Study of Helix Functions and Multi-Source Rauch Filters

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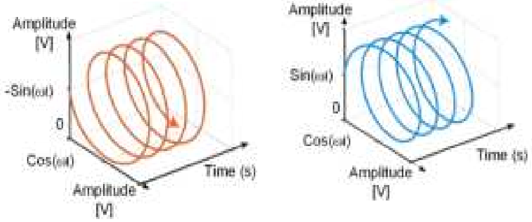
Outline

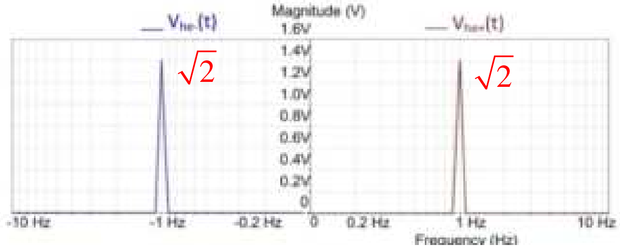
1. Research Background
   - Motivation, objectives and achievements
   - Helix functions and superposition formula
2. Ringing Test for Rauch Low-Pass Filter
   - Behaviors of fully differential op amp
   - Stability test for fully differential Rauch LPF
3. Analysis of Rauch Complex Filter
   - Spectrum of polyphase signals
   - Design of 4^{th}-order Rauch complex filter
4. Conclusions

1. Research Background

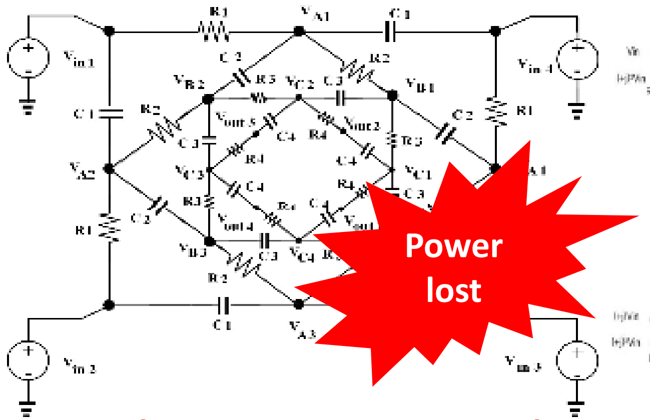
Motivation of Helix Waves and Multi-Source Circuits

Definition of Helix functions?



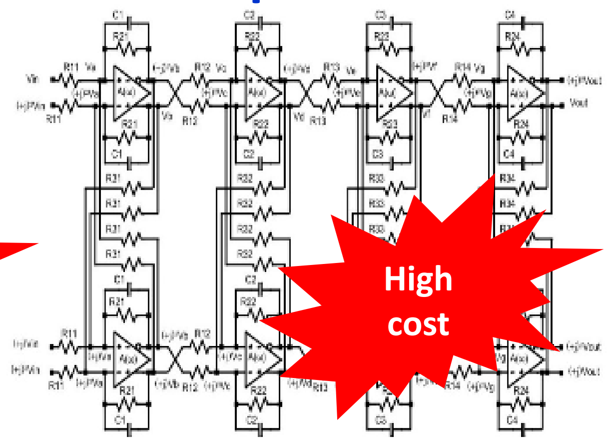


Polyphase filter



(Very complicated)

Complex filter



(High power consumption)

Spectrum?

- Fully differential Rauch LPF
- Rauch complex filter

New architectures

Undefined concepts of multi-source signals

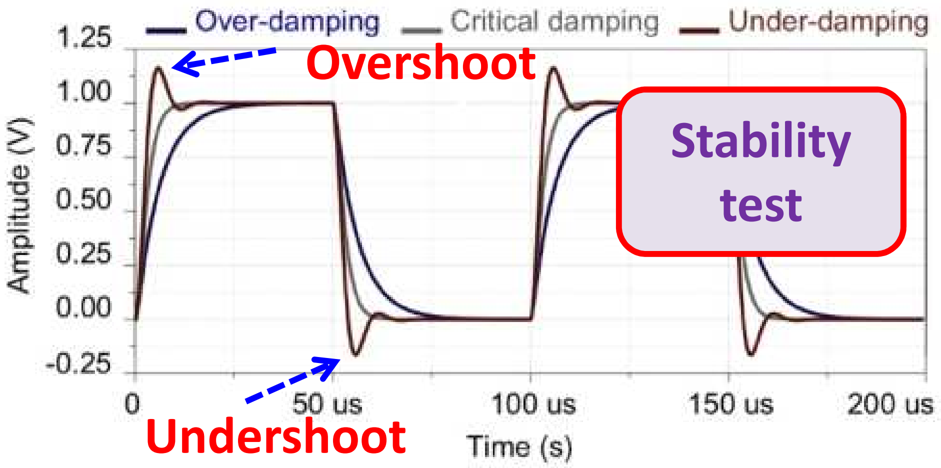
- Negative and positive frequencies?
- Negative and positive complex signals?
- Negative and positive polyphase signals?
- Spectrum of multi-source signals?

A general formula for multi-source networks?

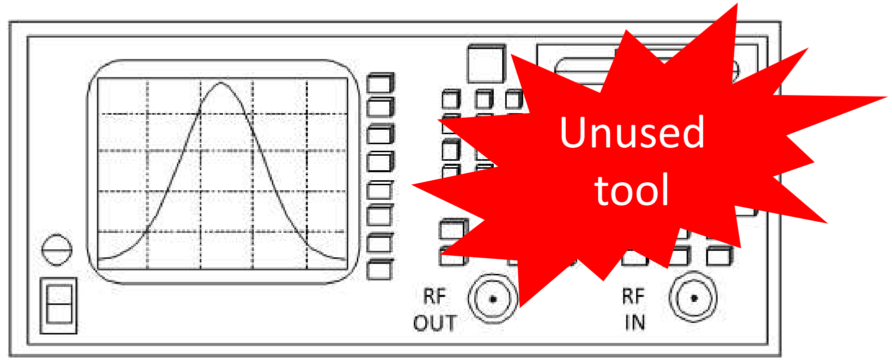
1. Research Background

Stability Test for Electronic Systems

Ringing in electronic systems

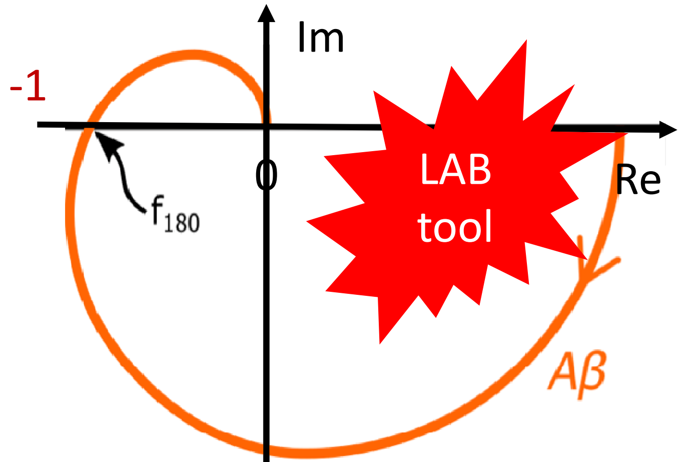


Nichols chart in Network Analyzer?



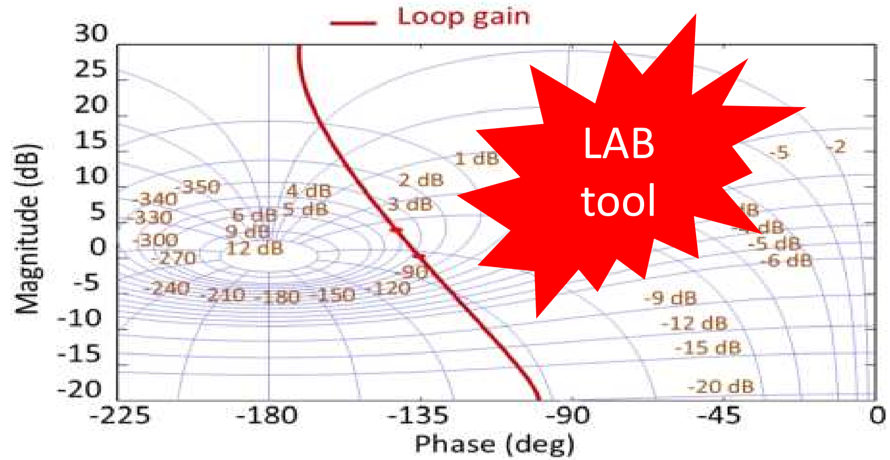
(Technology limitations)

Nyquist plot of loop gain



(Unclear operating region)

Nichols plot of loop gain



(Very complicated)

1. Research Background

Innovation of This Work

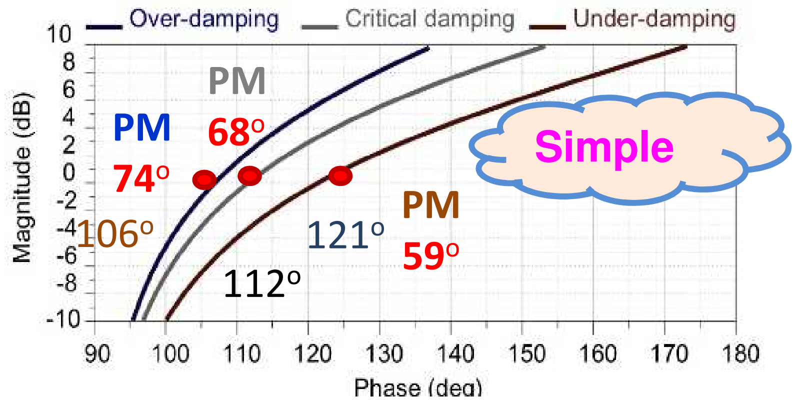
Merits of complex numbers

- Use of complex functions
  → Fundamental model of motion in both time and frequency domains
- Superposition formula for multi-source networks
- Nichols chart of self-loop function
  → A useful tool for stability test
  → Easily integrated in network analyzers

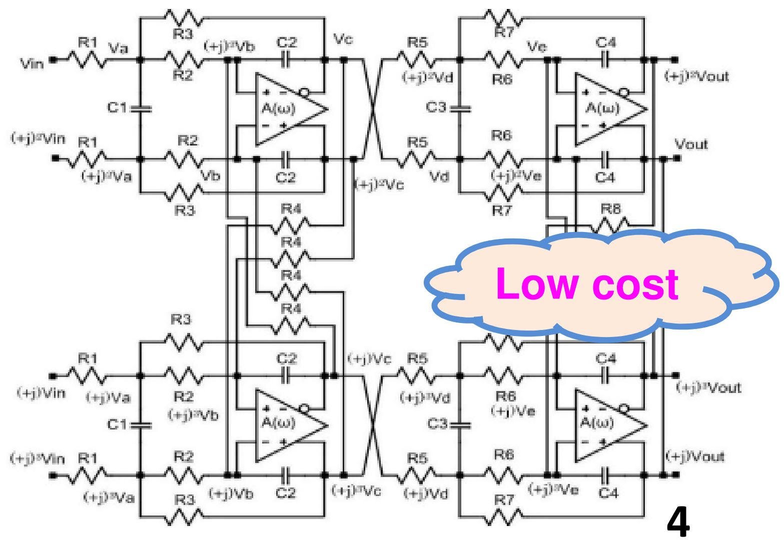
Merits of Rauch filters

- Easiest selection of components
- Lowest power consumption
- Simplest design in fully differential forms and complex topologies

Nichols plot of self-loop function



Rauch complex filter



1. Research Background

Objectives of Study

- Definitions of helix waves and polyphase signals
- Derivation of transfer functions in multi-source networks using superposition formula

○ Investigation of operating regions of 4^{th}-order fully differential Rauch low-pass filter

→ Over-damping (high delay in rising time)

→ Critical damping (max power propagation)

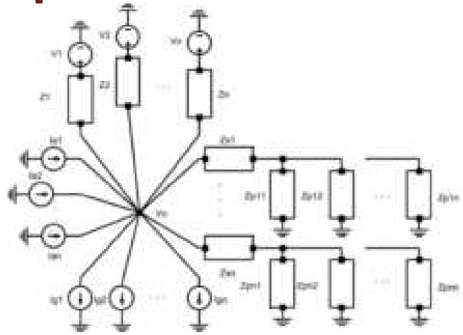
→ Under-damping (overshoot and ringing)

- Derivation of transfer function and image rejection ratio for 4^{th}-order Rauch complex filter

1. Research Background

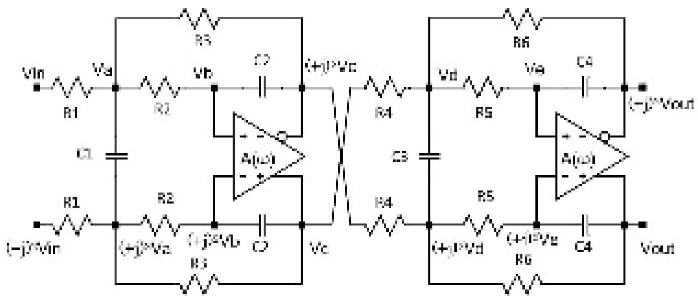
Achievements of Study

Superposition formula for multi-source networks



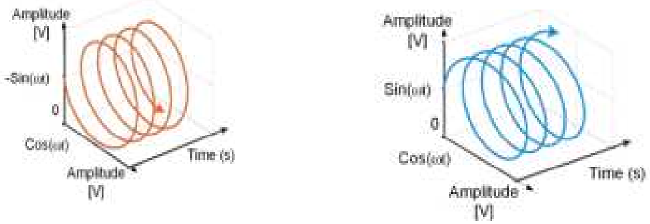
$$V_O(t)\sum_{i=1}^{n}\frac{1}{Z_i}+V_O(t)\sum_{i=1}^{n}\frac{1}{Z_{si}+\dfrac{1}{\sum_{k=1}^{n}\dfrac{1}{Z_{pik}}}}=\sum_{i=1}^{n}\left(\frac{V_i(t)}{Z_i}+I_{ai}(t)-I_{gi}(t)\right)$$

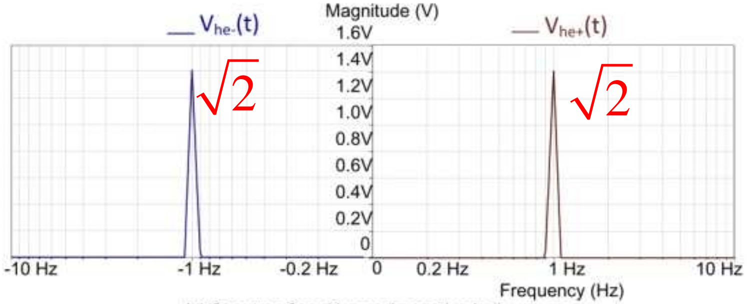
Stability Test for a 4th-order Rauch LPF



Definitions of helix waves

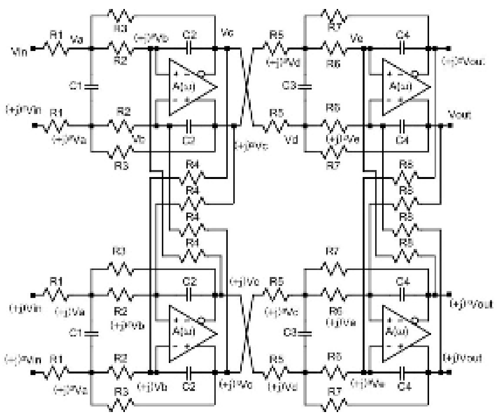
$$V_{he-}(t)=Ahe(-\omega_0 t-\theta_0) \qquad V_{he+}(t)=Ahe(\omega_0 t+\theta_0)$$

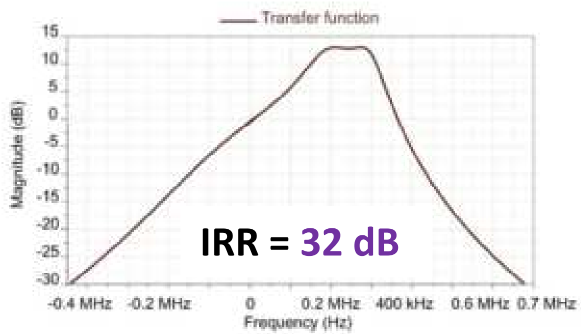




(a) Spectra of positive and negative helix waves

Analysis of a 4th-order Rauch complex filter



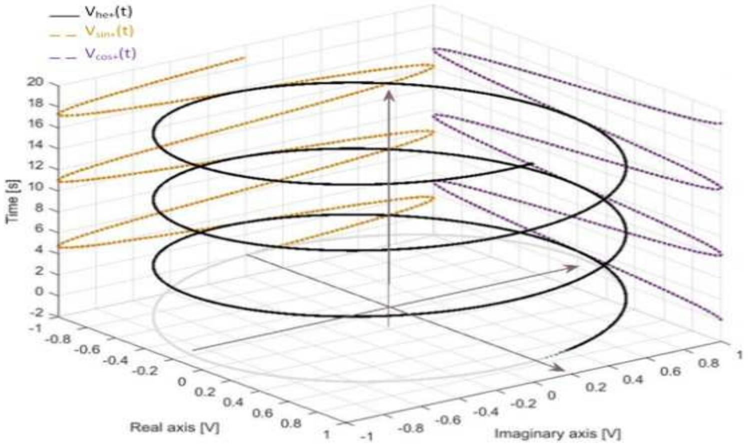


1. Research Background

Helix and Sinusoidal Waves

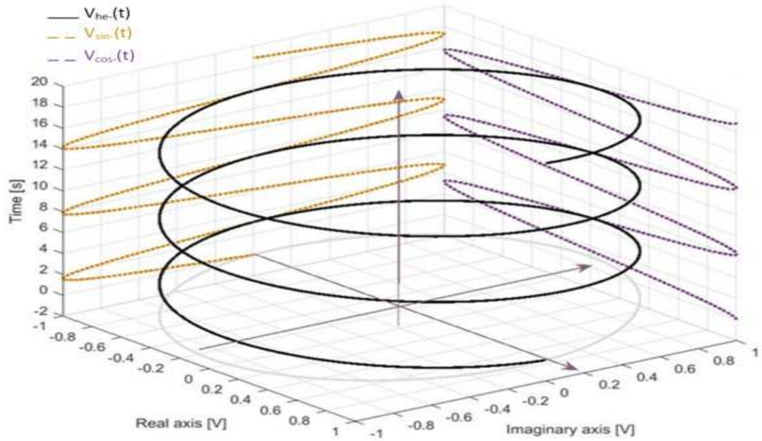
Positive helix function

$$V_{he+}(t) = Ahe(\omega_0 t + \theta_0) = A\sqrt{2}e^{j(\omega_0 T_0 + \theta_0)}$$
$$= A\cos(\omega_0 t + \theta_0) + jA\sin(\omega_0 t + \theta_0)$$

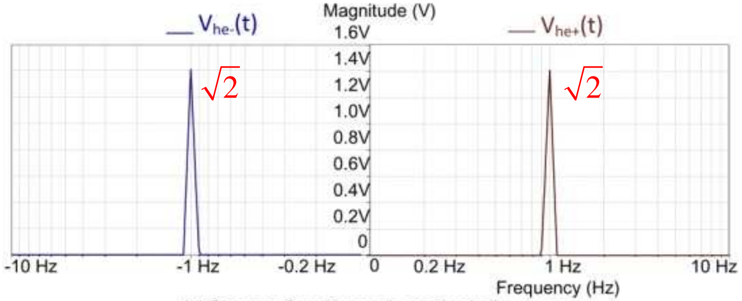


Negative helix function

$$V_{he-}(t) = Ahe(-\omega_0 t - \theta_0) = A\sqrt{2}e^{j(-\omega_0 T_0 - \theta_0)}$$
$$= A\cos(-\omega_0 t - \theta_0) + jA\sin(-\omega_0 t - \theta_0)$$

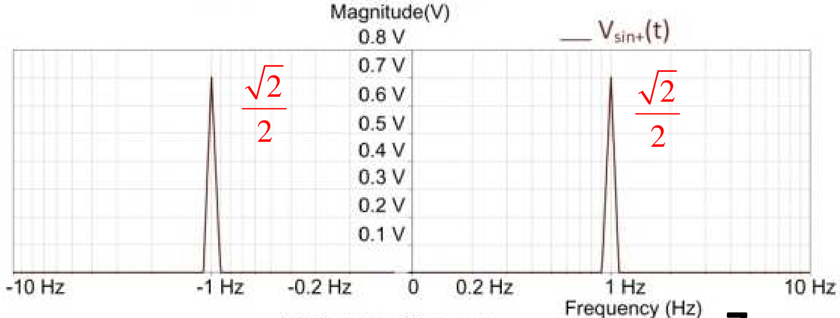


Spectrum of helix waves



(a) Spectra of positive and negative helix waves

Spectrum of sine wave



(b) Spectra of sine wave

1. Research Background

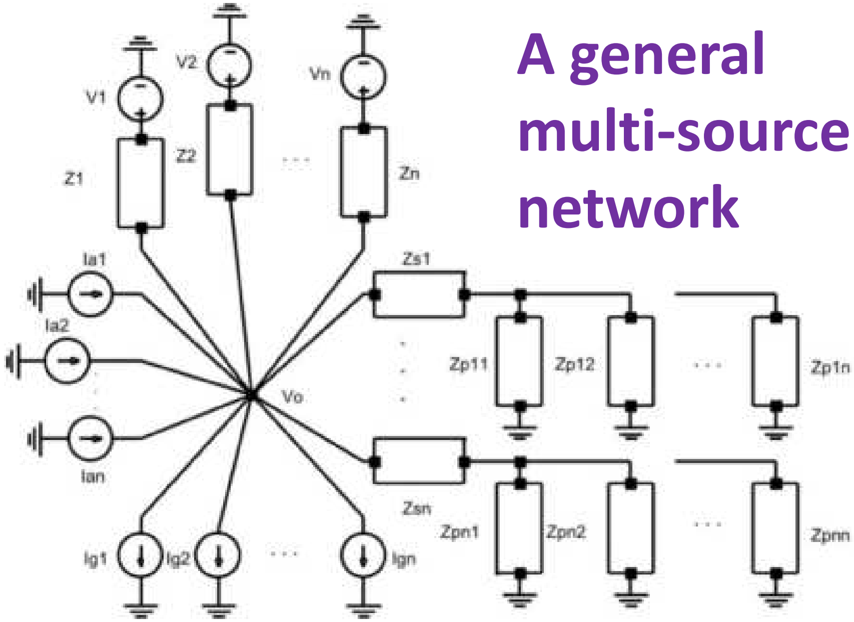
Superposition Theorem for Multi-Source Systems

Superposition formula:

$$V_O(t)\left(\sum_{i=1}^{n}\frac{1}{Z_i}+\sum_{i=1}^{n}\frac{1}{Z_{si}+\frac{1}{\sum_{k=1}^{n}\frac{1}{Z_{pik}}}}\right)=\sum_{i=1}^{n}\left(\frac{V_i(t)}{Z_i}+I_{ai}(t)-I_{gi}(t)\right)$$

$V_O(t)$: *Voltage at one node*
$V_i(t)$: *Input voltage sources*
$I_{ai}(t)$: *Ahead-toward current sources*
$I_{gi}(t)$: *Ground-toward current sources*
$Z_{i,\ si,\ pi,}(t)$: Impedances at each branch

○ **Multi-source systems, feedback networks (op amps, amplifiers, polyphase filters, complex filters…)**



A general multi-source network

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   - **Stability test for fully differential Rauch LPF**
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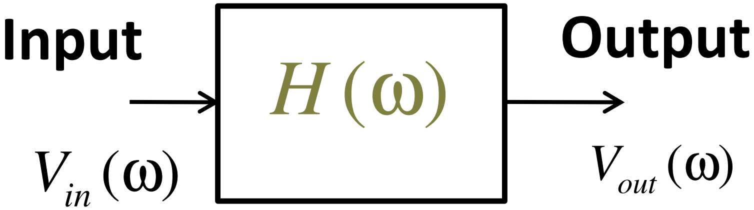
4. Conclusions

2. Ringing Test for Rauch Low-Pass Filter

Self-loop Function in A Transfer Function

Linear system



Model of a linear system

$$H(\omega) = \frac{b_0(j\omega)^n + \ldots + b_{n-1}(j\omega) + b_n}{a_0(j\omega)^n + \ldots + a_{n-1}(j\omega) + a_n}$$

Transfer function

$$H(\omega) = \frac{V_{out}(\omega)}{V_{in}(\omega)} = \frac{A(\omega)}{1 + L(\omega)}$$

$A(\omega)$ **: Numerator function**

$H(\omega)$ **: Transfer function**

$L(\omega)$ **: Self-loop function**

Variable: angular frequency (ω)

- **Polar chart → Nyquist chart**
- **Magnitude-frequency plot**
- **Angular-frequency plot**

  (Magnitude-frequency plot and Angular-frequency plot) → **Bode plots**
- **Magnitude-angular diagram → Nichols diagram**

2. Ringing Test for Rauch Low-Pass Filter

Operating Regions of 4th-Order System

Pascal's Triangle

n = 2	1 2 1
n = 3	1 3 3 1
n = 4	1 4 6 4 1
n = 5	1 5 10 10 5 1

- **Under-damping:** 1 : 2 : 3 : 2 : 1

$$H_1(\omega) = \frac{1}{(j\omega)^4 + 2(j\omega)^3 + 3(j\omega)^2 + 2j\omega + 1}$$

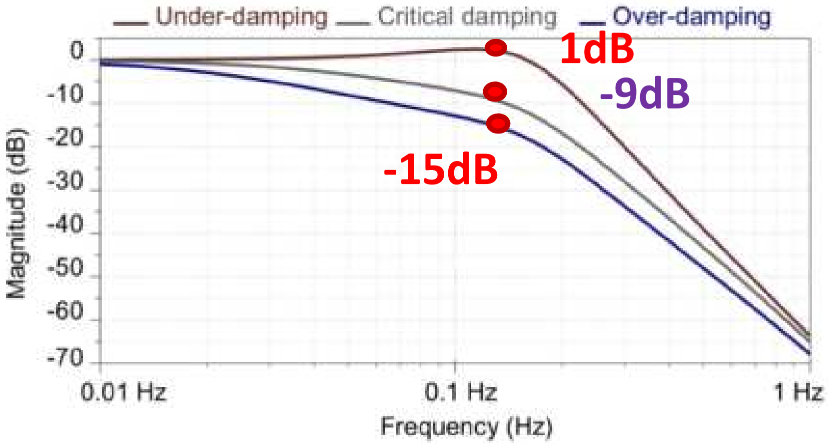
- **Critical damping:** 1 : 4 : 6 : 4 : 1

$$H_2(\omega) = \frac{1}{(j\omega)^4 + 4(j\omega)^3 + 6(j\omega)^2 + 4j\omega + 1}$$

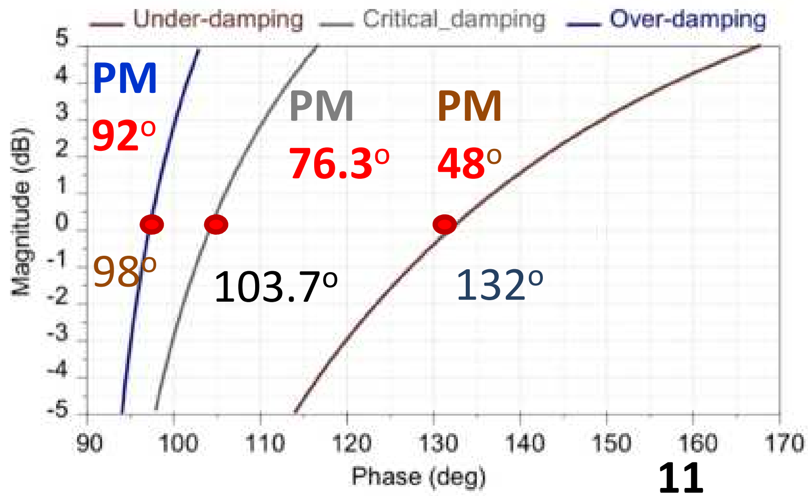
- **Over-damping:** 1 : 9 : 10 : 9 : 1

$$H_3(\omega) = \frac{1}{(j\omega)^4 + 9(j\omega)^3 + 10(j\omega)^2 + 9j\omega + 1}$$

Bode plot of transfer function



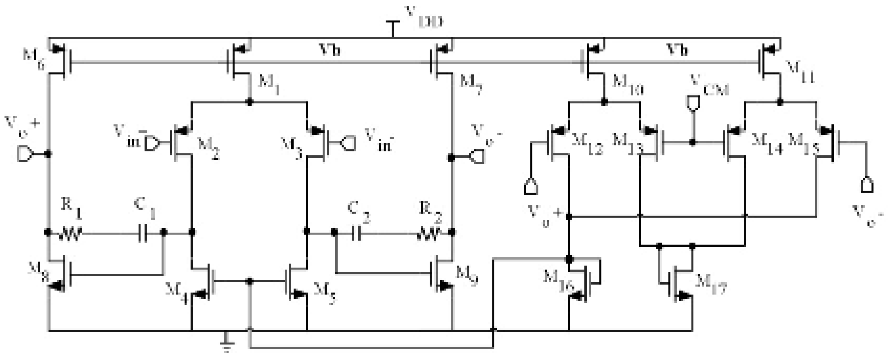
Nichols plot of self-loop function



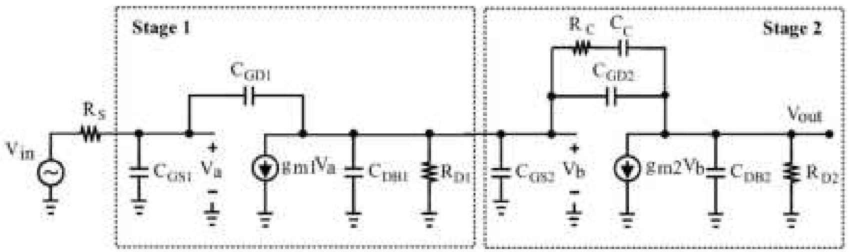
3. Ringing Test for Rauch Low-Pass Filter

Behaviors of Fully Differential Op Amp

Fully differential two-stage op amp



Small signal model



Applying superposition formula at each node

$$V_a\left[\frac{1}{R_S}+j\omega\left(C_{GS1}+C_{GD1}\right)\right]=\frac{V_{in}}{R_S}+V_b j\omega C_{GD1};$$

$$V_b\left[j\omega\left(C_{GD1}+C_{DB1}+C_{GS2}+C_{GD2}\right)+\frac{1}{R_{D1}}+\frac{j\omega C_C}{1+j\omega R_C C_C}\right]$$

$$=V_a\left(j\omega C_{GD1}-g_{m1}\right)+V_{out}\left(j\omega C_{GD2}+\frac{j\omega C_C}{1+j\omega R_C C_C}\right);$$

$$V_{out}\left[j\omega\left(C_{GD2}+C_{DB2}\right)+\frac{j\omega C_C}{1+j\omega R_C C_C}+\frac{1}{R_{D2}}\right]=V_b\left(j\omega C_{GD2}+\frac{j\omega C_C}{1+j\omega R_C C_C}-g_{m2}\right);$$

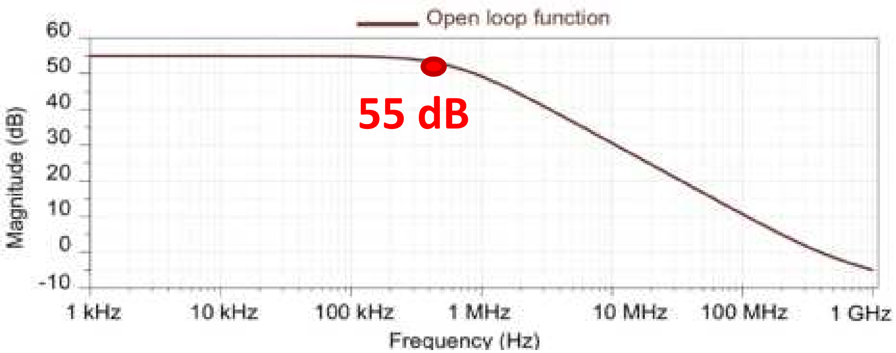
Open-loop function A(ω)

$$A(\omega)=\frac{b_0(j\omega)^4+b_1(j\omega)^3+b_2(j\omega)^2+b_3(j\omega)^1+b_4}{a_0(j\omega)^5+a_1(j\omega)^4+a_2(j\omega)^3+a_3(j\omega)^2+a_4 j\omega+1};$$

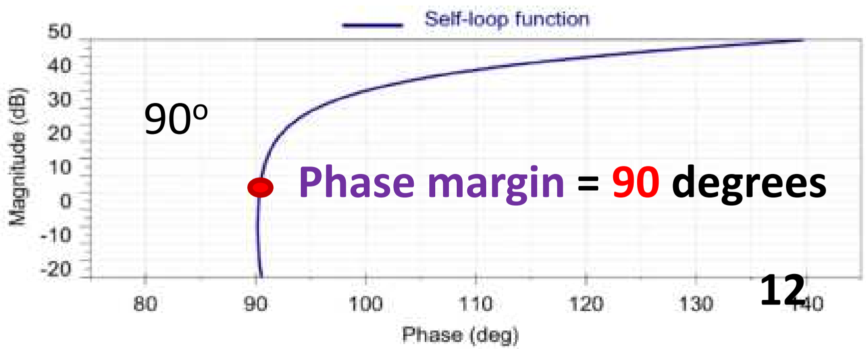
Self-loop function L(ω)

$$L(\omega)=a_0(j\omega)^5+a_1(j\omega)^4+a_2(j\omega)^3+a_3(j\omega)^2+a_4 j\omega;$$

Bode plot of open-loop function A(ω)



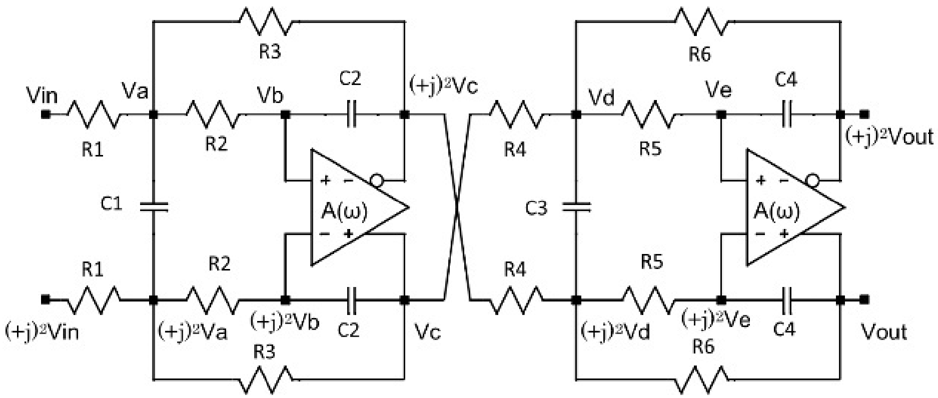
Nichols plot of self-loop function L(ω)



3. Ringing Test for Rauch Low-Pass Filter

Analysis of Fully Differential Rauch Low-Pass Filter

Fully differential Rauch LPF



Applying superposition formula at each node

$$V_a\left(\frac{1}{R_1}+j\omega C_1+\frac{1}{R_2}+\frac{1}{R_3}\right)=\frac{V_{in}}{R_1}+\frac{V_b}{R_2}+\frac{(+j)^2V_c}{R_3}+(+j)^2V_a j\omega C_1;$$

$$V_b\left(\frac{1}{R_2}+j\omega C_2\right)=\frac{V_a}{R_2}+(+j)^2V_c j\omega C_2;\ V_c=\left(V_b-(+j)^2V_b\right)A(\omega);$$

$$V_d\left(\frac{1}{R_4}+j\omega C_3+\frac{1}{R_5}+\frac{1}{R_6}\right)=\frac{V_c}{R_4}+\frac{V_e}{R_5}+\frac{(+j)^2V_{out}}{R_6}+(+j)^2V_d j\omega C_3;$$

$$V_e\left(\frac{1}{R_5}+j\omega C_4\right)=\frac{V_d}{R_5}+(+j)^2V_{out} j\omega C_4;\ V_{out}=\left(V_e-(+j)^2V_e\right)A(\omega);$$

Transfer function H(ω) and self-loop function L(ω)

$$H(\omega)=\frac{b_0}{1+a_0(j\omega)^4+a_1(j\omega)^3+a_2(j\omega)^2+a_3 j\omega};$$

$$L(\omega)=a_0(j\omega)^4+a_1(j\omega)^3+a_2(j\omega)^2+a_3 j\omega;$$

Operating regions

- **Over-damping (C3 = 0.1 nF),**
- **Critical damping (C3 = 0.5 nF),**
- **Under-damping (C3 = 1.4 nF).**

Here, parameters are given as

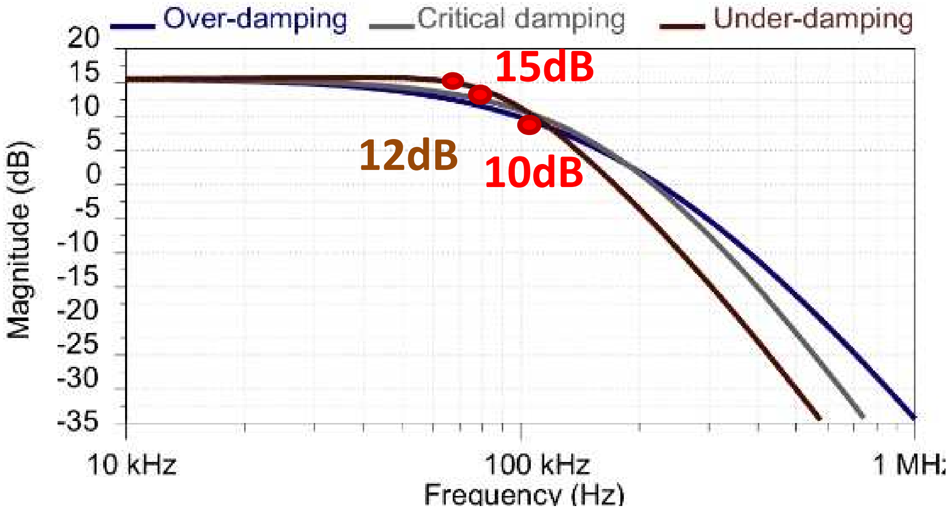
$$a_1=R_2R_3\left(R_5+R_6+\frac{R_5R_6}{R_4}\right)C_1C_2C_4+R_5R_6\left(R_2+R_3+\frac{R_2R_3}{R_1}\right)C_2C_3C_4;\ a_3=\left(R_2+R_3+\frac{R_2R_3}{R_1}\right)C_2+\left(R_5+R_6+\frac{R_5R_6}{R_4}\right)C_4;$$

$$a_2=R_2R_3C_1C_2+R_5R_6C_3C_4+\left(R_2+R_3+\frac{R_2R_3}{R_1}\right)\left(R_5+R_6+\frac{R_5R_6}{R_4}\right)C_2C_4;\ b_0=\frac{R_3R_6}{R_1R_4};\ a_0=R_2R_3R_5R_6C_1C_2C_3C_4;$$

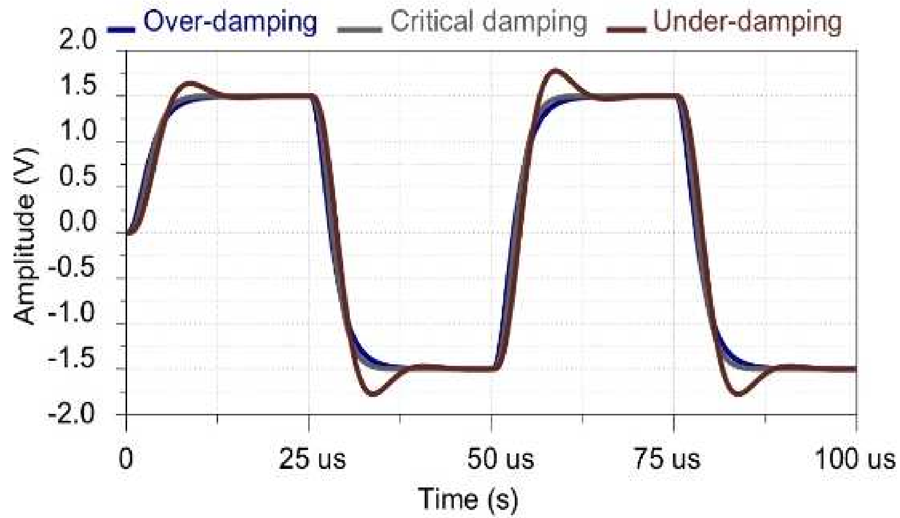
3. Ringing Test for Rauch Low-Pass Filter

Behaviors of Fully Differential Rauch Low-Pass Filter

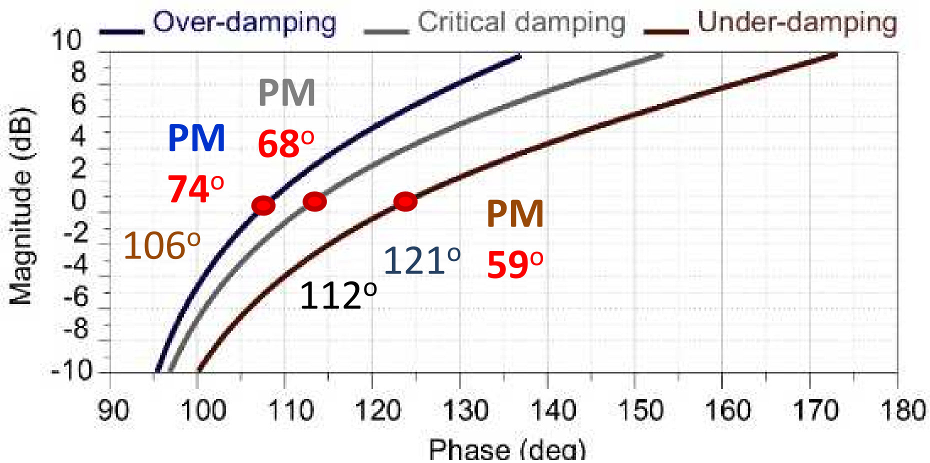
Bode plot of transfer function



Transient response



Nichols plot of self-loop function



Over-damping:

→**Phase margin is 74 degrees.**

Critical damping:

→**Phase margin is 68 degrees.**

Under-damping:

→**Phase margin is 59 degrees.**

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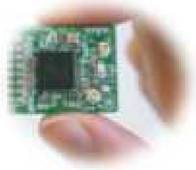
4. Conclusions

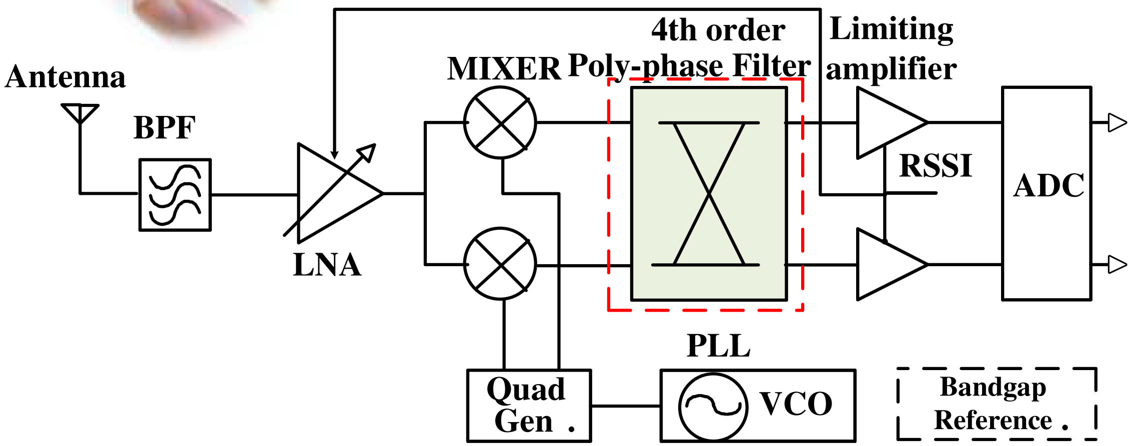
3. Analysis of Rauch Complex Filter

Characteristics of Low-IF Receiver

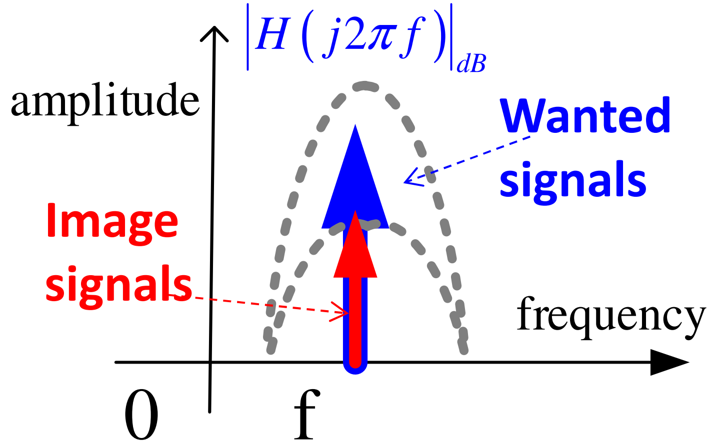
Block diagram of Low-IF receiver



This Work



Spectrum of received signals



Step-down frequency converter

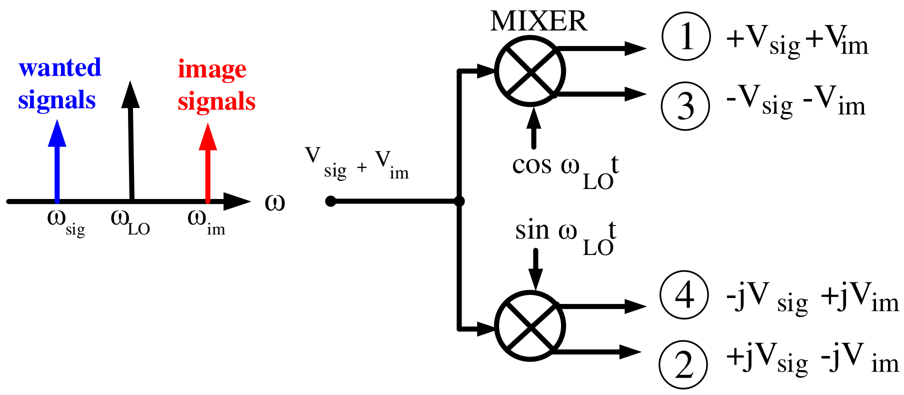
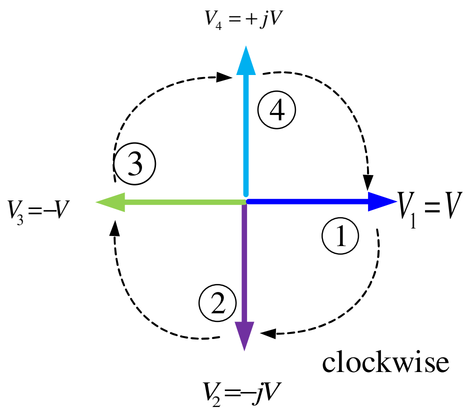
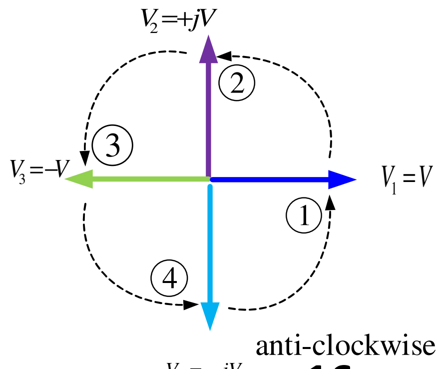


Image Signals



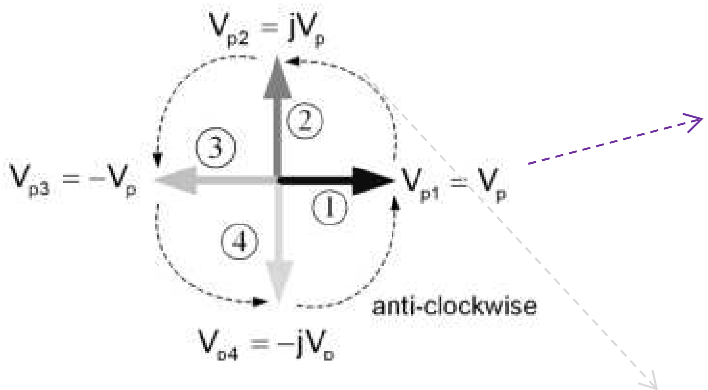
Wanted Signals



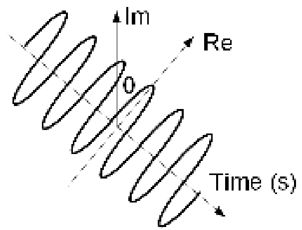
3. Analysis of Rauch Complex Filter

Positive Polyphase Signals on Frequency Domain

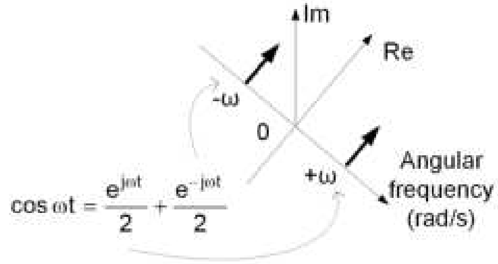
Positive polyphase signals



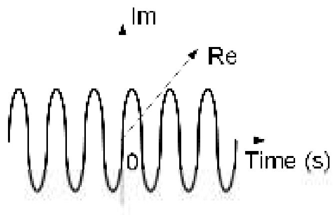
$$S_{Pos\_poly}\{V_1(t);V_2(t);V_3(t);V_4(t)\}$$
$$=\{1;+j;(+j)^2;(+j)^3\}V_{pos}(t)$$



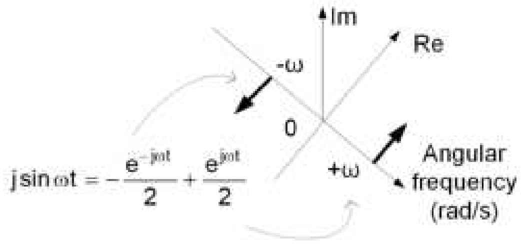
(a) Cosine wave on real axis



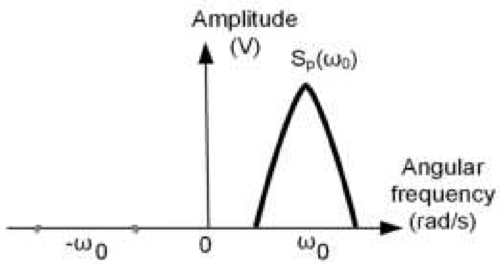
(b) Spectrum of cosine wave



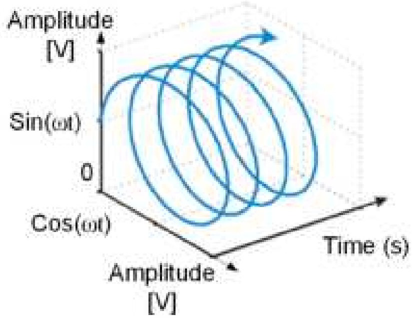
(c) Plus sine wave on imaginary axis



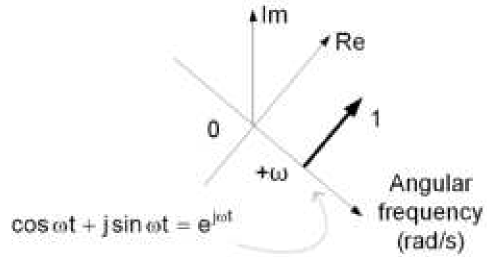
(d) Spectrum of plus sine wave



(c) Angular frequency plane for polyphase signals



(e) Positive angular frequency wave

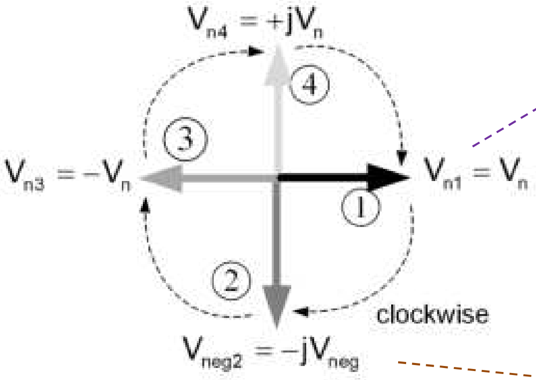


(f) Spectrum of positive angular frequency wave

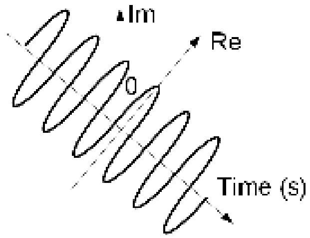
3. Analysis of Rauch Complex Filter

Negative Polyphase Signals on Frequency Domain

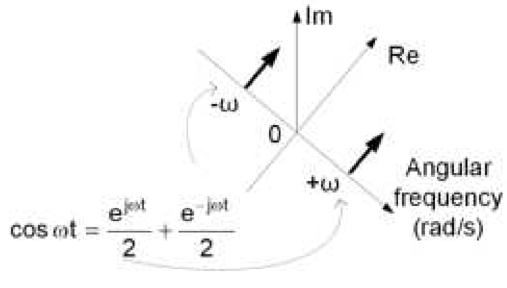
Negative polyphase signals



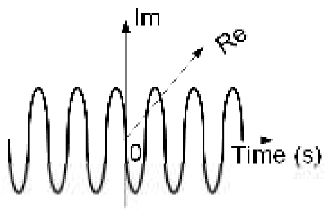
$$S_{Neg\_poly}\{V_1(t);V_2(t);V_3(t);V_4(t)\} = \{1;-j;(-j)^2;(-j)^3\}V_{neg}(t)$$



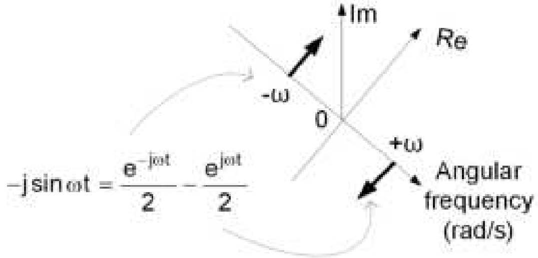
(a) Cosine wave on real plane



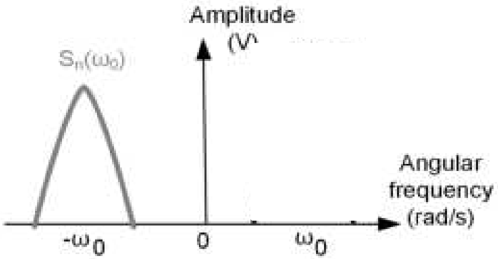
(b) Spectrum of cosine wave



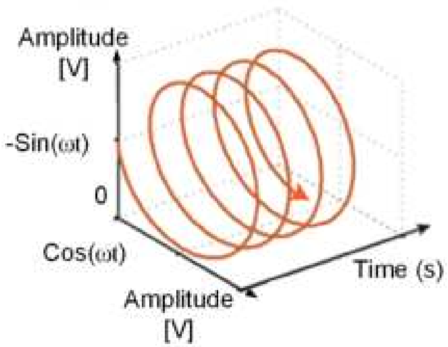
(c) Minus sine wave on imaginary plane



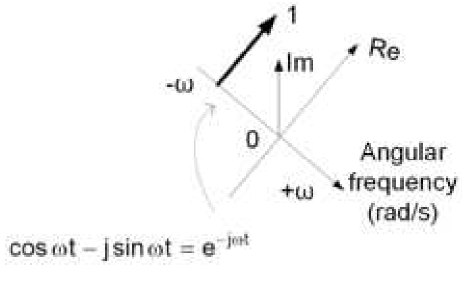
(d) Spectrum of minus sine wave



(c) Angular frequency plane for polyphase signals



(e) Negative angular frequency wave

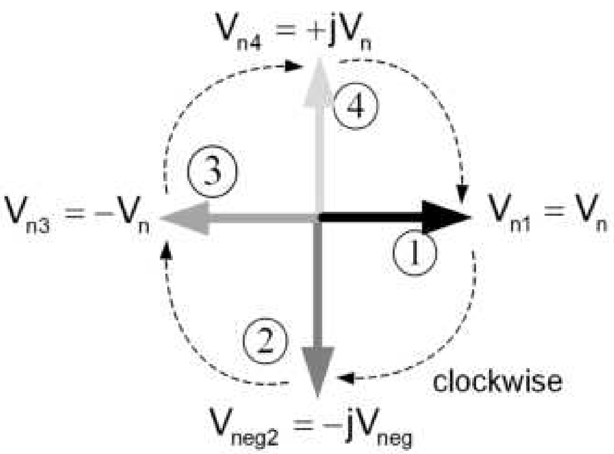


(f) Spectrum of negative angular frequency wave

3. Analysis of Rauch Complex Filter

Polyphase Signals in All Frequency Domains

Negative polyphase signals



Complex number

Imaginary unit j
= 90° phase shift

$$(+j)^2 = e^{+j\pi} = -1$$

$$(-j)^2 = e^{-j\pi} = -1$$

Positive polyphase signals

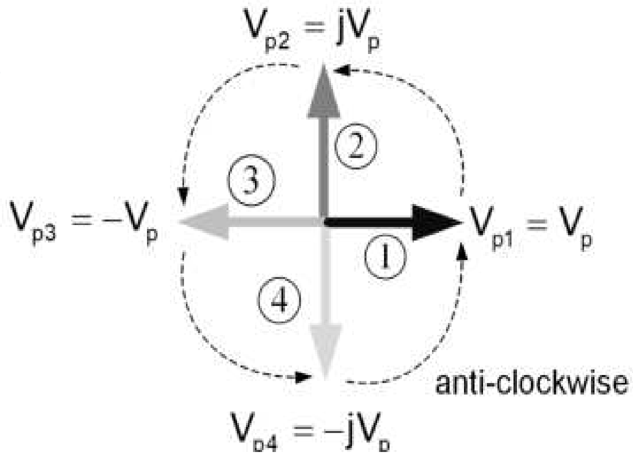
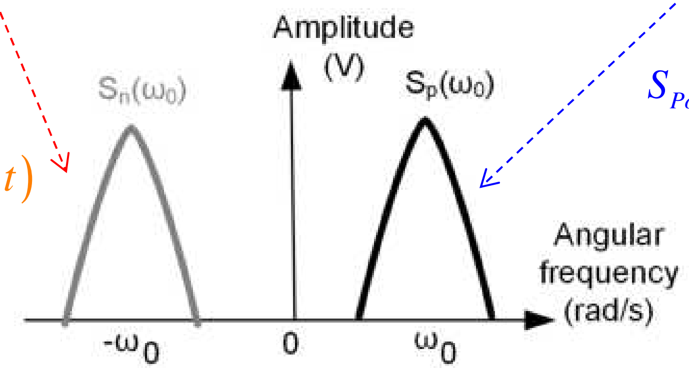


Image signals

$$S_{Neg\_poly}\{V_1(t);V_2(t);V_3(t);V_4(t)\} = \{1;-j;(-j)^2;(-j)^3\}V_{neg}(t)$$



Wanted signals

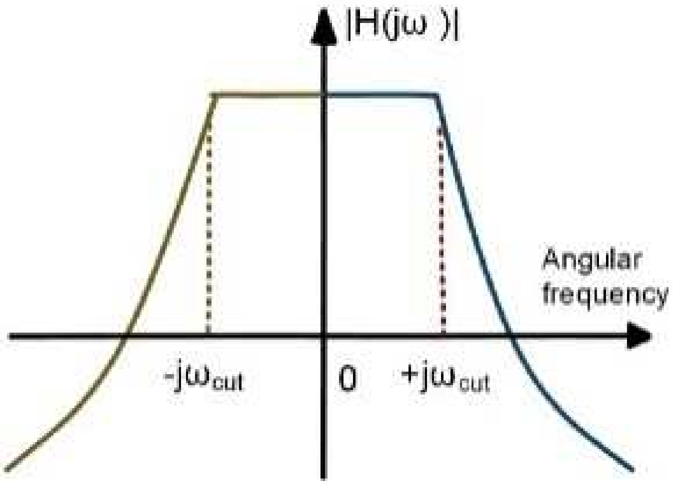
$$S_{Pos\_poly}\{V_1(t);V_2(t);V_3(t);V_4(t)\} = \{1;+j;(+j)^2;(+j)^3\}V_{pos}(t)$$

3. Analysis of Rauch Complex Filter

Design Principle for Complex Filter Networks

Frequency shifting of real low-pass filter in all frequency domains → an active complex filter

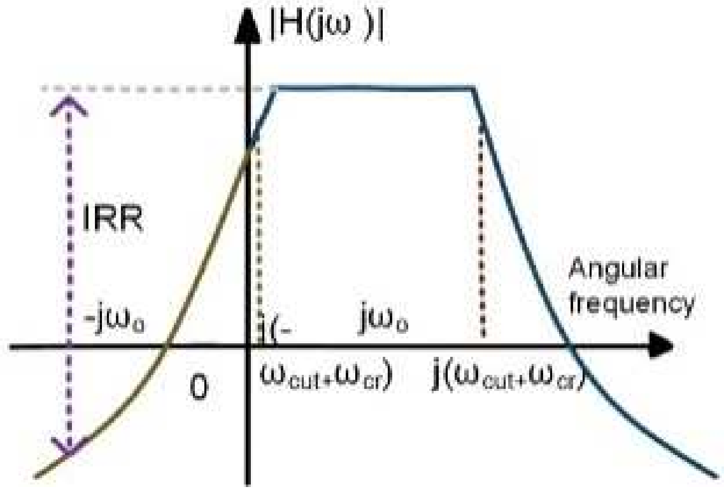
Low-pass filter (LPF)



Angular frequency shifting

j(ω.ω_cr)

Complex filter (CF)



$$H_{LPF}(\omega) = -\frac{A_{21}}{\left(j\frac{\omega}{\omega_{cut}}+1\right)}$$

$\omega - \omega_{cr}$ →

$$\omega_{cr} = \frac{1}{R_3 C_1}$$

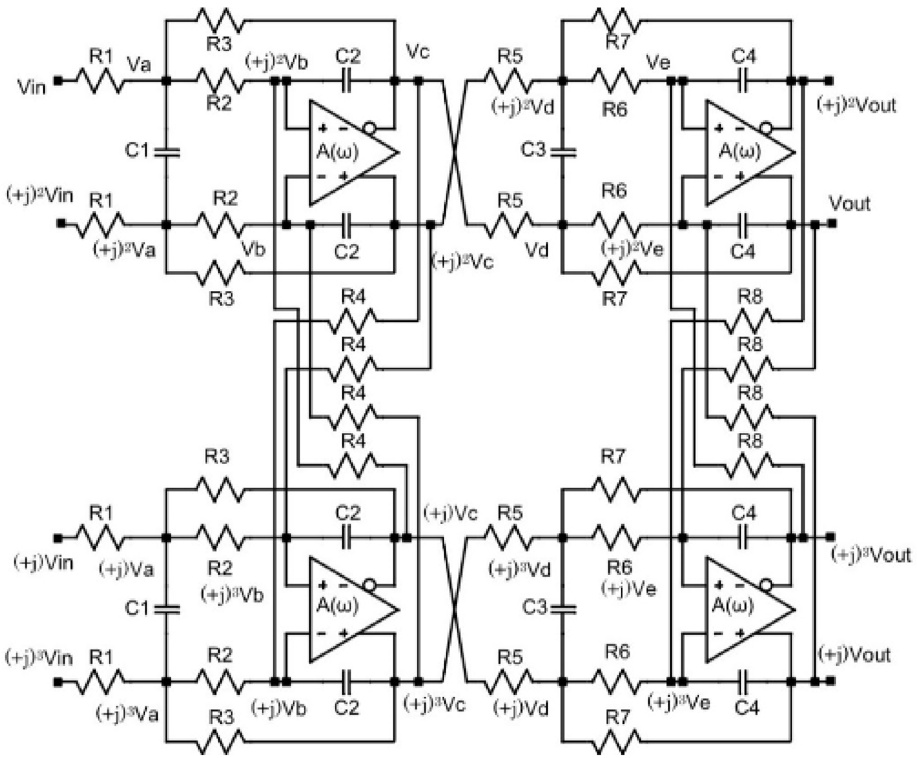
$$H_{CF}(\omega) = -\frac{A_{21}}{\left(j\frac{\omega-\omega_{cr}}{\omega_{cut}}+1\right)}$$

ω_{cr} : cross angular frequency

3. Analysis of Rauch Complex Filter

Analysis of 4th-Order Rauch Complex Filter

4th-order Rauch complex filter



Applying superposition formula at each node

$$V_a\left(\frac{1}{R_1}+j\omega C_1+\frac{1}{R_2}+\frac{1}{R_3}\right)=\frac{V_{in}}{R_1}+(+j)^2V_a j\omega C_1+\frac{V_b}{R_2}+\frac{(+j)^2V_c}{R_3};$$

$$V_b\left(\frac{1}{R_2}+j\omega C_2+\frac{1}{R_4}\right)=\frac{V_a}{R_2}+(+j)^2V_c j\omega C_2+\frac{(+j)^3V_c}{R_4};$$

$$V_c=\left[V_b-(+j)^2V_b\right]A(\omega);V_{out}=\left[V_e-(+j)^2V_e\right]A(\omega);$$

$$V_d\left(\frac{1}{R_5}+j\omega C_3+\frac{1}{R_6}+\frac{1}{R_7}\right)=\frac{V_c}{R_5}+(+j)^2V_d j\omega C_3+\frac{V_e}{R_6}+\frac{(+j)^2V_{out}}{R_7};$$

$$V_e\left(\frac{1}{R_6}+j\omega C_4+\frac{1}{R_8}\right)=\frac{V_d}{R_6}+(+j)^2V_{out} j\omega C_4+\frac{(+j)^3V_{out}}{R_8};$$

Positive transfer function

$$H_P(\omega)=\left(\frac{b_0}{a_0(j\omega)^2+a_{P1}j\omega+a_{P2}}\right)\left(\frac{b_1}{a_3(j\omega)^2+a_{P4}j\omega+a_{P5}}\right);$$

Image rejection ratio

$$IRR(\omega)=\left(\frac{a_0(j\omega)^2+a_{N1}j\omega+a_{N2}}{a_0(j\omega)^2+a_{P1}j\omega+a_{P2}}\right)\left(\frac{a_3(j\omega)^2+a_{N4}j\omega+a_{N5}}{a_3(j\omega)^2+a_{P4}j\omega+a_{P5}}\right);$$

Negative transfer function

$$H_N(\omega)=\left(\frac{b_0}{a_0(j\omega)^2+a_{N1}j\omega+a_{N2}}\right)\left(\frac{b_1}{a_3(j\omega)^2+a_{N4}j\omega+a_{N5}}\right);$$

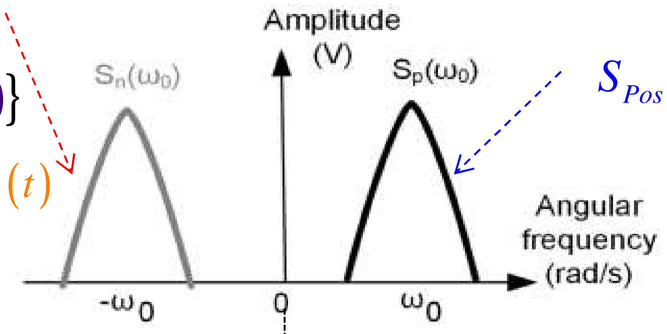
3. Analysis of Rauch Complex Filter

Behaviors of 4th-Order Rauch Complex Filter

Image signals

Wanted signals

$$S_{Neg\_poly}\{V_1(t);V_2(t);V_3(t);V_4(t)\} = \{1;-j;(-j)^2;(-j)^3\}V_{neg}(t)$$

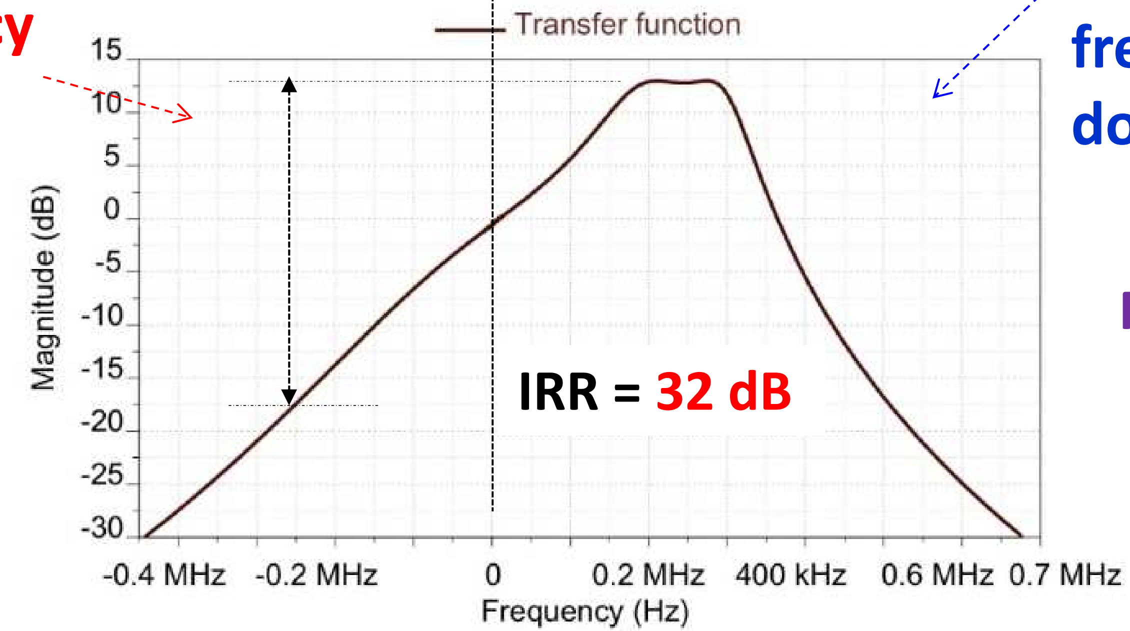


$$S_{Pos\_poly}\{V_1(t);V_2(t);V_3(t);V_4(t)\} = \{1;+j;(+j)^2;(+j)^3\}V_{pos}(t)$$

Negative frequency domain

Bode plot of transfer function

Positive frequency domain



Bandwidth = 200 kHz

Pass-band gain = 13 dB

Outline

1. Research Background
   - Motivation, objectives and achievements
   - Helix functions and superposition formula
2. Ringing Test for Rauch Low-Pass Filter
   - Behaviors of fully differential op amp
   - Stability test for fully differential Rauch LPF
3. Analysis of Rauch Complex Filter
   - Spectrum of polyphase signals
   - Design of 4^{th}-order Rauch complex filter
4. **Conclusions**

4. Comparison

Features	Proposed formula	Conventional Superposition	Millan's theorem
Effects of all actuating sources	At one time	Several times	At one time
Transfer function accuracy	Yes	No	No
Single-input network analysis	Yes	Yes	Yes
Polyphase network analysis	Yes	No	No
Complex network analysis	Yes	No	No
Image rejection ratio accuracy	Yes	No	No

4. Discussions

- Ringing test for electronic networks using Nichols chart of self-loop function

→ Observation of phase margin can help us determine the operating regions of high-order systems.

- Transfer function and image rejection ratio give useful information about the behaviors of polyphase filters and complex filters.
- Superposition formula: fundamental network analysis theory for multi-source systems

→ Compute the effects of all sources at one time,

→ Get the transfer function faster, and

→ Reduce the network complexity.

4. Conclusions

This work:

- **Definitions of helix functions and polyphase signals**
- **Proposal of superposition formula for deriving transfer function in multi-source networks**
- **Stability test for 4^{th}-order fully differential Rauch LPF**
- **Derivation of transfer function and image rejection ratio for 4^{th}-order Rauch complex filter**
  →Theoretical concepts of stability test are verified by laboratory simulations.

Future work:

- **Stability test for parasitic components in transmission lines, printed circuit boards, physical layout layers**
- **Investigation of DC offset and IQ mismatches in polyphase filters and complex filters**

References

[1] M. Tran, A. Kuwana, H. Kobayashi, "*Derivation of Loop Gain and Stability Test for Multiple Feedback Low Pass Filter Using Deboo Integrator*", The 8th IIAE Int. Conf. on Industrial Application Engineering, Shimane, Japan, March, 2020.

[4] M. Tran, A. Kuwana, H. Kobayashi "*Ringing Test for Negative Feedback Amplifiers*" 11th IEEE Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON 2020), Vancouver, Canada, Nov. 2020.

[6] M. Tran, A. Kuwana, H. Kobayashi, "*Design of Active Inductor and Stability Test for Passive RLC Low Pass Filter*", 10th Int. Conf. on Computer Science, Engineering and Applications (CCSEA 2020), London, United Kingdom, Jul. 2020.

[7] M. Tran, A. Kuwana, H. Kobayashi, "*Ringing Test for Tow-Thomas Low-Pass Filters*", Int. Conf. on Promising Electronic Technologies (ICPET 2020), Jerusalem, Palestine, 16-17, Dec. 2020.

[9] M. Tran, A. Kuwana, H. Kobayashi, "*Study of Behaviors of Electronic Amplifiers using Nichols Chart*", IEEE the 3rd Int. Conf. on Electronics and Communication Engineering (ICECE 2020), Xi'an, China, 14-16, Dec. 2020.

[10] M. Tran, "*Study of Multiphase Networks, Noise Reduction for DC-DC Converters, and Stability Test for Electronic Systems*", ATS Doctoral Dissertation Award Contest, 29th IEEE Asian Test Symposium, Penang, Malaysia, Nov. 2020.

[12] M. Tran, A. Kuwana, H. Kobayashi, "*Ringing Test for 2nd-order Sallen-Key Low-Pass Filters*", IEEE 2nd Int. Conf. on Circuits and Systems (ICCS 2020), Chengdu, China, 10-13, Dec. 2020.

[17] M. Tran, A. Hatta, A. Kuwana, H. Kobayashi, "*Derivation of Image Rejection Ratio for High-Order Complex Filters,*" 6th Taiwan and Japan Conf. on Circuits and Systems (TJCAS 2020), Nov. 2020.

[18] M. Tran, A. Kuwana, H. Kobayashi, "*Ringing Test for 3rd-order Ladder Low-Pass Filters*", 11th IEEE Annual Ubiquitous Computing, Electronics & Mobile Communication Conference (UEMCON 2020), NY, USA, Oct. 2020.

[20] M. Tran, A. Kuwana, H. Kobayashi, "*Derivation of Loop Gain and Stability Test for Low Pass Tow-Thomas Biquad Filter*", 10th Int. Conf. on Computer Science, Engineering and Applications (CCSEA 2020), United Kingdom, Jul. 2020.

[21] M. Tran, N. Kushita, A. Kuwana, H. Kobayashi, "*Mathematical Analysis and Design of 4-Stage Passive RC Network in RF Front-End System*", 3rd Int. Conf. on Technology and Social Science (ICTSS 2019), Kiryu, Japan, May, 2019.

[22] M. Tran, A. Hatta, A. Kuwana, H. Kobayashi, "*Design of 6th-order passive quadrature signal generation network based on polyphase filter*", IEEE 15th Int. Conf. on Solid-State and Integrated Circuit Technology (ICSICT2020), Kunming, China, Nov. 2020.

[23] M. Tran, N. Kushita, A. Kuwana, H. Kobayashi, "*Mathematical Model and Analysis of 4-Stage Passive RC Polyphase Filter for Low-IF Receiver*", Journal of Mechanical and Electrical Intelligent System, vol. 3, no. 2, May 2020.

[25] M. Tran, N. Kushita, A. Kuwana, H. Kobayashi, "*Flat Pass-Band Method with Two RC Band-Stop Filters for 4-Stage Passive RC Polyphase Filter in Low-IF Receiver Systems*", 3th IEEE Int. Conf. on ASIC (ASICON 2019), Oct. 2019.

Thank you very much!

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