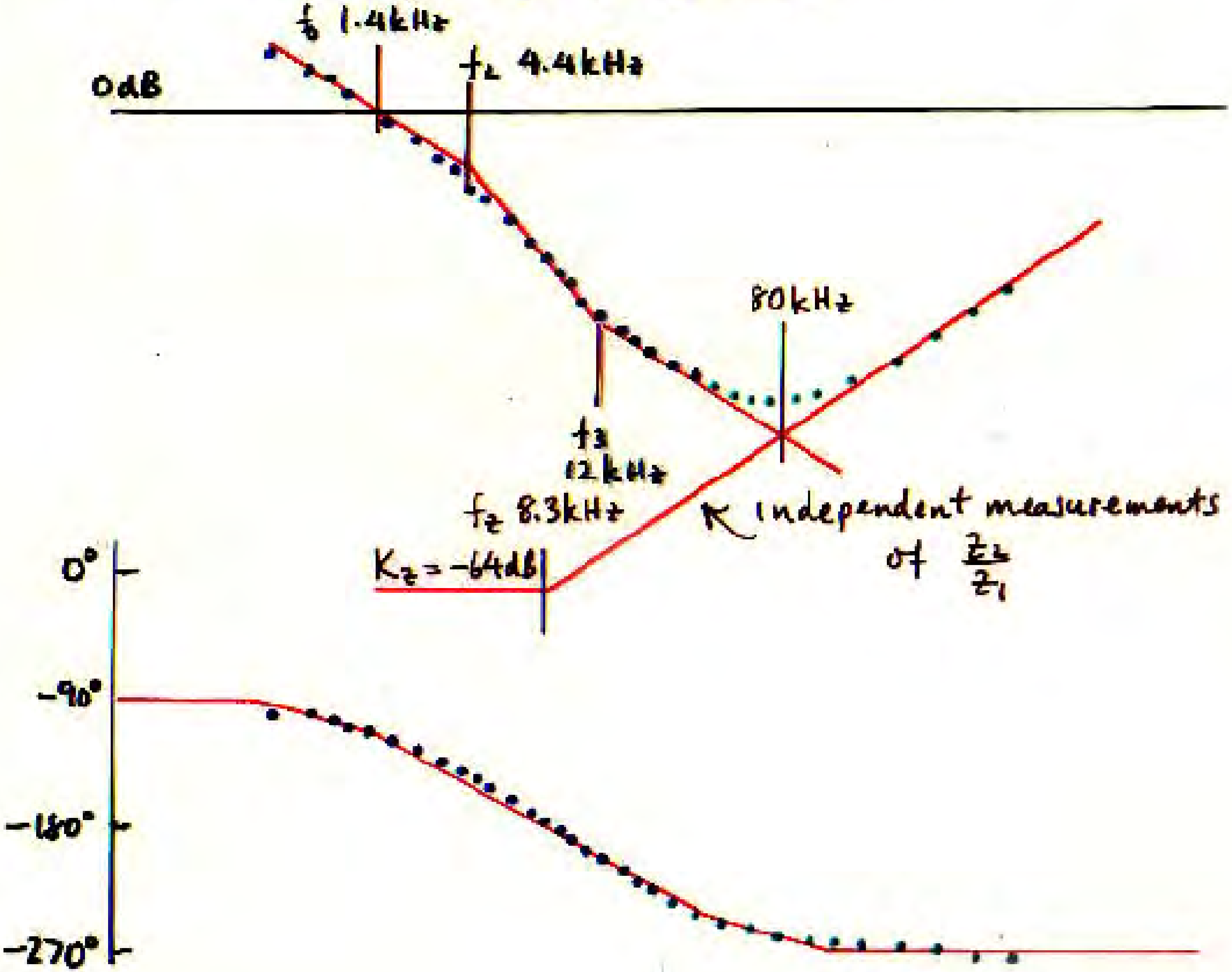
Example of T_v not being equal to T: the previous opamp circuit at high frequencies.



Analytically:

$$T_v = \left(1+\frac{Z_2}{Z_1}\right)T + \frac{Z_2}{Z_1} \approx T + \frac{Z_2}{Z_1}$$

$$= \frac{1-\frac{s}{\omega_3}}{\frac{s}{\omega_0}\left(1+\frac{s}{\omega_2}\right)} + K_z\left(1+\frac{s}{\omega_z}\right)$$

In the neighborhood of the crossover:

$$T_v = \frac{-\frac{s}{\omega_3}}{\frac{s}{\omega_0}\cdot\frac{s}{\omega_2}} + K_z\frac{s}{\omega_z}$$

$$= \frac{-\frac{s}{\omega_3}\left[1-\left(\frac{s}{\omega_c}\right)^2\right]}{\frac{s}{\omega_0}\cdot\frac{s}{\omega_2}}$$

where

$$\omega_c \equiv \sqrt{\frac{\omega_0\,\omega_2\,\omega_z}{K_z\,\omega_3}} \qquad f_c = 81\,\text{kHz}$$

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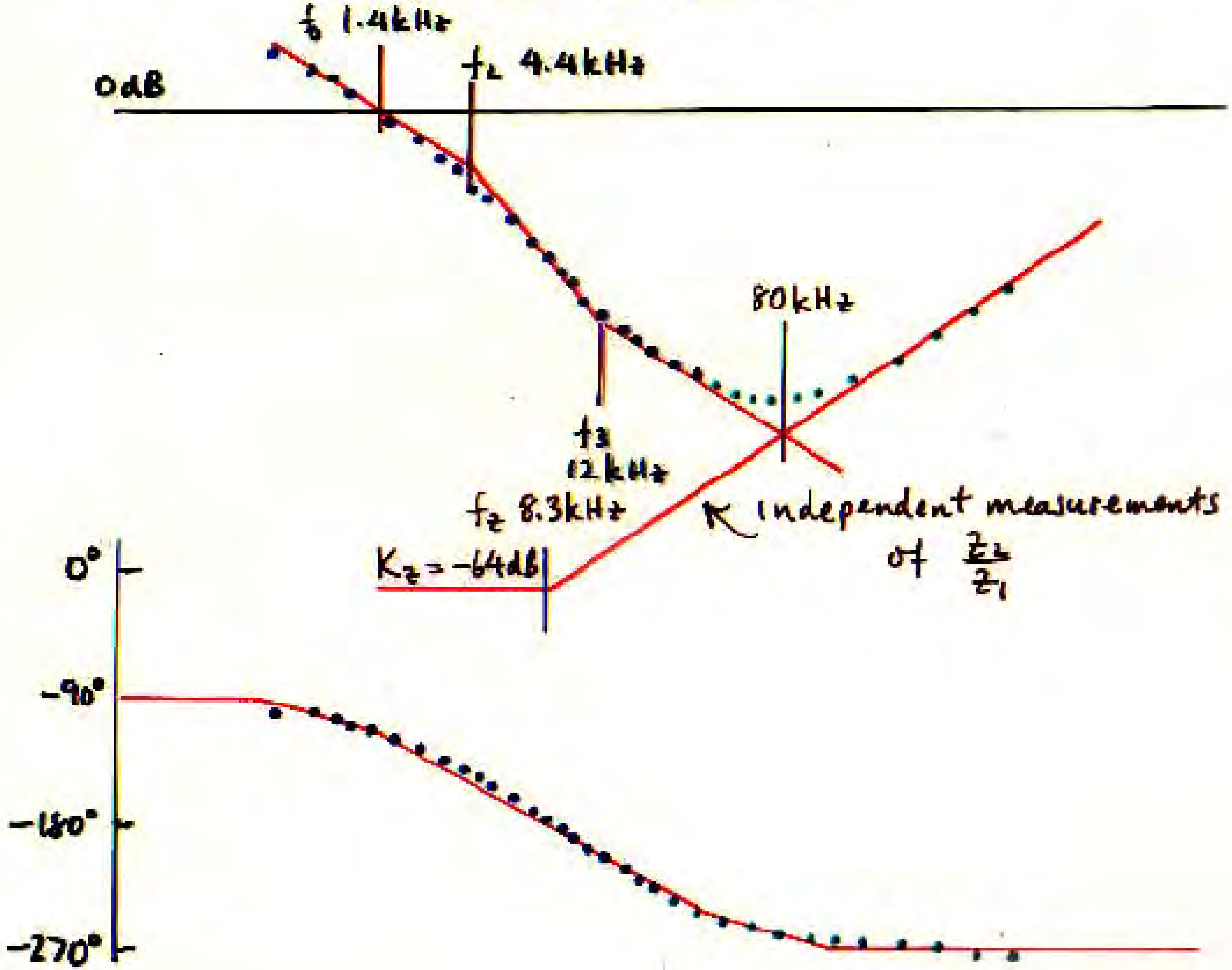

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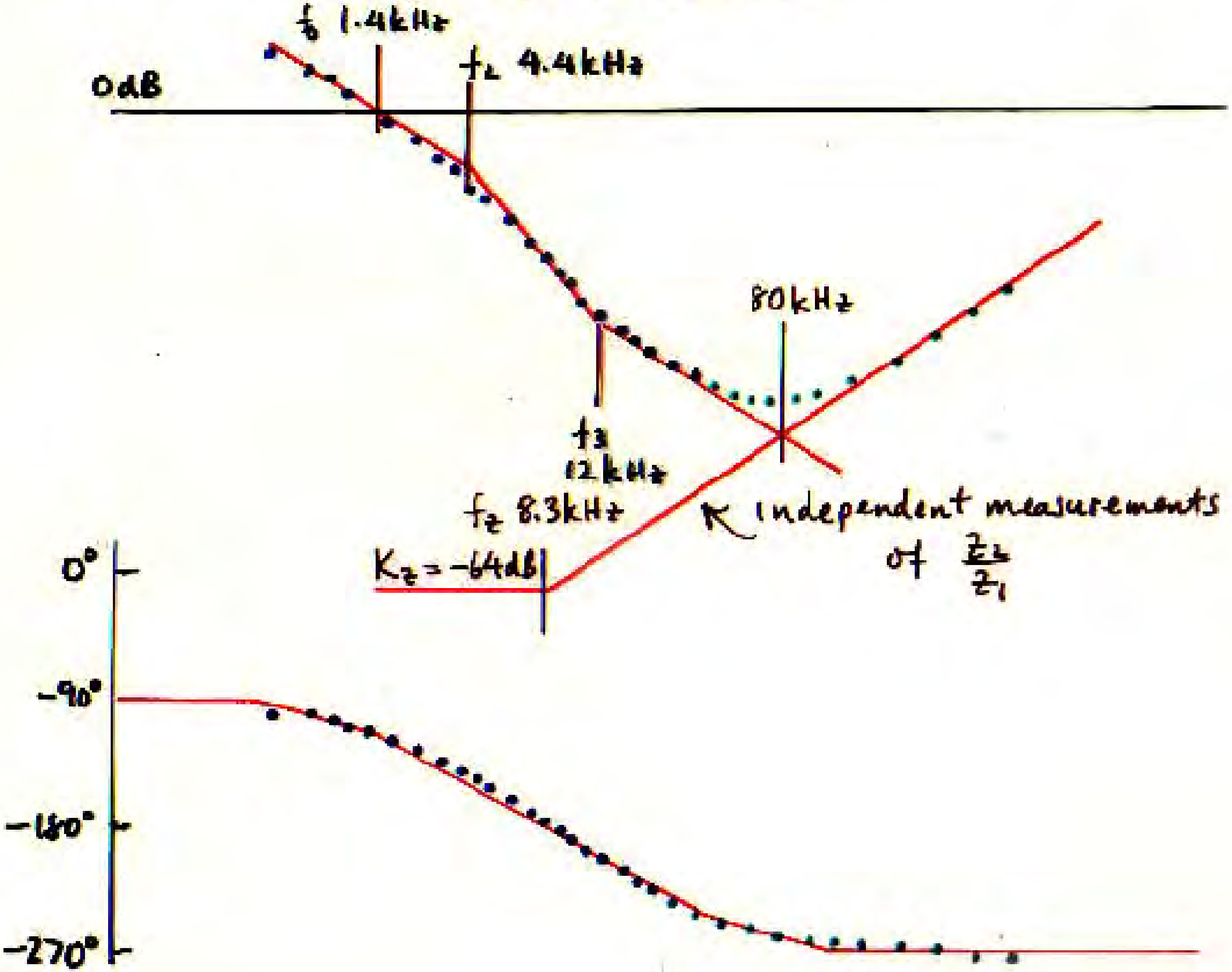

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where

$$\omega_c \equiv \sqrt{\frac{\omega_0\,\omega_2\,\omega_z}{K_z\,\omega_3}}$$

$f_c = 81\,\text{kHz}$

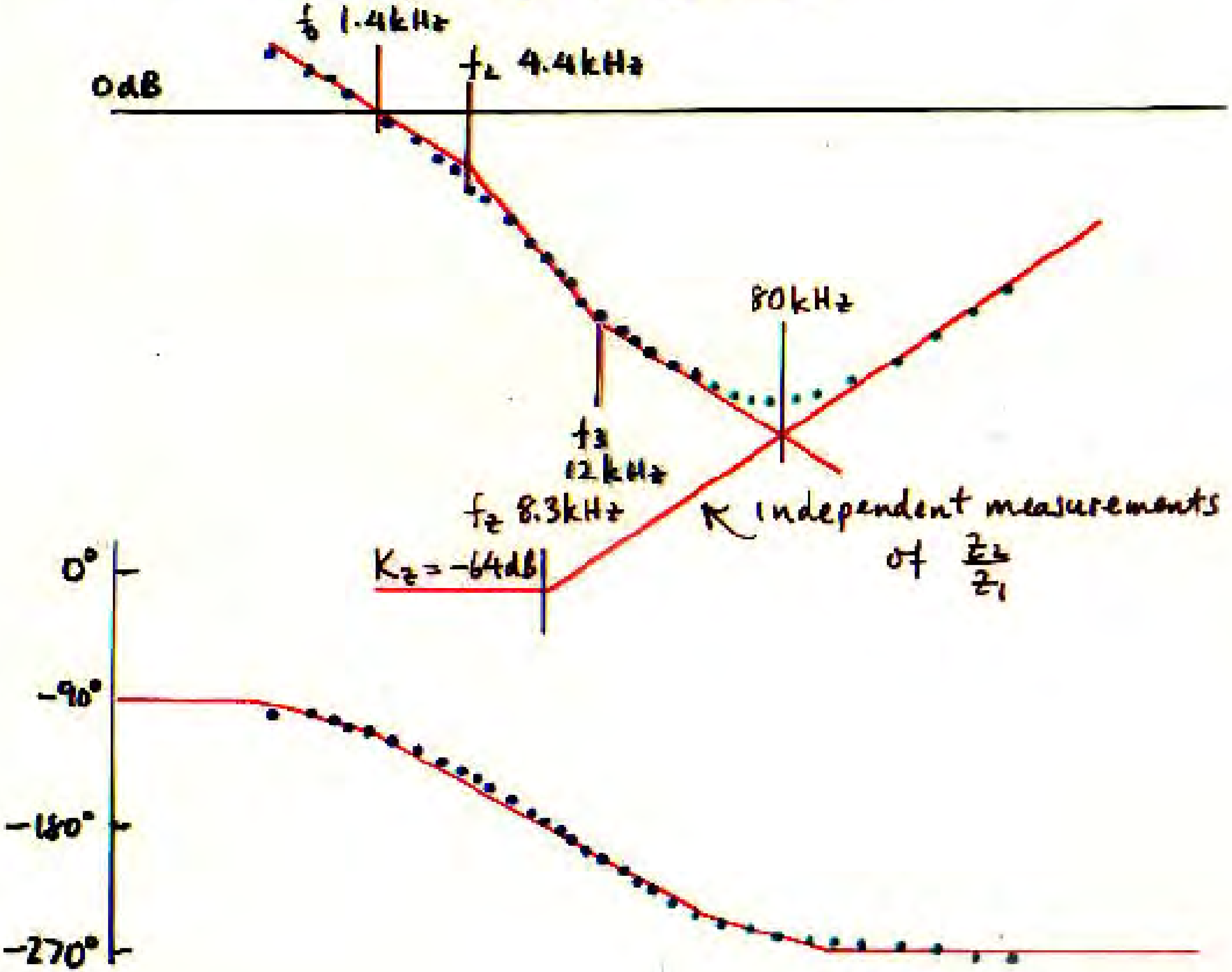
Hence, over the entire frequency range:

$$T_v = \frac{\left(1-\frac{s}{\omega_3}\right)\left(1+\frac{s}{\omega_c}\right)\left(1-\frac{s}{\omega_c}\right)}{\frac{s}{\omega_0}\left(1+\frac{s}{\omega_2}\right)}$$

This is the same as the original T multiplied by a correction factor having a lhp and a rhp zero at the same frequency. This causes the change of magnitude slope from the original, without a change of phase asymptote.

Hence, the true T is as previously determined, but the deviation of the measured T_v at high frequencies results from Z_2/Z_1 no longer being small compared to T.

Example of T_v not being equal to T: the previous opamp circuit at high frequencies.



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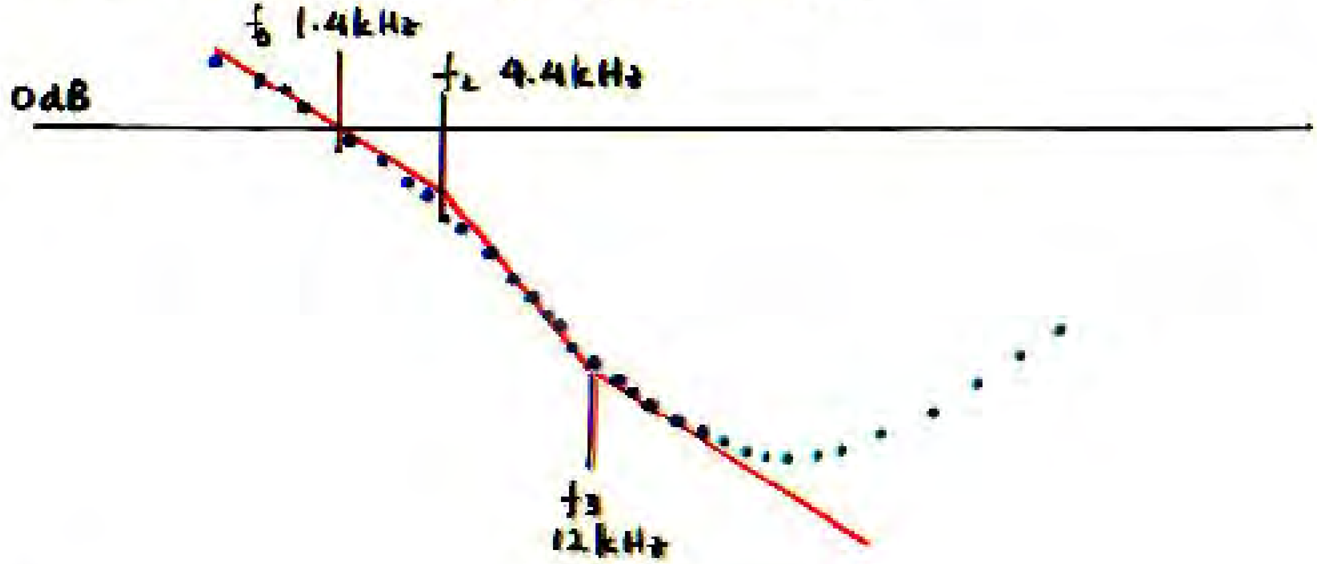


Generalization: Loop Gain Test Signal Injection at a Nonideal Point

In order to satisfy the requirement that injection of the test signal should add to the forward signal without affecting the loading, the following conditions are required, where Z_1 is the impedance looking "forward" from the injection point, and Z_2 is the impedance looking "backwards" from the injection point:

1. For series voltage injection:

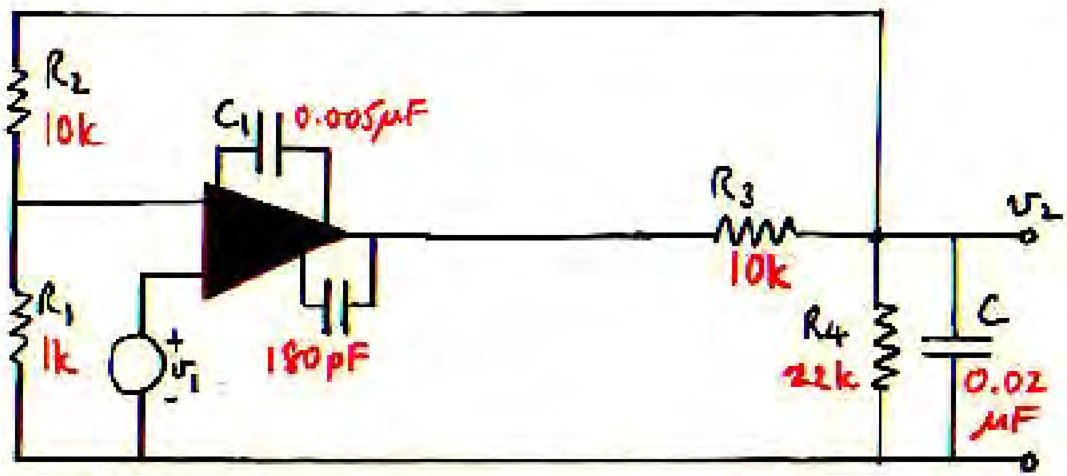
$$\frac{Z_2}{Z_1} \ll 1, \qquad \frac{Z_2}{Z_1} \ll T$$

2. For shunt current injection:

$$\frac{Z_1}{Z_2} \ll 1, \qquad \frac{Z_1}{Z_2} \ll T$$

Measurement of an unstable loop gain.

Suppose the following amplifier has been designed:



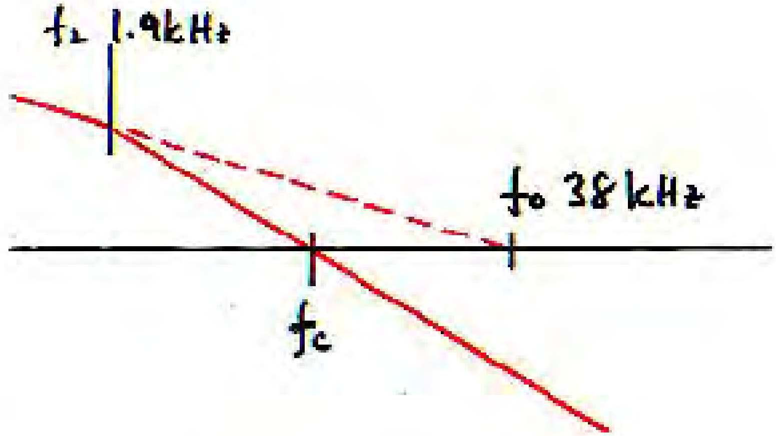
Predicted loop gain: $T = A_1 A_2 K_0 \dfrac{1}{1+\frac{s}{\omega_2}}$

where $A_1 = \dfrac{\omega_a}{s}$, $f_a = 1MHz$ $\quad A_2K_0 = \dfrac{R_4\|(R_1+R_2)}{R_3+R_4\|(R_1+R_2)} \dfrac{R_1}{R_1+R_2} = 0.038$

$$\omega_2 = \frac{1}{C[R_3\|R_4\|(R_1+R_2)]} \qquad f_2 = 1.9kHz$$

Hence $T = \dfrac{1}{\frac{s}{\omega_0}\left(1+\frac{s}{\omega_2}\right)}$

where $\omega_0 = A_2 K_0 \omega_a$ $\quad f_0 = 0.038 \times 1 = 38 kHz$



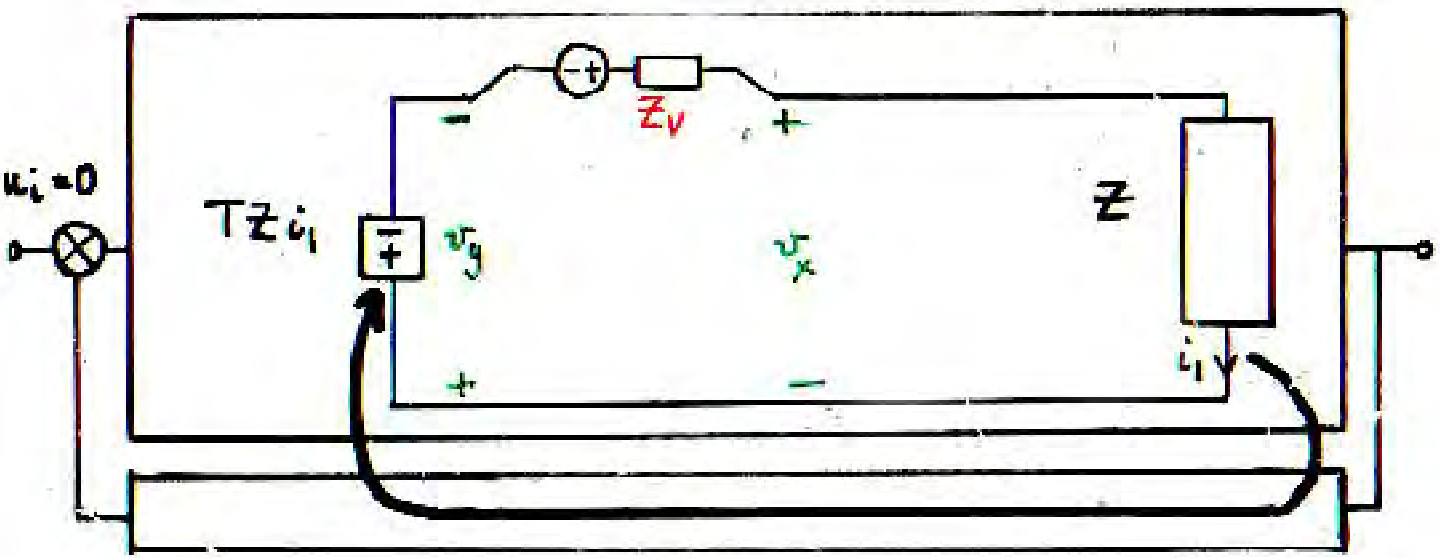
The Q of the quadratic in $T/(1+T)$ is

$$Q = \sqrt{\frac{\omega_0}{\omega_2}} = \sqrt{\frac{38}{1.9}} = 4.5 \Rightarrow 13\,dB$$

Hence $\phi_M = 14°$

Since f_c is far from f_2, the actual crossover frequency is essentially f_c, so ϕ_M can be checked directly from:

$$\phi_M = 180 + \angle T\big|_{f=f_c} =$$



Loop gain by injection of a test signal at an "ideal" point:

$$T_v \equiv \frac{v_y}{v_x} = T \quad \longleftarrow \quad \begin{cases} v_y = TZi_1 \\ i_1 = \dfrac{v_x}{Z} \end{cases}$$

regardless of Z_V

However, the actual circuit is unstable.

Objective: find a way to stop the oscillation without changing the measurement of the original unstable T.

Solution: Insert a sufficient impedance Z_v in series with the injected voltage source that is to be used to measure T. As already seen, this impedance Z_v does not affect the measurement of T, but can be made large enough to stop the oscillation.

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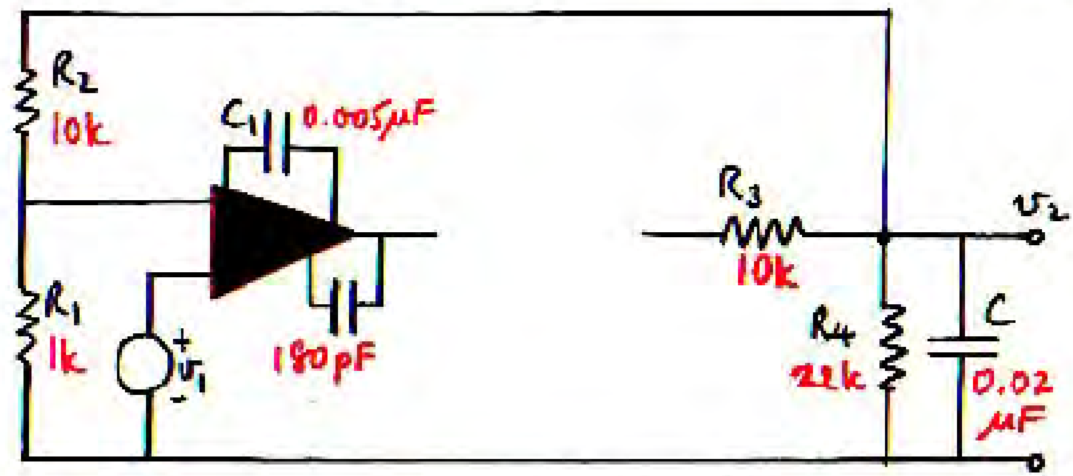

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Hence $T = \frac{1}{\frac{s}{\omega_0}\left(1+\frac{s}{\omega_2}\right)}$

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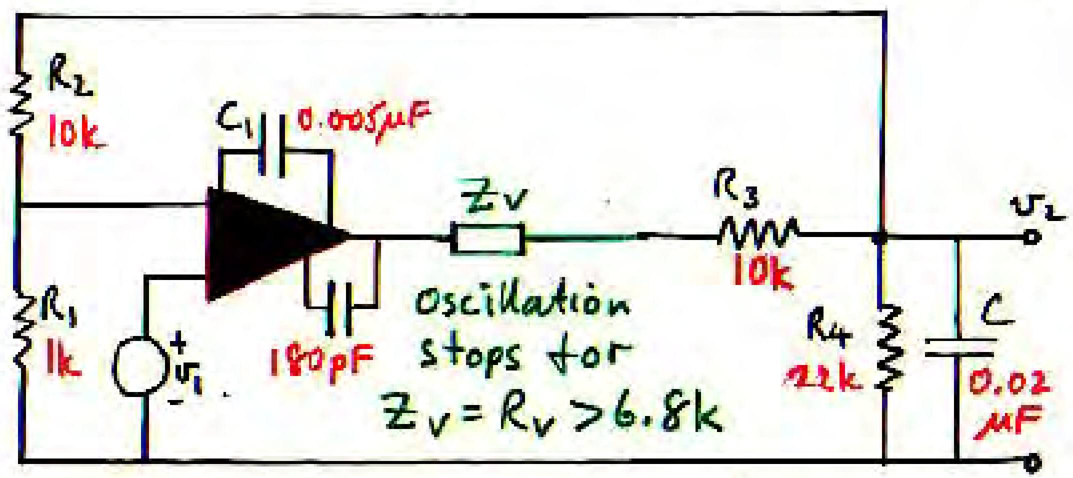

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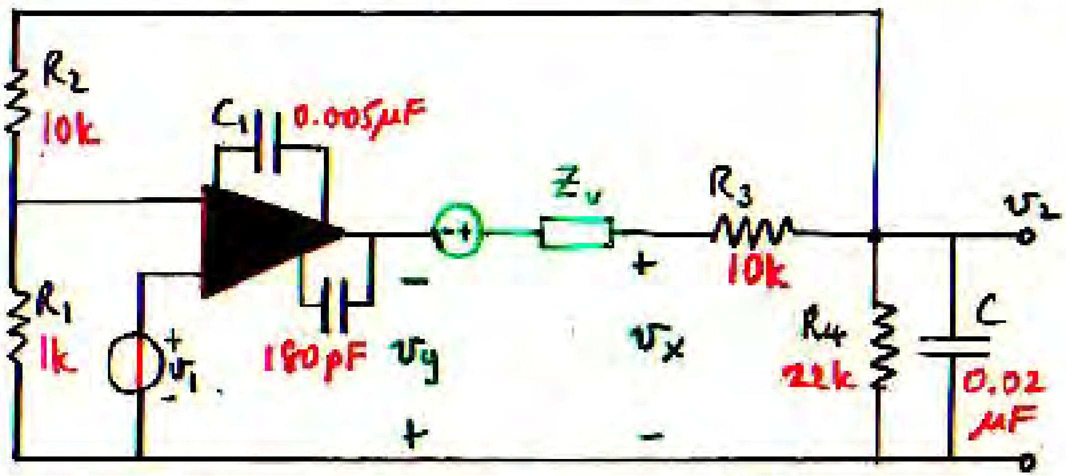

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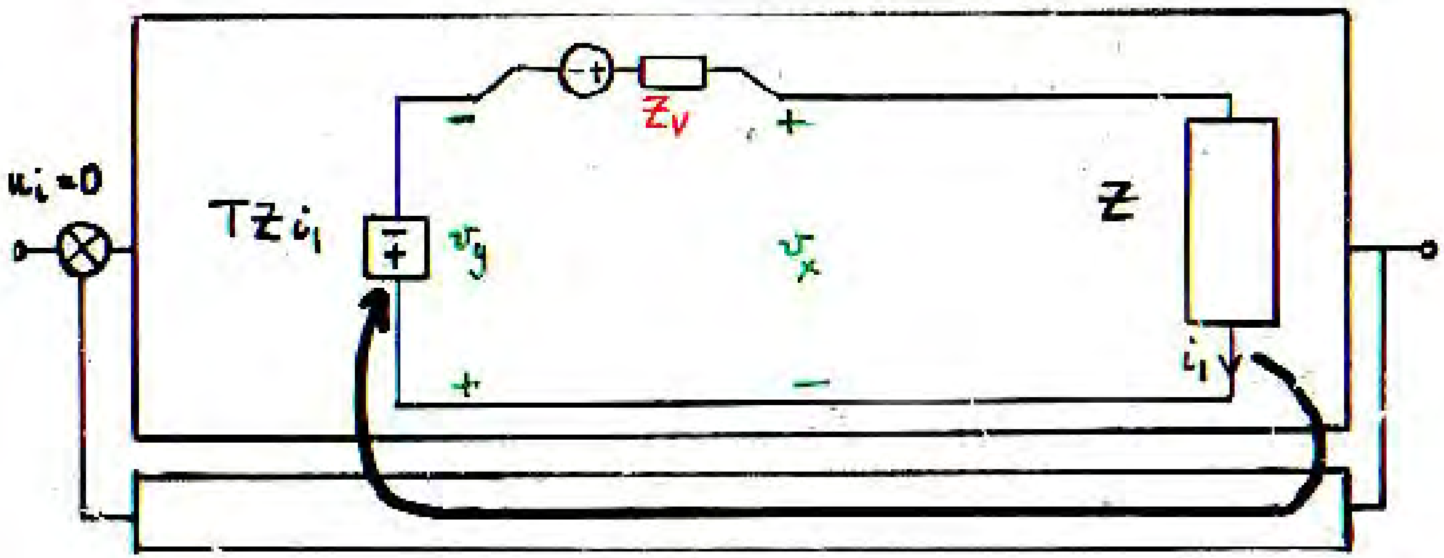

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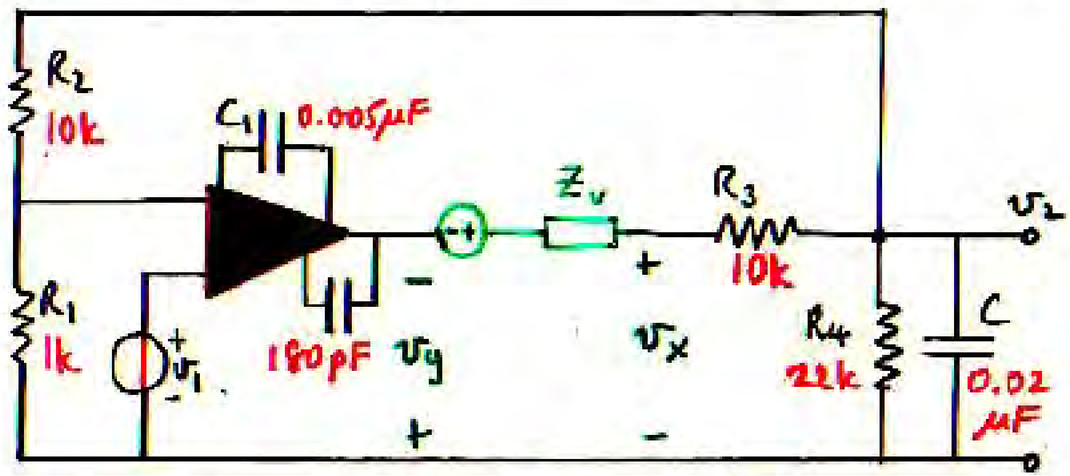

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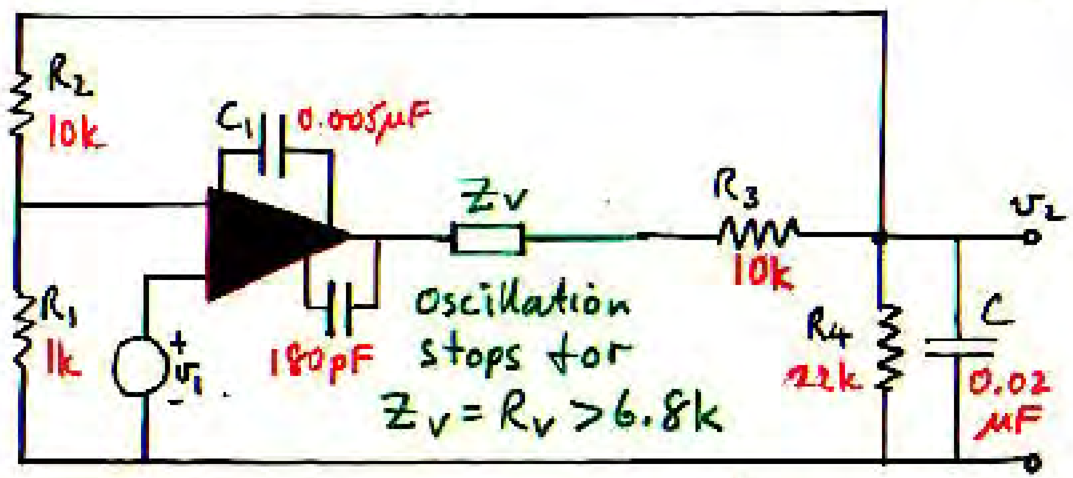

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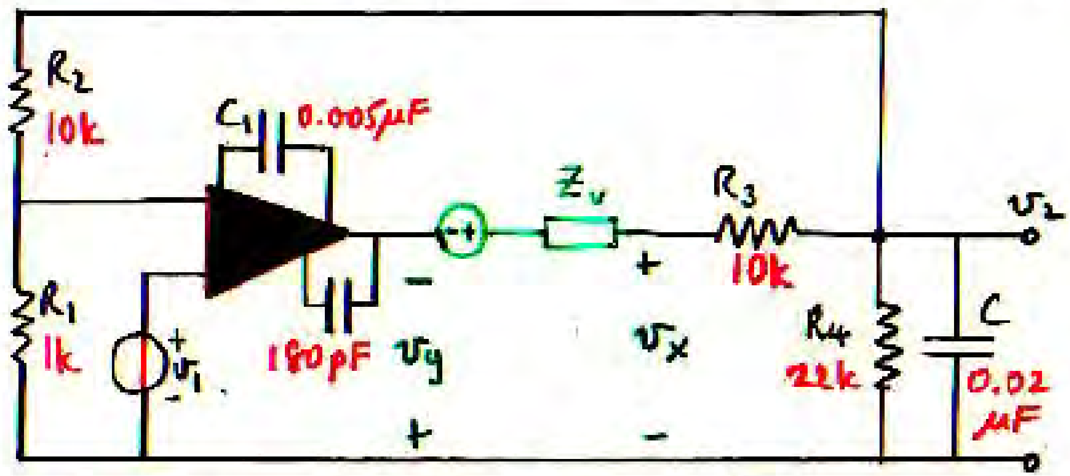

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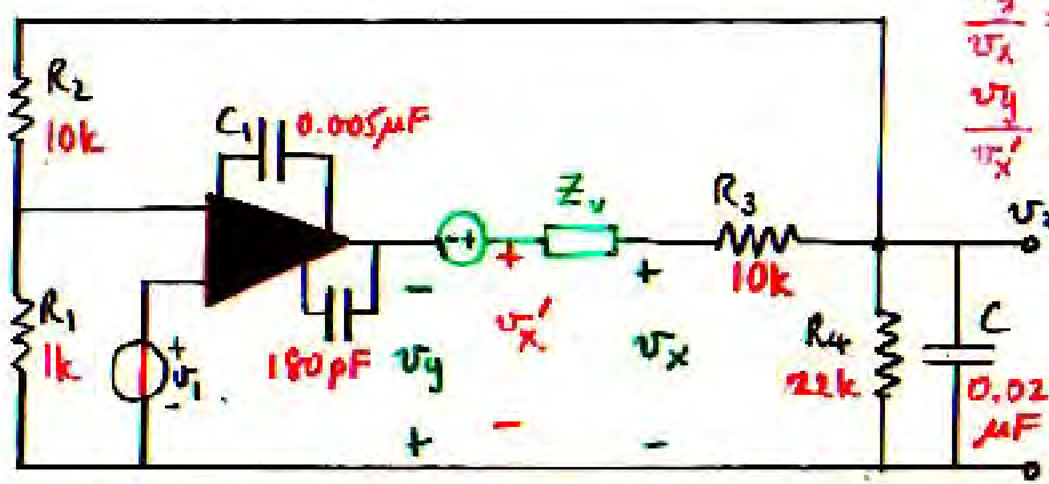
Measurement of an unstable loop gain.

Suppose the following amplifier has been designed:

$\frac{v_y}{v_x} = T(\text{old})(\text{unstable})$

$\frac{v_y}{v_x'} = T(\text{new})(\text{stable})$



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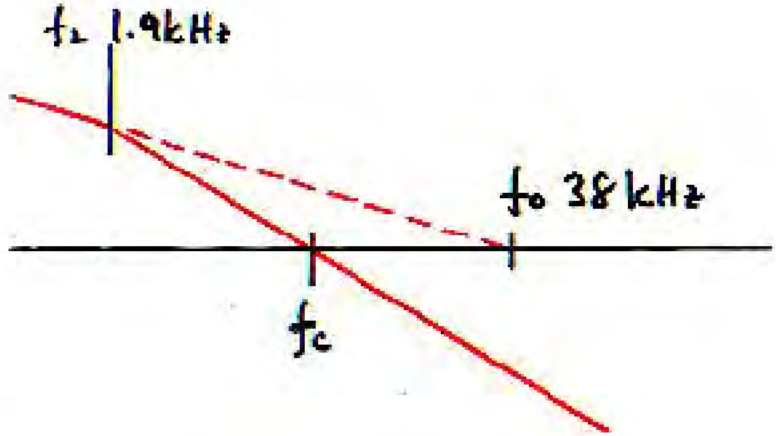

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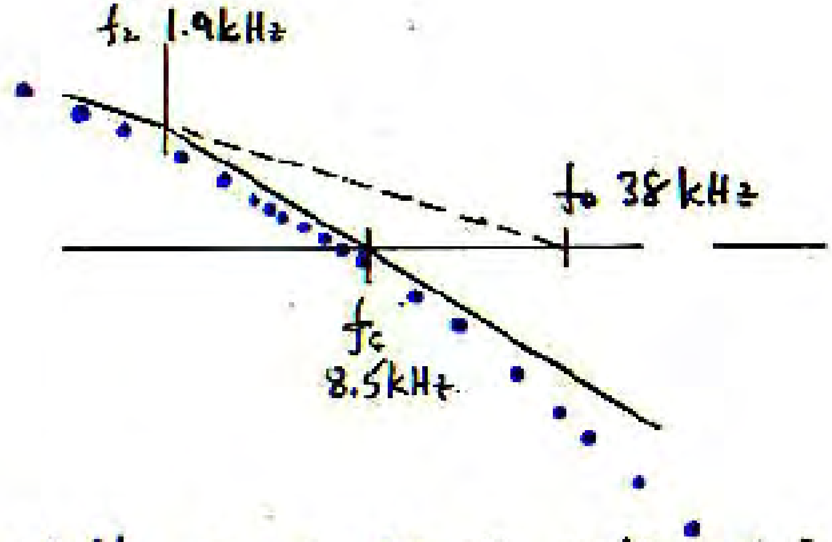

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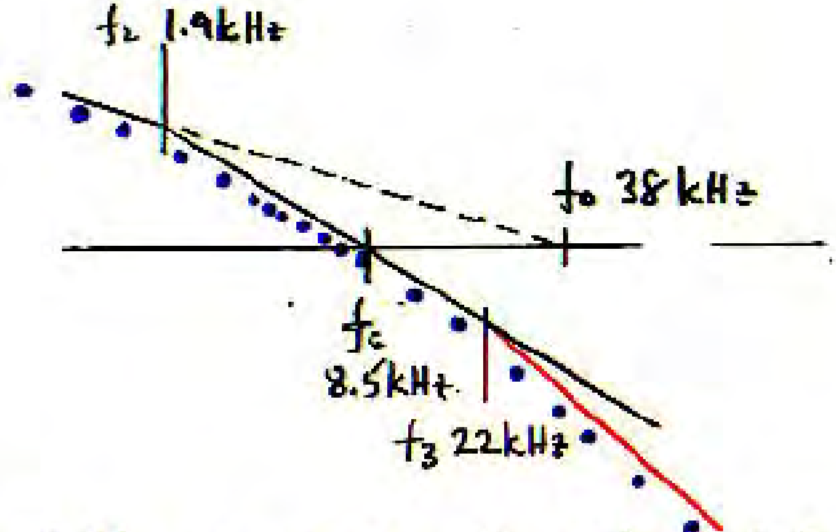

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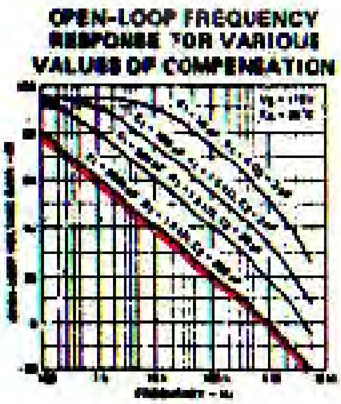
There is actually a third pole at $f_3 = 22\,kHz$, giving an additional phase lag at the crossover frequency of $\tan^{-1}\frac{8.5}{22} = 21°$.

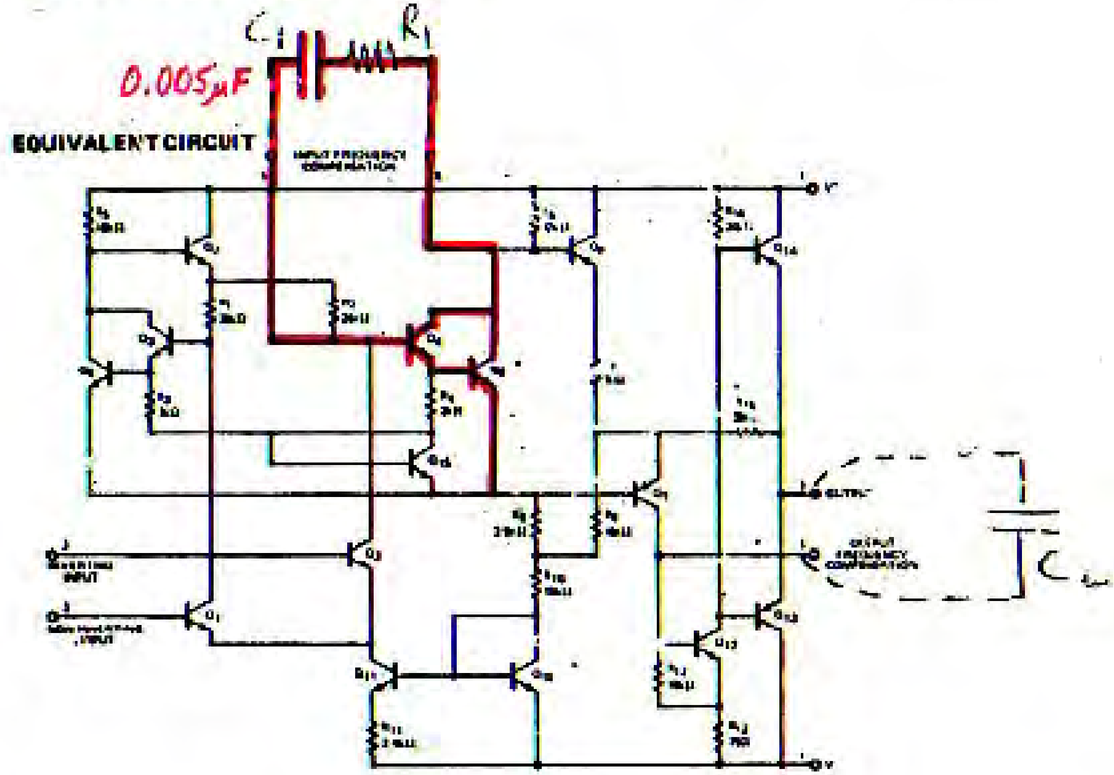
Hence, the actual phase margin is

$$\phi_M = 14° - 21° = -7°$$

and the circuit is unstable.

In the normal design–analyze–measure sequence, the loop gain T is first predicted analytically.





With a 0.005uF compensating capacitor C_1, the gain-bandwidth product is 1 MHz

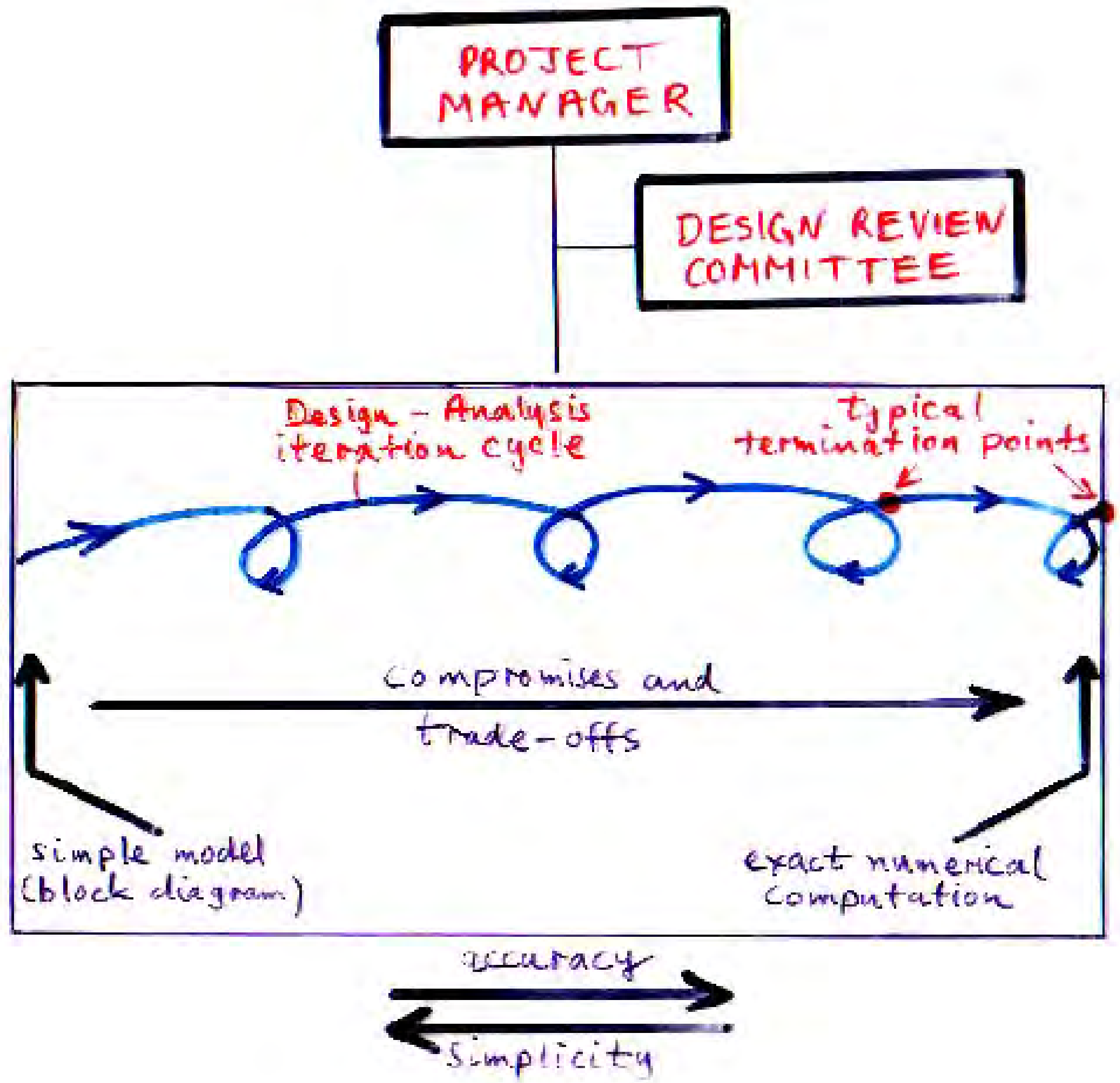
The third pole at f_3 occurs because the 1.5k resistance in series with the 709 compensating capacitor $C_1 = 0.005\,\mu F$ was omitted; this should provide a zero at $159/0.005 \times 1.5 = 22\,kHz$ that is to compensate an internal pole at 22 kHz. This is the observed pole that was omitted from the prediction, and caused the instability.

Generalization: Measurement of Loop Gain in an Unstable System

The system can be made stable without affecting the measurement of the original unstable loop gain:

At the point where signal injection is to be done, insert a sufficient impedance to stop the oscillation. Then, inject the test signal and measure the original unstable loop gain on either side of the combination test signal source and stabilizing impedance.

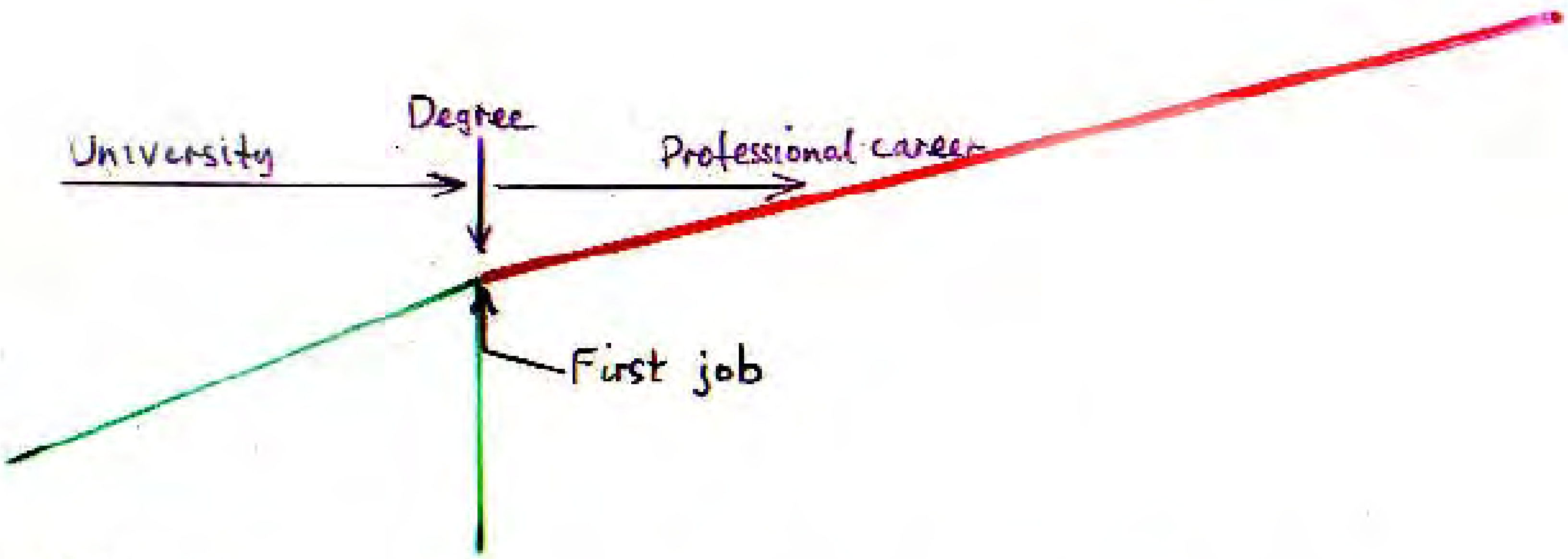
This result also implies that the source impedance of the test signal is irrelevant in the measurement of any loop gain, stable or not.


PROJECT MANAGER
DESIGN REVIEW COMMITTEE
Design - Analysis iteration cycle
typical termination points
compromises and trade-offs
simple model (block diagram)
exact numerical computation
accuracy
simplicity

Problem:

New graduate engineers are unable to translate the principles and methods they have learned to the real world.

What can be done?



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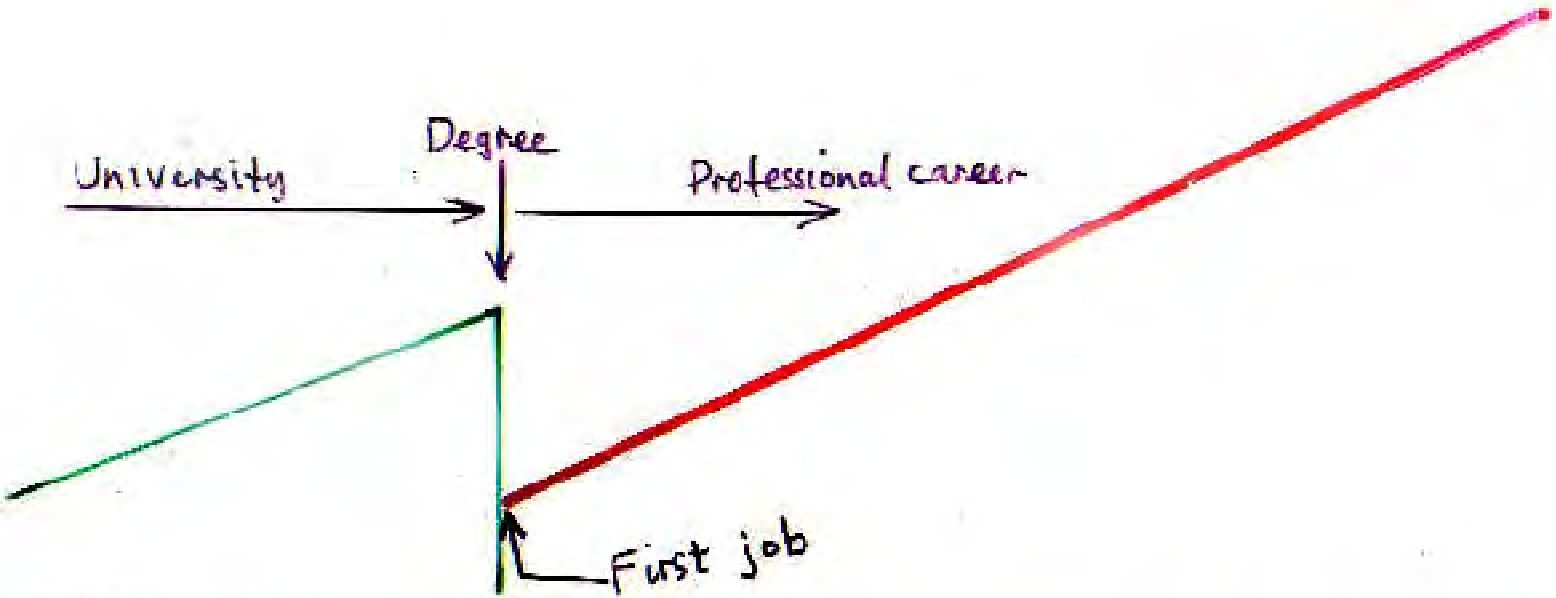

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