_s \)
This is known as regenerative action
Regenerative Comparator (contd.,)

- It cannot be remaining stably at any value in between whatever be the input value.
- Within the hysteresis it is either $V_s$ and beyond that it is one of the saturation states.
- A comparator is called as limiter by communication engineers and as zero crossing detector by power electronics engineers if one end of the input is connected to ground.
Regenerative Comparator (contd.,)

\[ V_{\text{ref}} (1 - \beta) \pm \beta V_s = V_i \]
Regenerative Comparator (contd.,)

for low $\beta$ values
PWM (Linear)

- The output waveform is a rectangular wave of the same frequency but having a duty cycle.
- Using similar triangles $abc$ and $ade$
- This circuit is a duty cycle generator (DCG) or pulse width modulator (PWM)

\[ \frac{\tau}{T/2} = \frac{V_p - V_R (1 - \beta)}{V_p} \]

\[ \frac{\tau}{T} = \frac{1}{2} \left( 1 - \frac{V_R (1 - \beta)}{V_p} \right) \]

for low $\beta$ values
Uses

- Switched mode power supplies
- Class D power amplifiers
- Analog multiplier
- DC to DC converters
- Analog multiplication using PWM and PAM
Simulation 1

\[ V_{\text{ref}} = 10 \text{V} ; \quad b = 1/2 \]
Simulation 2

\[ V_{\text{ref}} = 20\text{V} ; \ b = 1/2 \]
Pulse Width Modulator (PWM)

- Used in DC to DC converters and Class D power Amplifiers
- $V_{\text{ref}} = 10; \ b = 1/2$
PWM (contd.,)

- $V_{\text{ref}} = -10$; $b = 1/2$
Frequency Shift Keying (FSK)

- Modulating Frequency: Square Wave – 100 Hz; 7V
Frequency Modulator or FM Generator

- Modulating Frequency: Sine Wave – 100 Hz; 8V

![Graph showing FM Generation with modulating sine wave and output waveform.](chart)
Inverting Schmitt trigger

[Diagram of an inverting Schmitt trigger with resistors and an operational amplifier]
Non-inverting Schmitt trigger
Hysteresis

Now change of state at the output occurs when

\[ \beta = \frac{R_1}{R_1 + R_2} \]

\[ V_i (1 - \beta) + V_o \beta = V_R \]

\[ V_i (1 - \beta) \pm V_o \beta = V_R \]

\[ V_i = m \frac{V_s \beta}{1 - \beta} + \frac{V_R}{1 - \beta} \]
Simulation 2
Conclusion