Developing and Delivering Online Course Material

Professor Al Gasiewski

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My Background in Remote Instruction

- Georgia Inst. of Technology video course on “Instrumentation for Test and Evaluation” (1993)
  - VHS video tapes
  - Sent using a new service called “Fedex”

- Five courses at CU (1 UG, 4 G)
  - EM Radiation and Antennas (ECEN 5134)
  - Stochastic Environmental Signal Processing (ECEN 5244)
  - Remote Sensing Signals & Systems (ECEN 5254)
  - Electromagnetic Absorption, Scattering, and Propagation (ECEN 5264)
  - Circuits as Systems (Circuits II, ECEN 2260)

- ECEN 5244 MOOC under development

My Philosophy of Remote Instruction

- How do we define **Quality**?

A property which someone wants.

The problem in course development is that Quality is most readily apparent in student success after (sometimes years after) the course is completed.

- Why is this the case?

Because a valuable course (i.e., one of high academic quality) is necessarily both complex and challenging.

My Philosophy of Remote Instruction

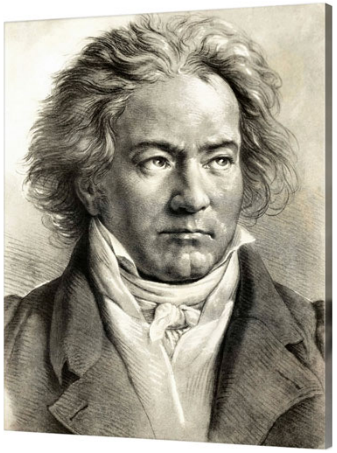
A quality course provides an experience that changes a student.

A student should not think the same way after taking a quality course (about the subject material, that is).

Symphonic Quality and Complexity

Why do certain symphonies endure?

What do they exhibit?



- Deep complexity but uniform balance
- Ring of truth throughout each movement
- Precision in composition

The same can be said to apply to much enduring popular music, classic and modern literature, etc…

Q: How does this notion of symphonic quality and complexity apply to our development of online course material?

ECEN 2260 – Circuits as Systems / Circuits II - Spring 2020 Semester

Professor A.J. Gasiewski – ECOT 246 – gasiewsk@colorado.edu

Schedule of Lectures, Assignments, and Exams (Revised 4/6/20)

Lectures: ECCR 1B40 MWF 9:00-9:50 AM Office Hours: 10:30 AM-12:00 Noon

ELAs : Steven Im Office Hours: T1-2, 3:15-4 pm & WF2-3:30 pm SRC (ECEE 1B08)

Kaiyuan Hou Office Hours: TTh 3-5 pm & W 2-4 pm SRC (ECEE 1B08)

Graders: Natalie Betts, Sunandhitha Venkatachari

Note: All lectures and office hours via Zoom telecon after 3/10/20

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
12 January	***13*** **Lecture #1** Introduction & objectives Administrative issues Review of RC transient response	***14***	***15*** **Lecture #2** RC filter steady state response Phasor impedance Phasor analysis of RC filter ***TRT 7-1 to 7-4, 8-1 to 8-3***	***16***	***17*** **Lecture #3** Circuit phasor analysis RL circuit ***TRT 7-1 to 7-4, 8-1 to 8-3*** **HW#1 Issued**	***18***
19	***20*** ***MLK Day***	***21***	***22*** **Lecture #4** Series RLC circuits Transients, overdamping, underdamping, critical damping ***TRT 7-5, 8-3 to 8-4***	***23***	***24*** **Lecture #5** Series RLC phasor circuit Sinusoidal resonance Input impedance Energy and power ***TRT 8-3 to 8-4*** **HW#1 Due**	***25***
26	***27*** **Lecture #6** Maximum available power Load-source matching Loop & mesh phasor analysis Impedance bridge ***TRT 8-5 to 8-6,*****HW#2 Issued**	***28***	***29*** **Lecture #7** Intro to Laplace transforms Laplace transform properties Step, delta, exponential, Linearity, cos, sin ***TRT 9-1 to 9-4***	***30***	***31*** **Lecture #8** Laplace transform properties Integration, differentiation, translation Transfer function for R, L, C ***TRT 9-6 to 9-7***	***1 February***
2	***3*** **Lecture #9** Circuit analysis in *s*-domain Series RLC circuit step response Partial fraction expansion Cover up algorithm ***TRT 9-4 to 9-7, 10-1, 11-1*** **HW#2 Due, HW#3 Issued**	***4***	***5*** **Lecture #10** Series RLC circuit /step input Critical damping and ramp exponential response Relation to damping factor & natural frequency ***TRT 9-4 to 9-7, 10-1 , 11-1***	***6***	***7*** **Lecture #11** Network functions: Impedance Series RLC current Time shift property Boxcar pulse function ***TRT 9-5 to 9-7, 10-1 to 10-3***	***8***
9	***10*** **Lecture #12** Network functions: Transfer Series RLC pulse response *s*-domain loop and mesh analysis Admittance impulse response ***TRT 11-1 to 11-2*** **HW#3 Due, HW#4 Issued**	***11***	***12*** **Lecture #13** Series & parallel RLC circuits General Laplace inversion Proper rational functions Special cases: improper fractions, multiple poles, complex poles, repeated poles ***TRT 9-4 to 9-5***	***13***	***14*** **Lecture #14** Initial conditions and superposition Zero input and zero state response Source transformation ***TRT 10-1 to 10-6***	***15***

16	***17* Lecture #15** Controlled sources Inverting op amp Non inverting op amp ***TRT 10-1 to 10-2*** **HW#4 Due**	***18***	***19* Lecture #16** Feedback Sallen Key topology Effect of gain on op-amp pole ***TRT 10-1 to 10-2*** ***(TA Review Session: Evening, Eng. Center)***	***20*** ***(TA Review Session: Evening, Eng. Center)***	***21*** **Midterm Exam #1**	***22***
23	***24* Lecture #17** SSS frequency response Use of transfer functions Bode diagrams, deciBels ***TRT 11-3 to 11-6*** **HW#5 Issued**	***25***	***26* Lecture #18** Multiple pole & zero Bode diagrams Impulse response Convolution ***TRT 11-6 to 11-7, 12-1 to 12-2***	***27***	***28* Lecture #19** LPF impulse response LPF pulse convolution example Graphical interpretation HPF impulse response HPF pulse convolution example ***TRT 11-5 to 11-7, 12-1 to 12-3***	***29***
1 March	***2* Lecture #20** Impedance impulse response Equivalence of *s*-domain & convolution Step response Relationship to impulse response ***TRT 11-5 to 11-7,*** ***12-1 to 12-3***	***3***	***4* Lecture #21** Second order RLC Second order RLC response Bode diagram interpretation ***TRT 12-8***	***5***	***6* Lecture #22** RLC BPF, Q factor Bode diagrams Real and complex poles/zeros ***TRT 12-6 to 12-7*** **HW#5 Due**	***7***
8	***9* Lecture #23** Band stop filter Transfer function synthesis ***TRT 12-6 to 12-7*** **HW#6 Issued**	***10***	***11* Lecture #24** Synthesis using op amps Loading and buffering Chain rule & block diagrams Dispersion compensation ***TRT 11-1 to 11-2, 11-5, 12-3***	***12***	***13* Lecture #25** Dispersion compensation Electrical/mechanical analogs Suspension systems ***TRT 11-5*** ***Notes on Analogs by DGM***	***14***
15	***16* Lecture #26** Electrical/mechanical analogs DC motors ***TRT 12-5***	***17***	***18* Lecture #27** Transducers Speakers & acoustics ***TRT 12-8***	***19***	***20* Lecture #28** *Transducers* *Microphones* Acoustic feedback Stability ***TRT 12-3, 12-8***	***21***
22	***23*** **Break**	***24*** **Break**	***25*** **Break**	***26*** **Break**	***27*** **Break**	***28***

29	***30* Lecture #29** Fourier series Series form and coefficients Examples ***TRT 13-1 to 13-2*** **HW#6 Due**	***31***	***1 April* Lecture #30** Fourier series (cont'd) Odd and even symmetry Square wave, triangle wave Triangle waves and spectra of Fourier coefficients ***TRT 13-3*** **HW#7 Issued**	***2***	***3* Lecture #31** Fourier series (cont'd) Half-wave symmetry Pulse, delta, and sawtooth waveforms Comb generation ***TRT 13-3***	***4***
5	**6 Lecture #32** Fourier series (cont'd) Magnitude and phase Waveform filtering Harmonic generation **TRT 13-4**	***7*** ***(TA Review Session: Evening, via Zoom)***	***8* Lecture #33** Ideal diode waveform RMS and average power Full-wave rectifier ***TRT 13-5*** ***(TA Review Session: Evening, via Zoom)***	***9*** **Midterm Exam #2 7:00-8:30 PM (via Canvas)**	***10* Lecture #34** Filtering and filter design Sallen-Key 2nd order LP, HP ***TRT 14-1 to 14-2***	***11***
12	***13* Lecture #35** Filtering and filter design 2nd order bandpass, bandstop ***TRT 14-1 to 14-3*** **HW#7 Due** **HW#8 Issued**	***14***	***15* Lecture #36** Filtering and filter design First order cascade LPF Butterworth LPF ***TRT 14-4***	***16***	***17* Lecture #37** Filtering and filter design Chebyshev LPF ***TRT 14-4***	***18***
19	***20* Lecture #38** Filter transformations LP to HP, BP, BS ***TRT 14-4 to 14-7***	***21***	***22* Lecture #39** Feedback control circuits Feedback control system transfer function Op-amp as a feedback control system **HW#8 Due, HW#9 Issued**	***23***	***24* Lecture #40** Feedback control circuits Feedback system stability Phase margin	***25***
26	***27* Lecture #41** Phase locked loops Sinusoidal (AC) power Real, reactive, & complex power ***TRT 16-1 to 16-3***	***28***	***29* Lecture #42** Power factor & impedance Transformers Load flow and 3-phase Review of course ***TRT 16-4 to 16-6***	***30* LDOC** **HW#9 Due**	***1 May*** **Reading Day** ***(TA Review Session: Evening, via Zoom)***	***2***
3	***4*** ***(TA Review Session: Evening, via Zoom)***	***5*** **Final Exam 1:30-4:00 PM (via Canvas)**	***6***	***7***	***8***	***9***

Here's an Example Lecture

ECEN 2260
Circuits as Systems / Circuits II

Professor Albin J. Gasiewski

Lecture #28 – March 20, 2020

ECOT 246
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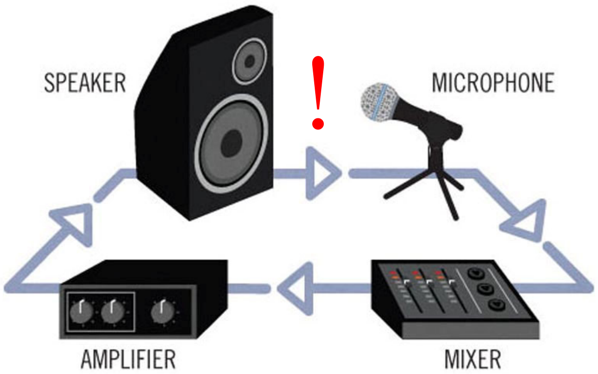
Classes: MWF 9:00-9:50 AM (Zoom telecon)

Public Address Systems

Audio for communications & entertainment
Frequency range 20-20,000 Hz
Power range of watts to 10’s of kilowatts
Small rooms to large outdoor events



Administration (1/2)

- HW6 issued on Canvas, due date postponed to Monday 3/30/20 by 11:59 pm
  - Please plan on submitting all homework assignments electronically via Canvas.
  - Either electronic or scanned paper versions are acceptable.

Administration (2/2)

- COVID-19 planning
  - We recognize the hardships that are being undertaken, and are committed to ensuring continuity of the course.
  - Lectures will be delivered and recorded by Zoom telecon. During Zoom lectures, **please MUTE your microphones**. Q&A will be taken at the end of the regular lecture and during office hours.
  - Office hours are being held at our regular times (MWF 10:30-12) by telecon. A recurring Zoom link is on Canvas.
  - **Practice smart social distancing**. Maintain at least a 2 m distance from others, use extreme personal hygiene. Avoid all gatherings outside of your immediate living group.
  - **Please follow CU, State of Colorado, and CDC guidelines, and stay alert for updates.**

Last Lecture

- Transducers
- Speakers & acoustics

Reading: TRT 12-8

Today's Lecture

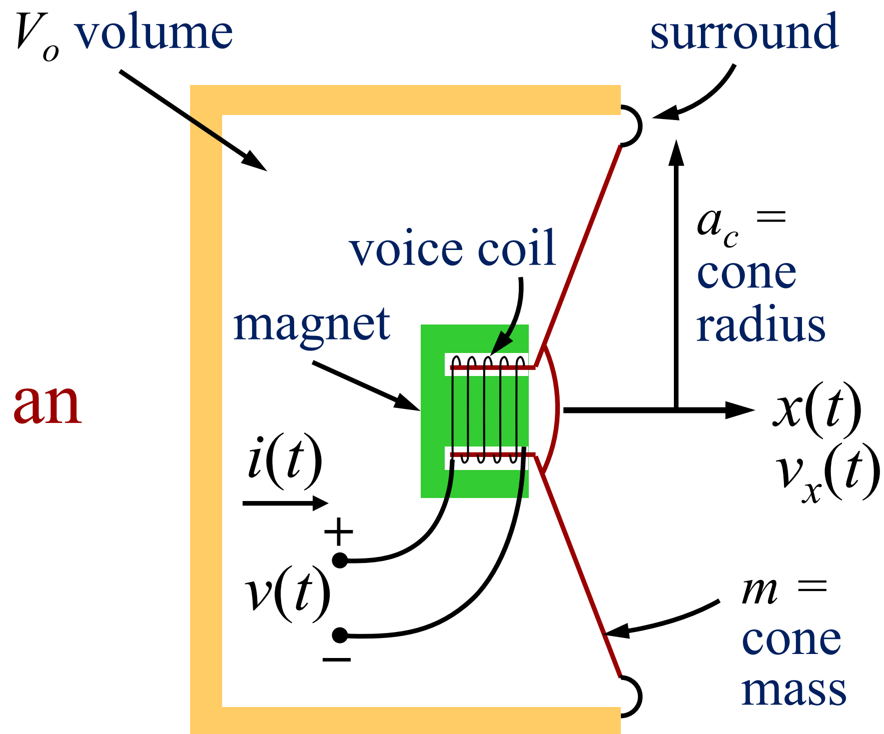
- Transducers
- Microphones
- Acoustic feedback
- Stability

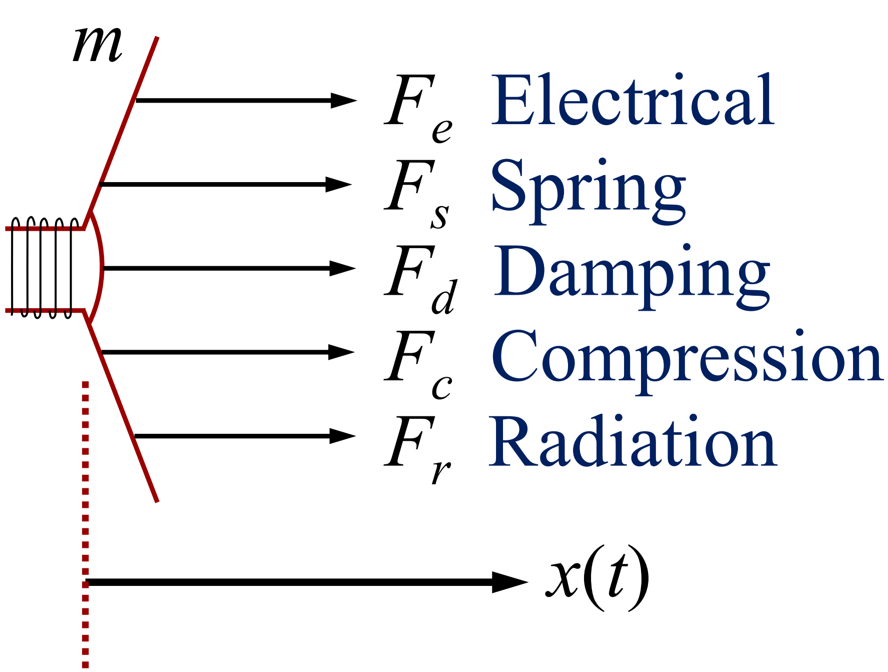
Reading: TRT 12-3, 12-8

Transducers

Electromechanical Transducers: Loudspeakers

We considered the permanent magnet loudspeaker with voice coil of N turns and cone radius a_c. A free body force diagram permitted analysis as an electro-mechanical system:





$$\sum F_x = m\frac{d^2x}{dt^2}$$

We considered each force, developed a differential equation, then transformed to an s-domain model…

Adding the Forces

Adding up the various forces yielded the differential equation of motion needed for *s*-domain analysis:

$$\begin{aligned}
\sum F_x &= m\frac{d^2x}{dt^2} = F_e + F_s + F_d + F_c + F_r \\
F_e &= 2\pi r_c N B i\left(t\right) \\
F_s &= -kx\left(t\right) \\
F_d &= -b\frac{dx}{dt} \\
F_c &= -\frac{\rho_o c_s^2 A_c^2}{V_o} x\left(t\right) \\
F_r &= -\rho_o c_s A_c \left[R_1\left(\frac{2\omega a_c}{c_s}\right)\frac{dx}{dt} + \frac{1}{\omega} X_1\left(\frac{2\omega a_c}{c_s}\right)\frac{d^2x}{dt^2}\right]
\end{aligned}$$

Electrical
Spring
Damping
Compression
Radiation

The mechanical parameters are m, r_c, b, k, a_c, N, B, V_o.

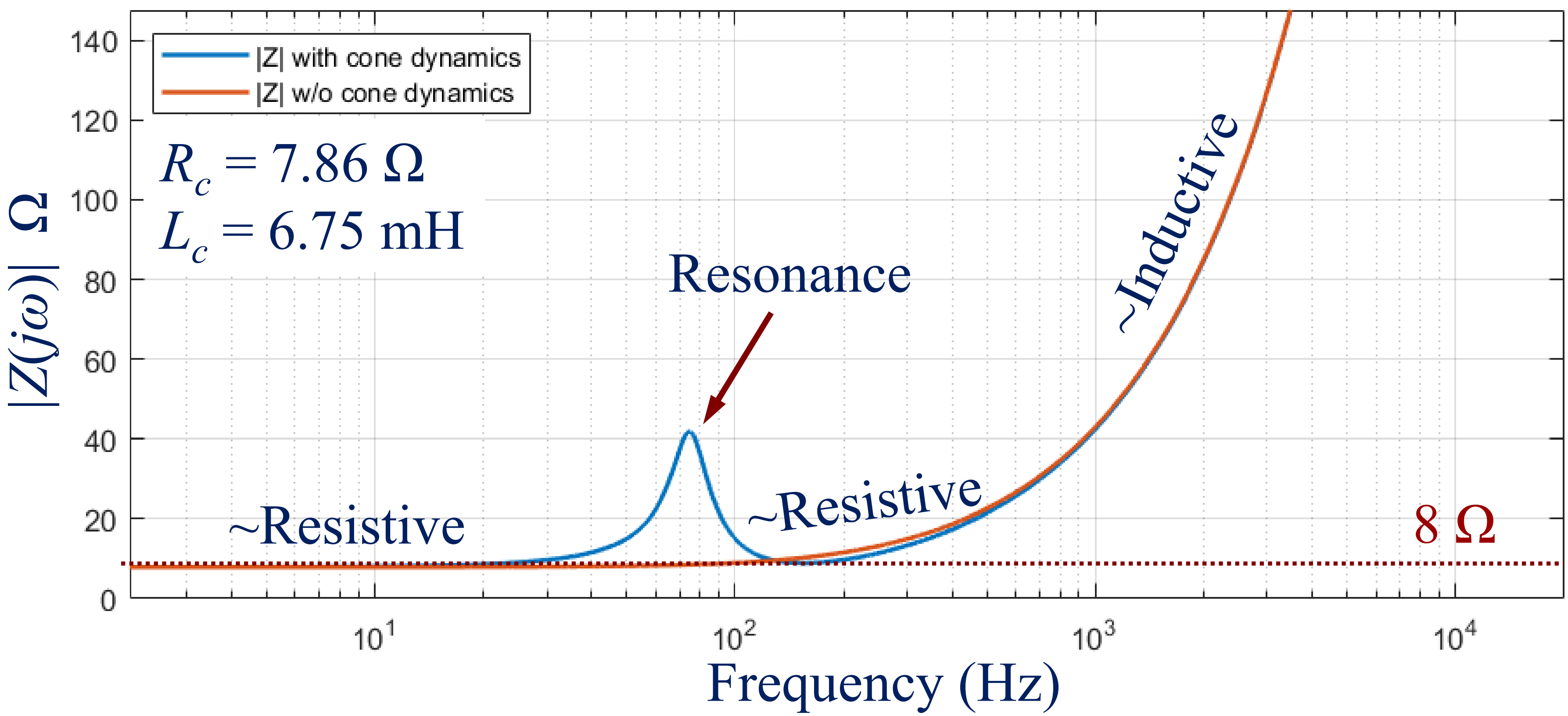
Loudspeaker Input Impedance

Plotted is the input impedance for some typical parameters:

$a_c = 10$ cm
$m = 20$ g
$b = 2.5$ kg/s
$k = 3000$ N/m

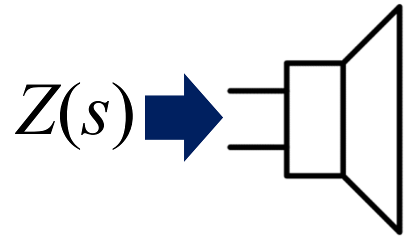
$B = 1$ T
$r_c = 1$ cm
$l_c = 3$ cm
$g_c = 1$ mm

$N = 150$ turns
#34 AWG
$\mu_c = 250\mu_o$ (H/m)
$V_o = 0.064$ m^3



Loudspeaker Equivalent Circuit

By considering the electrodynamics of the loudspeaker we found the input impedance to be:



$$
\begin{aligned}
Z(s) &= R_c + sL_c + \frac{(2\pi r_c N B)^2 s}{m_e s^2 + b_e s + k_e} \\
&= R_c + sL_c + \frac{(2\pi r_c N B)^2}{m_e} \frac{s}{s^2 + \frac{(2\pi r_c N B)^2 b_e}{(2\pi r_c N B)^2 m_e} s + \frac{(2\pi r_c N B)^2 k_e}{(2\pi r_c N B)^2 m_e}} \\
&= R_c + sL_c + \frac{1}{C} \frac{s}{s^2 + s\frac{1}{RC} + \frac{1}{LC}} = R_c + sL_c + Z_{||}(s)
\end{aligned}
$$

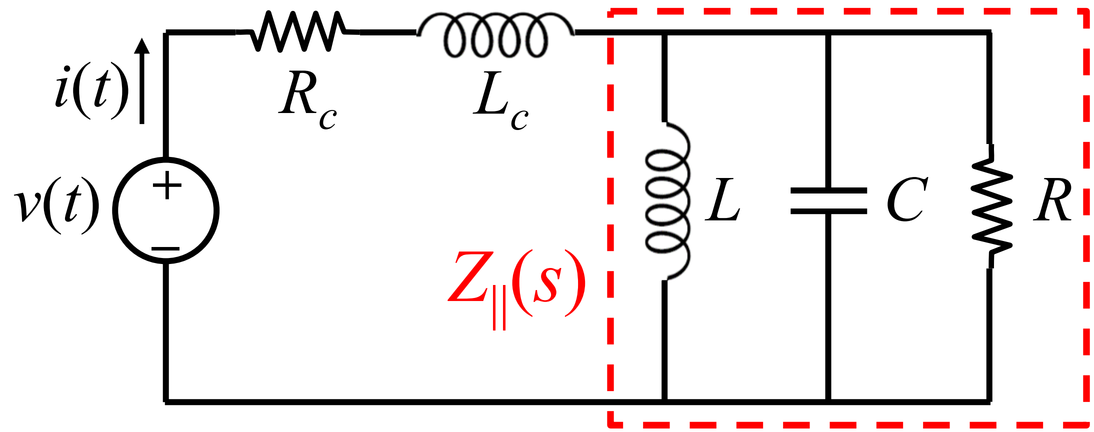
where the mechanical part of the impedance can be modeled by a parallel RLC circuit of impedance $Z_{||}(s)$ with the following identifications:

$$
L \leftrightarrow \frac{(2\pi r_c N B)^2}{k_e} \qquad C \leftrightarrow \frac{m_e}{(2\pi r_c N B)^2} \qquad R \leftrightarrow \frac{(2\pi r_c N B)^2}{b_e}
$$

An equivalent electrical circuit model follows…

Loudspeaker Equivalent Circuit

An equivalent electrical circuit incorporating the mechanical dynamics is:



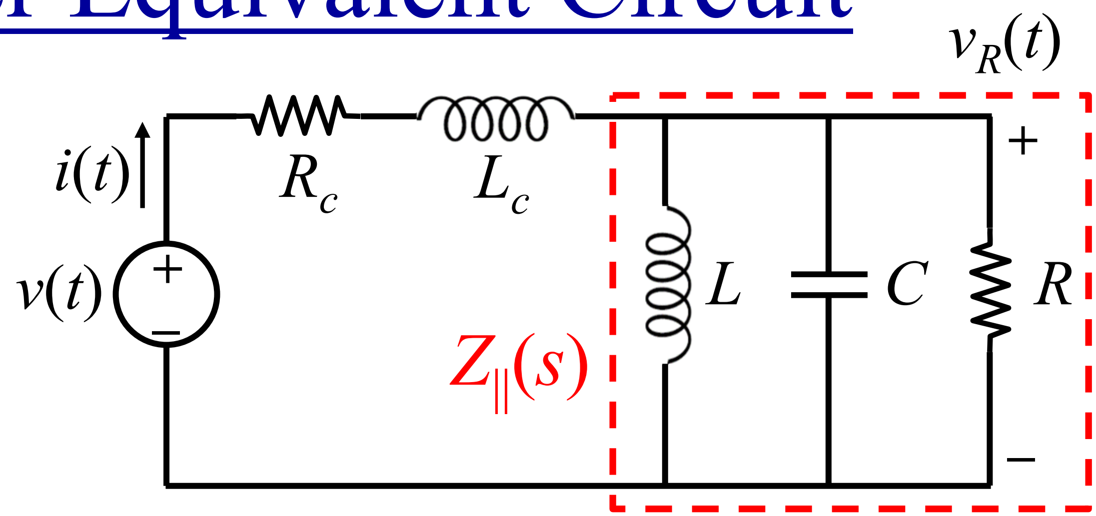
Where:

$$\begin{cases} m_e = m + \dfrac{\rho_o c_s A_c X_1}{\omega} \\ b_e = b + \rho_o c_s A_c R_1 \\ k_e = k + \dfrac{\rho_o c_s^2 A_c^2}{V_o} \end{cases} \quad \text{and} \quad \begin{cases} L = \dfrac{(2\pi r_c N B)^2}{k_e} = \dfrac{(2\pi r_c N B)^2}{k + \frac{\rho_o c_s^2 A_c^2}{V_o}} \\ C = \dfrac{m_e}{(2\pi r_c N B)^2} = \dfrac{m + \frac{\rho_o c_s A_c X_1}{\omega}}{(2\pi r_c N B)^2} \\ R = \dfrac{(2\pi r_c N B)^2}{b_e} = \dfrac{(2\pi r_c N B)^2}{b + \rho_o c_s A_c R_1} \end{cases}$$

This circuit provides the correct input impedance, but also can be used to determine the acoustic power radiated versus that lost to resistance and damping…

Loudspeaker Equivalent Circuit

To find the power radiated, find the transfer function $T_{RV}(s)$ for the voltage $v_R(t)$ across the resistance R :



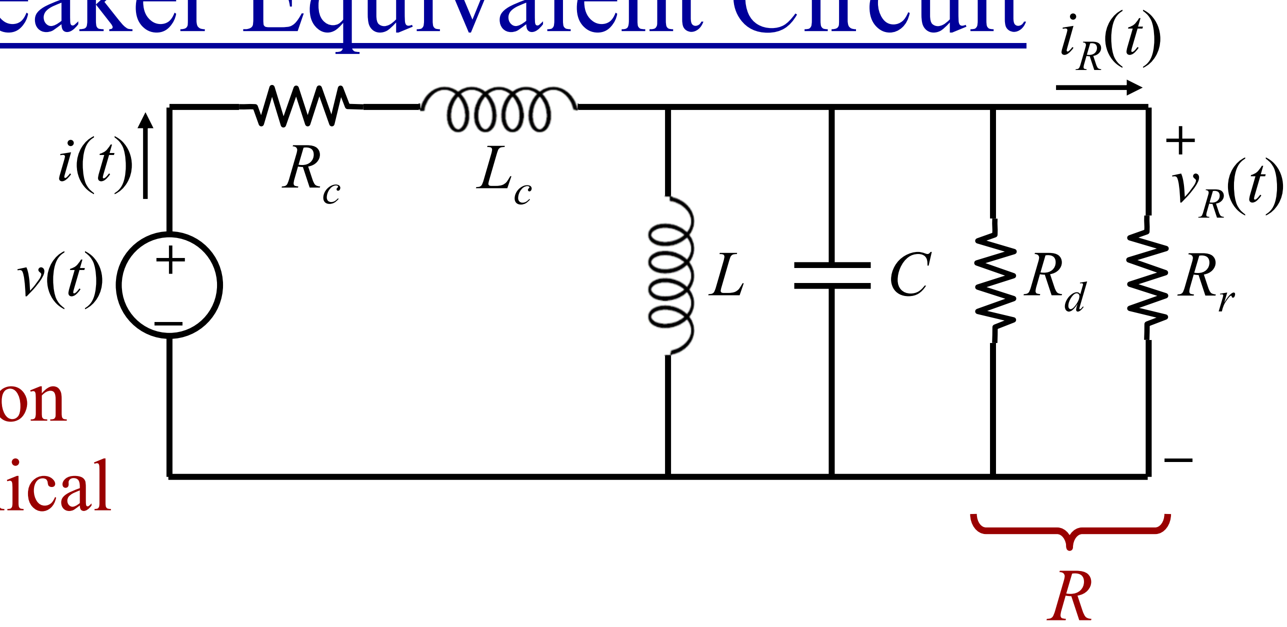
$$T_{RV}(s) = \frac{Z_{||}(s)}{R_c + sL_c + Z_{||}(s)} = \frac{\frac{1}{C}\frac{s}{s^2+s\frac{1}{RC}+\frac{1}{LC}}}{R_c + sL_c + \frac{1}{C}\frac{s}{s^2+s\frac{1}{RC}+\frac{1}{LC}}}$$

$$= \frac{1}{L_cC}\frac{s}{s^3 + s^2\left(\frac{1}{RC}+\frac{R_c}{L_c}\right) + s\left(\frac{1}{L_cC}+\frac{1}{LC}+\frac{R_c}{RCL_c}\right) + \frac{R_c}{LCL_c}}$$

Then, use this transfer function to determine the power delivered to the portion of this resistance R associated with the radiated acoustic power (remember, part of R is associated with damping, and not radiation)…

Loudspeaker Equivalent Circuit

…Model this mechanical resistance R as the parallel combination of the two mechanical resistances:



$$R = \frac{(2\pi r_c N B)^2}{b + \rho_o c_s A_c R_1} = \frac{1}{\frac{1}{\frac{(2\pi r_c N B)^2}{b}} + \frac{1}{\frac{(2\pi r_c N B)^2}{\rho_o c_s A_c R_1}}} = \frac{1}{\frac{1}{R_d} + \frac{1}{R_r}}$$

$$R_r = \frac{(2\pi r_c N B)^2}{\rho_o c_s A_c R_1}$$

→ Electrical resistance modeling the acoustic radiated power

Using the transfer function $T_{RV}(s)$ the power radiated is now easy to find…

Loudspeaker Radiated and Input Power

The radiated power for input phasor voltage *V* becomes:

$$
\begin{aligned}
P_{rad} &= \frac{1}{2}\operatorname{Re}\{V_R I_R^*\} = \frac{1}{2}\operatorname{Re}\left\{V_R \frac{V_R^*}{R_r}\right\} = \frac{1}{2}\operatorname{Re}\left\{(T_{RV}(j\omega)V)\frac{(T_{RV}(j\omega)V)^*}{R_r}\right\} \\
&= \frac{|V|^2}{2R_r}|T_{RV}(j\omega)|^2
\end{aligned}
$$

The input power to the electrical terminals for phase *V* is:

$$
\begin{aligned}
P_{in} &= \frac{1}{2}\operatorname{Re}\{VI^*\} = \frac{1}{2}\operatorname{Re}\left\{V\frac{V^*}{Z^*(j\omega)}\right\} = \frac{|V|^2}{2}\operatorname{Re}\left\{\frac{1}{Z(j\omega)}\right\} \\
&= \frac{|V|^2}{2}\operatorname{Re}\left\{\frac{1}{R_c + j\omega L_c + Z_{\|}(j\omega)}\right\}
\end{aligned}
$$

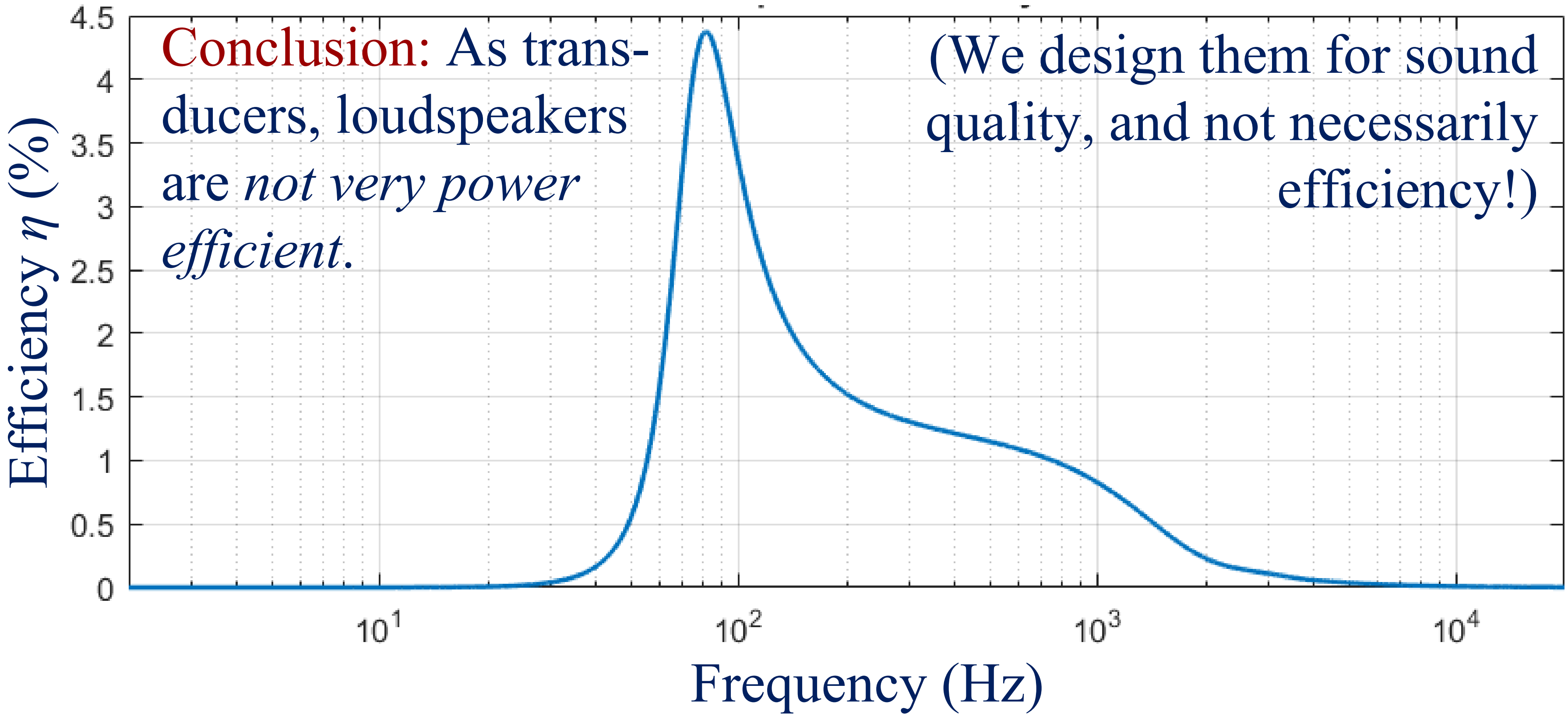
Therefore, the loudspeaker power *efficiency* η becomes:

$$
\eta = \frac{P_{rad}}{P_{in}} = \frac{|T_{RV}(j\omega)|^2}{\operatorname{Re}\left\{\frac{R_r}{R_c+j\omega L_c+Z_{\|}(j\omega)}\right\}} = \frac{\left|\frac{Z_{\|}(j\omega)}{R_c+j\omega L_c+Z_{\|}(j\omega)}\right|^2}{\operatorname{Re}\left\{\frac{R_r}{R_c+j\omega L_c+Z_{\|}(j\omega)}\right\}} = \frac{\left|\frac{Z_{\|}(j\omega)}{Z(j\omega)}\right|^2}{\operatorname{Re}\left\{\frac{R_r}{Z(j\omega)}\right\}}
$$

Loudspeaker Efficiency

Plotted is the power efficiency for the previous parameters:

$a_c = 10$ cm	$B = 1$ T	$N = 150$ turns
$m = 20$ g	$r_c = 1$ cm	#34 AWG
$b = 2.5$ kg/s	$l_c = 3$ cm	$\mu_c = 250\mu_o$ (H/m)
$k = 3000$ N/m	$g_c = 1$ mm	$V_o = 0.064$ m^3



Conclusion: As transducers, loudspeakers are *not very power efficient*.

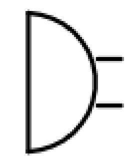
(We design them for sound quality, and not necessarily efficiency!)

Microphones

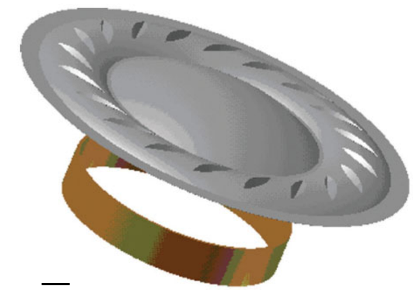
Types of Microphones

Devices to convert acoustic waves to electrical signals:

- Liquid microphone (Bell/Gray invention)
- Carbon microphone (resistive, telephones 1870s~1980s)
- Piezoelectric microphone (voltage source, contact sensing)
- Condenser microphone (capacitive, requires power source)
- Electret microphone (capacitive, permanent electric field)
- Ribbon microphone (inductive, permanent magnet)
- Fiber optic microphone (optical, extreme environments)
- Laser microphone (distant sound detection)
- Microelectromechanical system (MEMS) (capacitive, etched)
- Dynamic microphone (inductive, moving coil & PM)

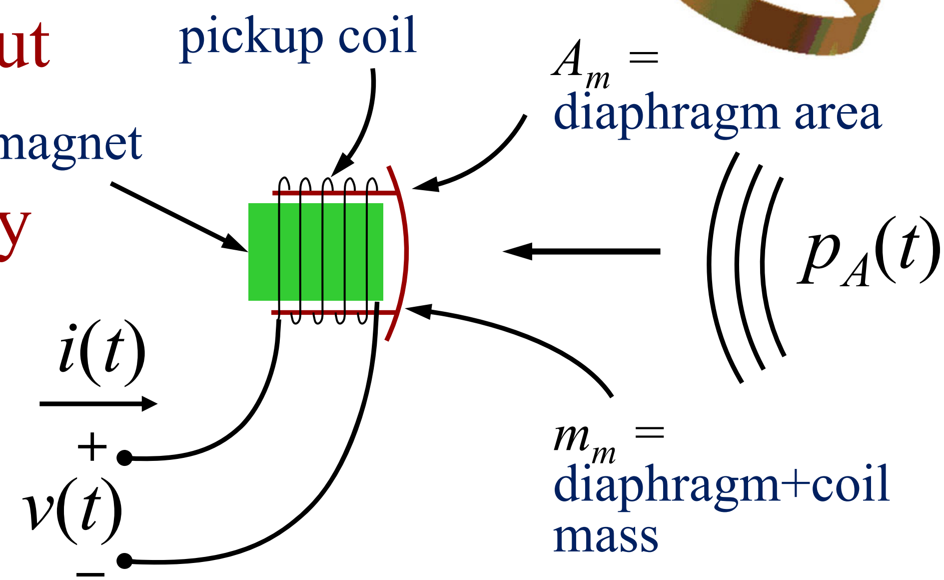


Dynamic Microphone



The dynamic microphone is analogous to a speaker but designed for high sensitivity over a wide frequency range. Typical parameters:

$A_m = 300\ \text{mm}^2$
$m_m = 0.03\ \text{g}$
$b_m = 0.1\ \text{kg/s}$
$k_m = 10\ \text{N/m}$
$B_m = 0.3\ \text{T}$
$r_m = 5\ \text{mm}$
$l_m = 2\ \text{mm}$
$N_m = 200$ turns #50 AWG
$\mu_m = 250\mu_o\ (\text{H/m})$

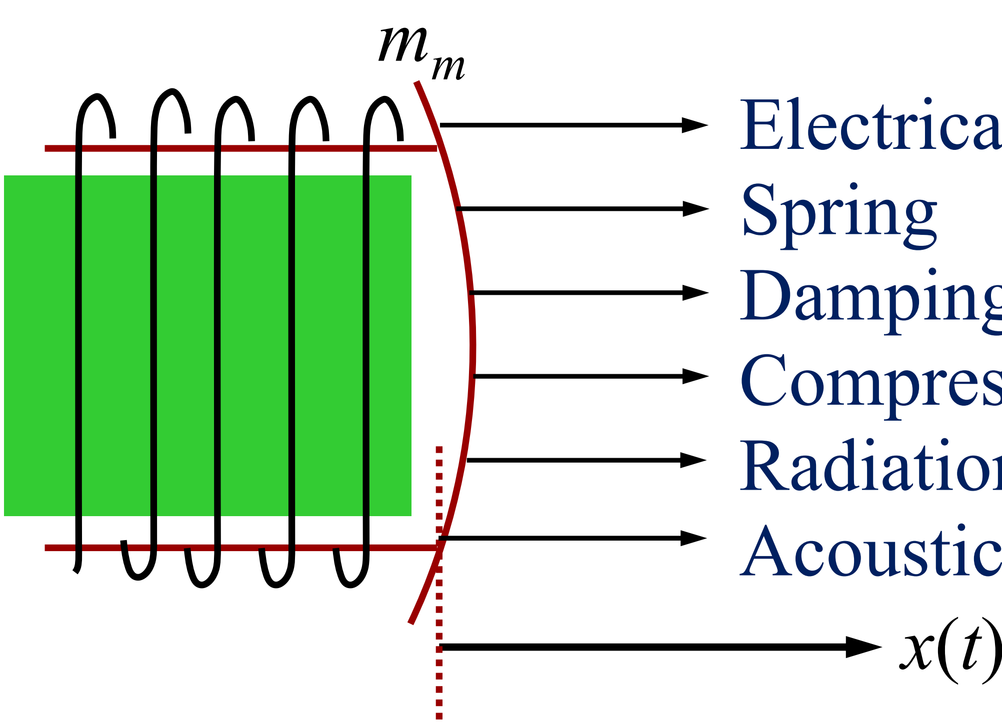


The diaphragm and pickup coil mass m_m is extremely small to respond to sound pressure waves across the audio spectrum from ~50 Hz to ~20 kHz.

Dynamic Microphone

As with the speaker, there are several forces on the diaphragm to consider in the free body diagram and equation of motion:

$$\sum F_x = m_m \frac{d^2 x}{dt^2}$$



Electrical	$F_e = 0$ (none)
Spring	$F_s = -k_m x(t)$
Damping	$F_d = -b_m \, dx(t)/dt$
Compression	$F_c \sim 0$ (small)
Radiation	$F_r \sim 0$ (small)
Acoustic pressure	$F_p = p(t) A_m$

Dynamical Equation of Motion and TF

The equation of motion becomes:

$$m_m \frac{d^2 x}{dt^2} = -k_m x(t) - b_m \frac{dx(t)}{dt} + p_A(t) A_m$$

Taking the Laplace transform of both sides yields:

$$\left(m_m s^2 + b_m s + k_m\right) X(s) = P_A(s) A_m$$

The induced voltage due to motion of the diaphragm becomes*:

$$v_m(t) = 2\pi r_m N_m B_m v_x(t) = 2\pi r_m N_m B_m \frac{dx(t)}{dt}$$

$$\Rightarrow V_m(s) = 2\pi r_m N_m B_m s X(s)$$

$$\Rightarrow \boxed{V_m(s) = \frac{2\pi r_m N_m B_m A_m s}{m_m s^2 + b_m s + k_m} P_A(s) \triangleq T_{VP}(s) P_A(s)}$$

* Studied in ECEN 3400, Fall 2020

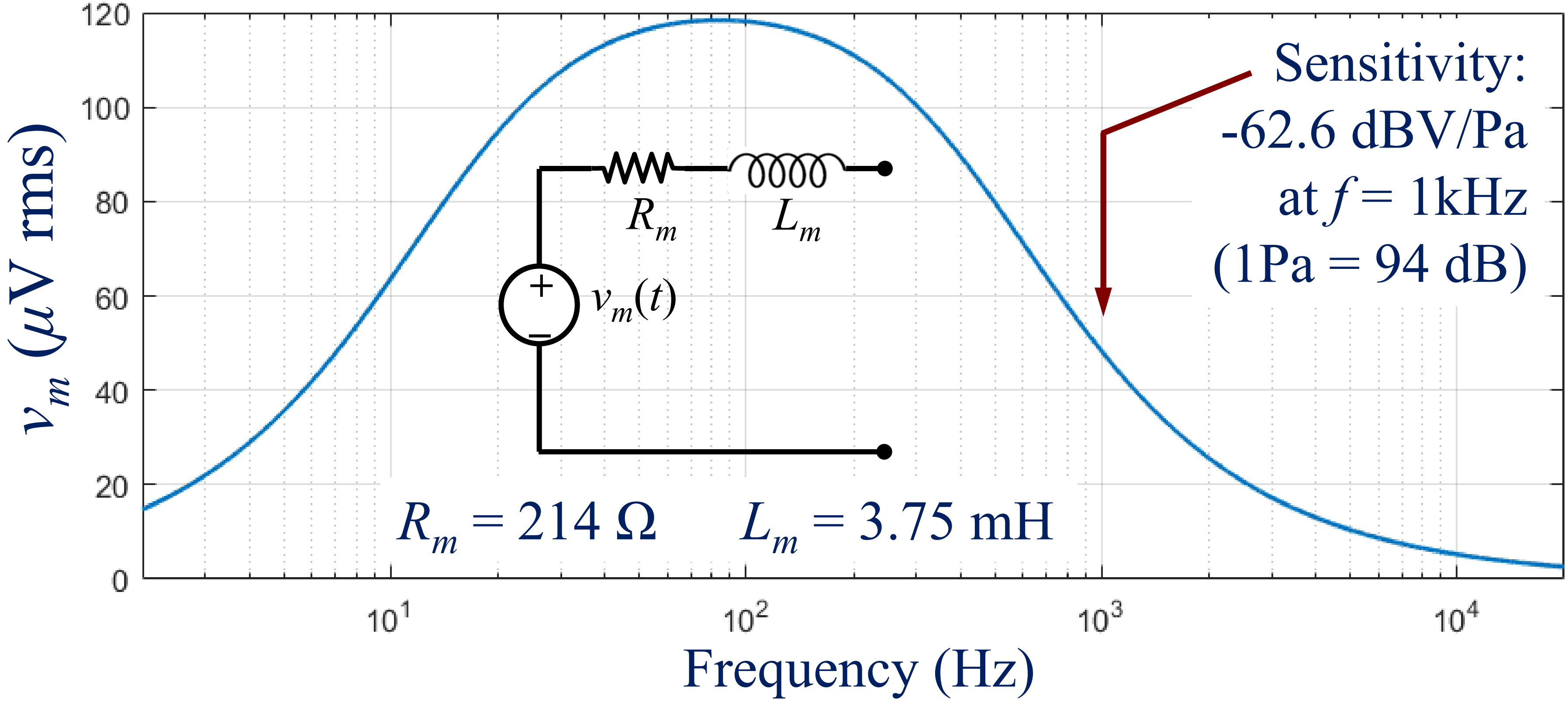
Microphone Sensitivity

Plotted is the RMS voltage for $P_A = 60$ dB sound pressure:

$a_m = 10$ mm
$A_m = 300\ \text{mm}^2$
$m_m = 0.03$ g
$b_m = 0.1$ kg/s

$k_m = 10$ N/m
$B_m = 0.3$ T
$r_m = 5$ mm
$l_m = 2$ mm

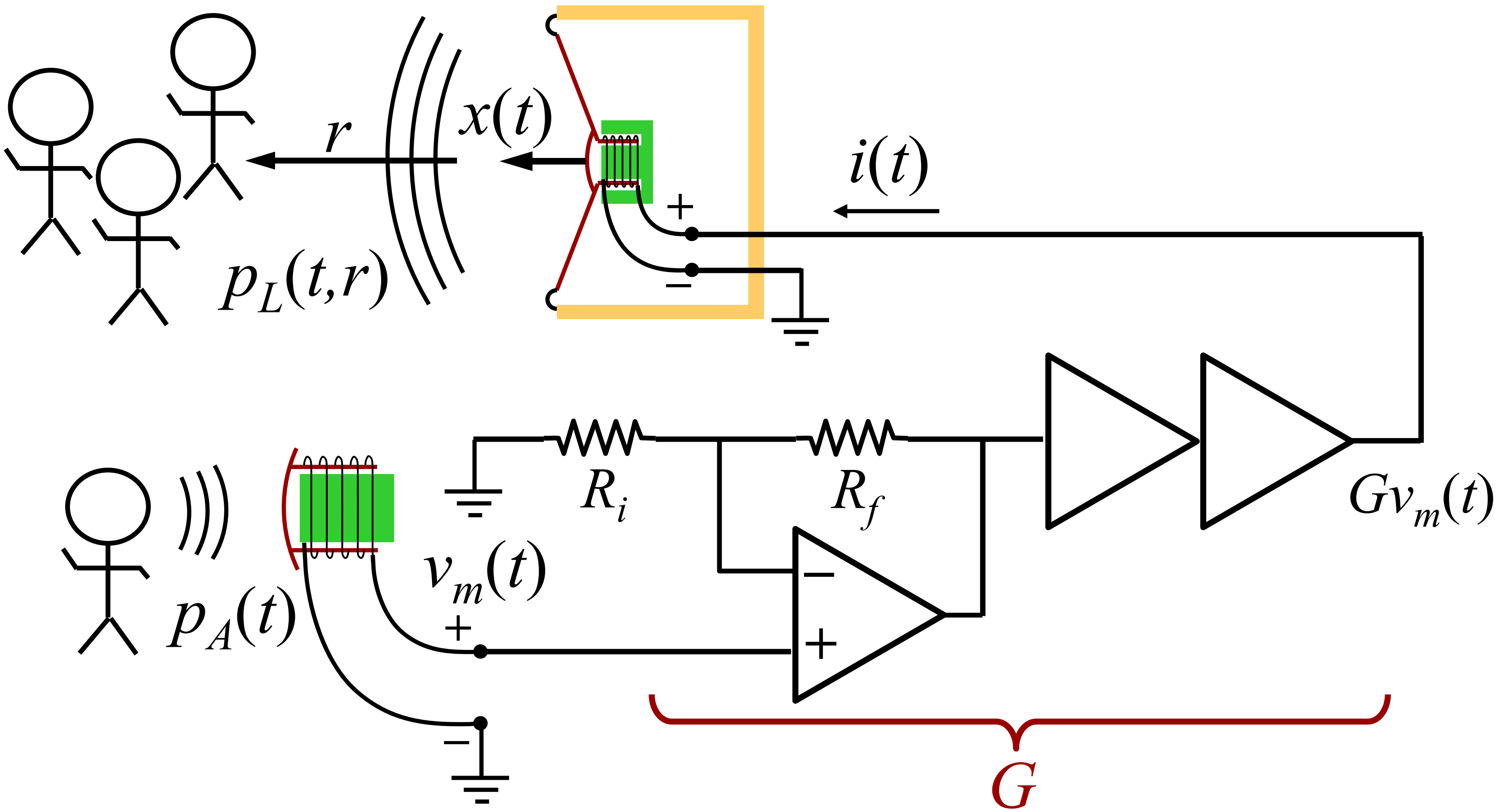
$N_m = 200$ turns
#50 AWG
$\mu_m = 250\mu_o$ (H/m)



Acoustic Feedback and Stability

Public Address System

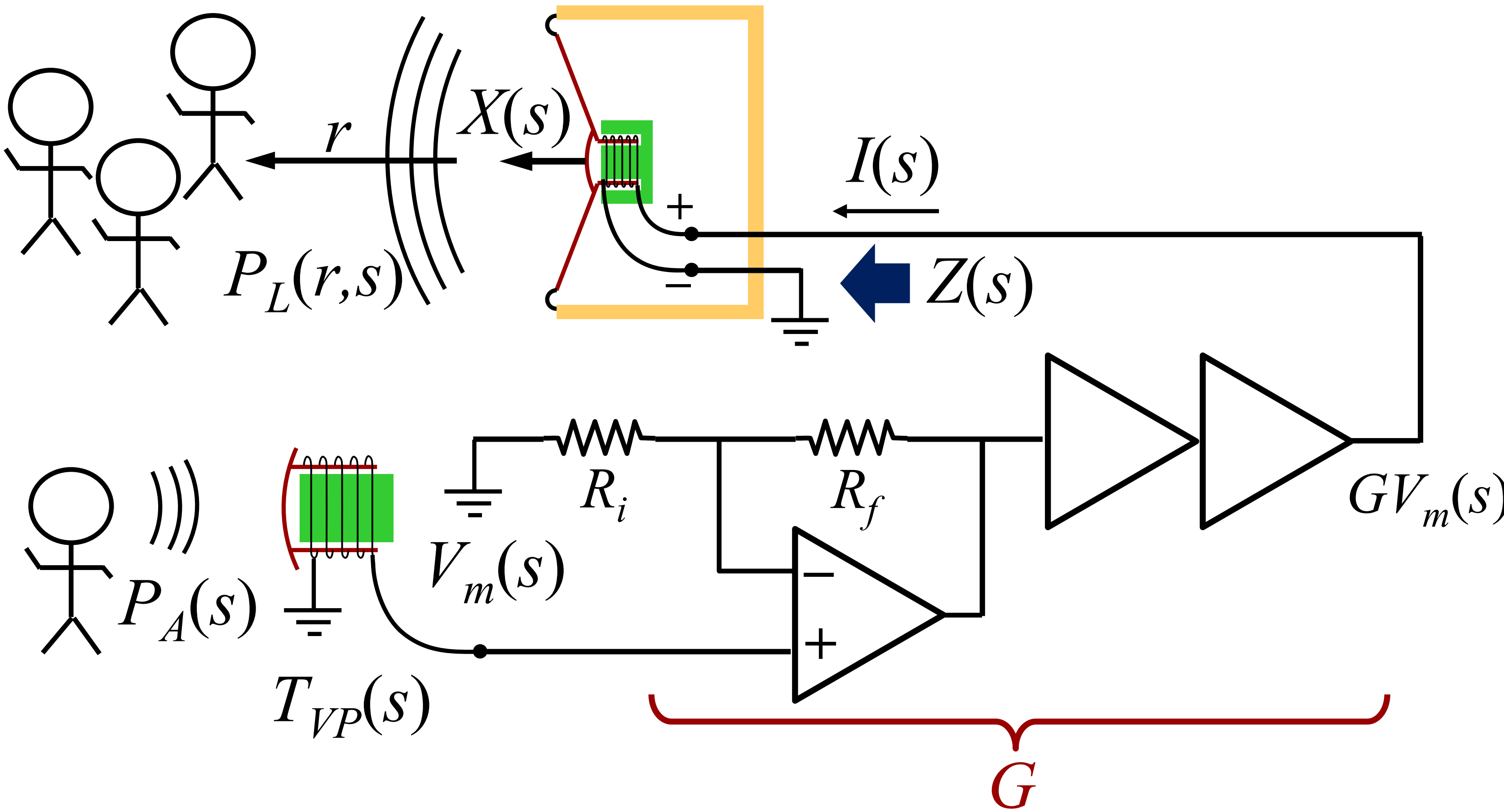
Let's now consider the transfer function for the entire public address system. Since the microphone produces a weak (~10's of μV to mV) level signal we'll need a large voltage gain G (of order ~10^4 to 10^6) to drive the speaker:



Public Address System

In the *s*-domain the signals are as shown. From Lecture 27 the transfer function of the loudspeaker $T_{XI}(s)$ is:

$$T_{XI}(s) = \frac{2\pi r_c N B}{m_e s^2 + b_e s + k_e}$$



PA System Transfer Function

Building the system transfer function:

$$X(s) = T_{XI}(s)\, I(s) = \frac{T_{XI}(s)}{Z(s)} G V_m(s) = \frac{T_{XI}(s)\, G T_{VP}(s)}{Z(s)} P_A(s)$$

How does the speaker radiate to the listeners? Recall from Lecture 27 (and consider the propagation delay r/c_s):

$$p_L(r,t) = \left. \frac{\rho_o A \frac{dv_r(t)}{dt}}{4\pi r} \right|_{t-\frac{r}{c_s}} \quad \Rightarrow \quad P_L(r,s) = \frac{\rho_o A_c}{4\pi r} s e^{-s\frac{r}{c_s}} X(s) \triangleq T_{PX}(s)\, X(s)$$

The overall transfer function from talker to listener is thus:

$$P_L(r,s) = \frac{T_{PX}(s)\, T_{XI}(s)\, G T_{VP}(s)}{Z(s)} P_A(s)$$

Great! What could possibly go wrong?

Feedback!

At the microphone we have some of the radiated acoustic signal added to the talker's signal:

$$\Rightarrow \quad P_A(s) \quad \rightarrow \quad P_A(s) + P_L(r,s)$$

Thus, the *s*-domain relationship between $P_A(s)$ and $P_L(s)$ now becomes:

$$\begin{aligned} P_L(r,s) &= \frac{T_{PX}(s)\,T_{XI}(s)\,G T_{VP}(s)}{Z(s)}\left(P_A(s) + P_L(r,s)\right) \\ &\triangleq T(s,r)\left(P_A(s) + P_L(r,s)\right) \end{aligned}$$

We now have to re-compute the relationship by bringing all terms in $P_L(r,s)$ onto the LHS of the equation. In doing so, the number and location of the poles of the TF between $P_A(s)$ and $P_L(s)$ are ***greatly*** modified…

Effect of Feedback

Re-computing the P_L to P_A transfer function relationship:

➡ $$P_L(r,s)\left(1 - T(s,r)\right) = T(s,r)\,P_A(s)$$

➡

$$P_L(r,s) = \frac{T(s,r)}{1 - T(s,r)} P_A(s) = \frac{\frac{T_{PX}(s)T_{XI}(s)GT_{VP}(s)}{Z(s)}}{1 - \frac{T_{PX}(s)T_{XI}(s)GT_{VP}(s)}{Z(s)}} P_A(s)$$

$$= \frac{T_{PX}(s)\,T_{XI}(s)\,GT_{VP}(s)}{Z(s) - T_{PX}(s)\,T_{XI}(s)\,GT_{VP}(s)} P_A(s) \triangleq T_{LA}(s)\,P_A(s)$$

we see that the poles of the TF $T_{LA}(s)$ are now the zeros of the function 1-$T(s,r)$. When any of these poles falls in the right half s-plane the system becomes unstable, producing the well-known and annoying acoustic feedback "howl".

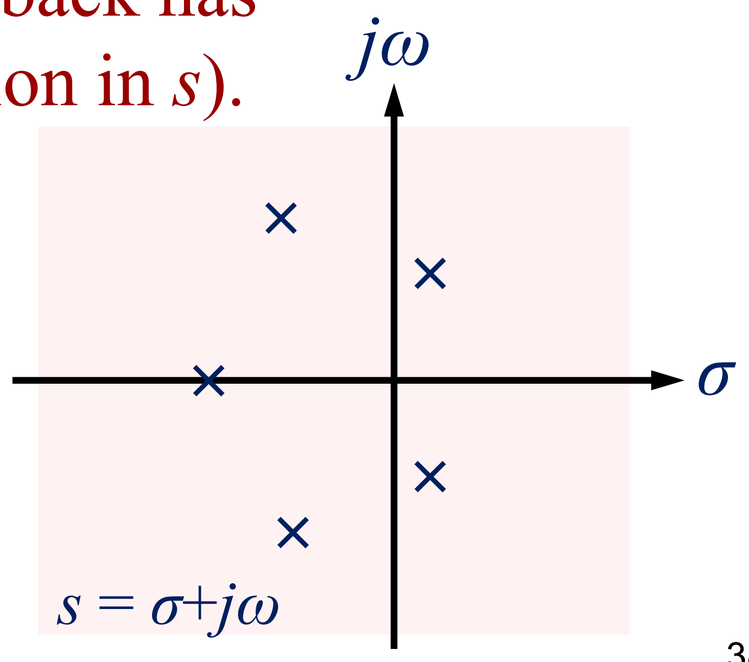
Poles of $T_{LA}(s)$

The poles of the TF $T_{LA}(s)$ are the zeros of 1-$T(s,r)$, and are changed by adjusting either the distance r or the gain G. New poles occur at values of s for which:

$$0 = 1 - T(s,r)$$

$$= 1 - \frac{G\left(2\pi r_c NB\right)^2\left(2\pi r_m N_m B_m\right) A_m \rho_o A_c s^2 e^{-s\frac{r}{c_s}}}{\left(m_e s^2 + b_e s + k_e\right)\left(m_m s^2 + b_m s + k_m\right)\left(4\pi r\right)\left(R_c + sL_c + \frac{s(2\pi r_c NB)^2}{m_e s^2 + b_e s + k_e}\right)}$$

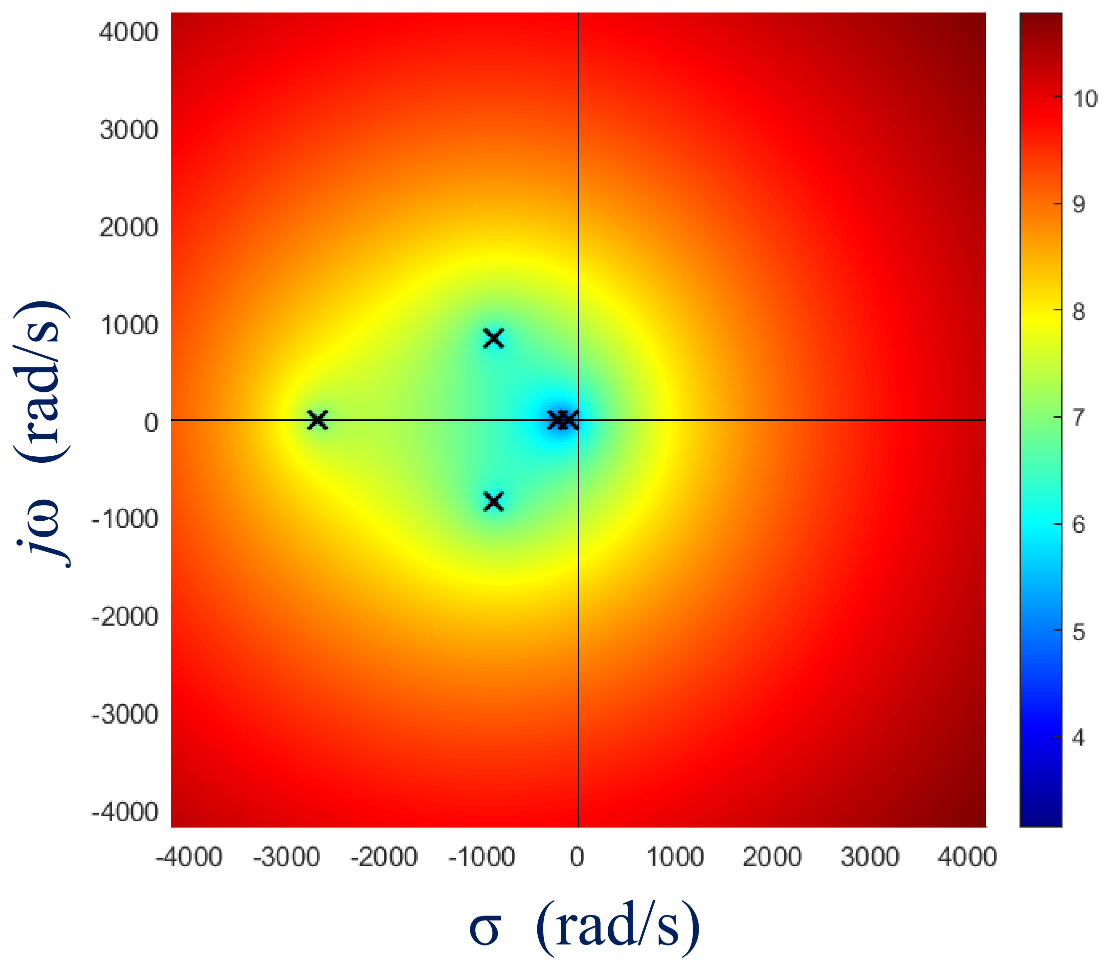
The PA system analyzed w/o feedback has five poles (i.e., a fifth order equation in s).



To stabilize the system, we need to make r large enough and/or G small enough to keep *all* five poles *and any new ones* in the left half of the s-plane.

Public Address TF $T_{LA}(s)$ w/o Feedback

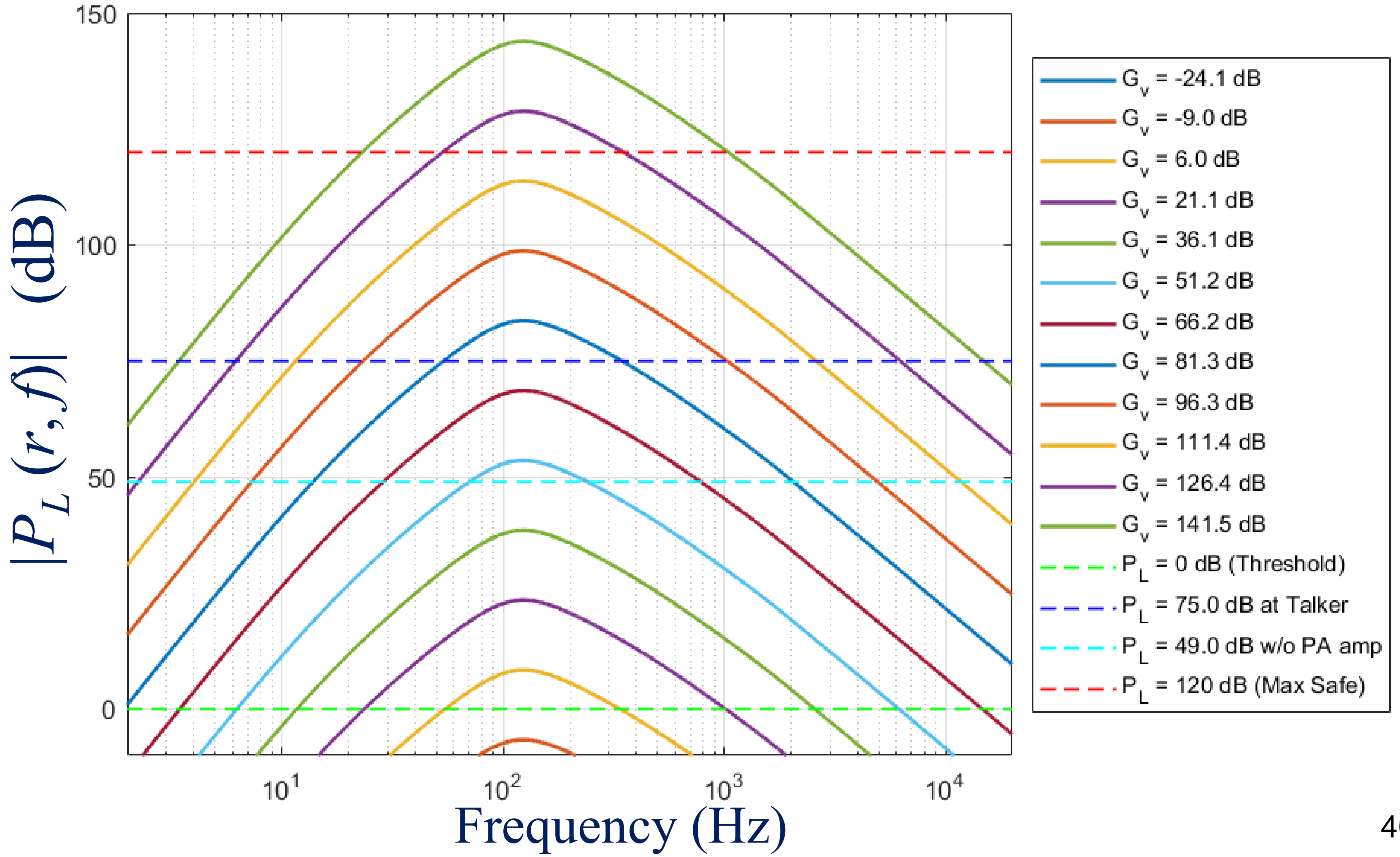
The poles of the TF $T_{LA}(r, s) = T(r, s)$ without modeling feedback (and for frequency-average radiation resistance R_1 and reactance X_1) are located in the s-plane below, and mapped with the magnitude of the denominator of $T(r, s)$:



Note how the poles' locations are coincident with minima (actually, zeros) in the magnitude of the transfer function denominator – as expected!

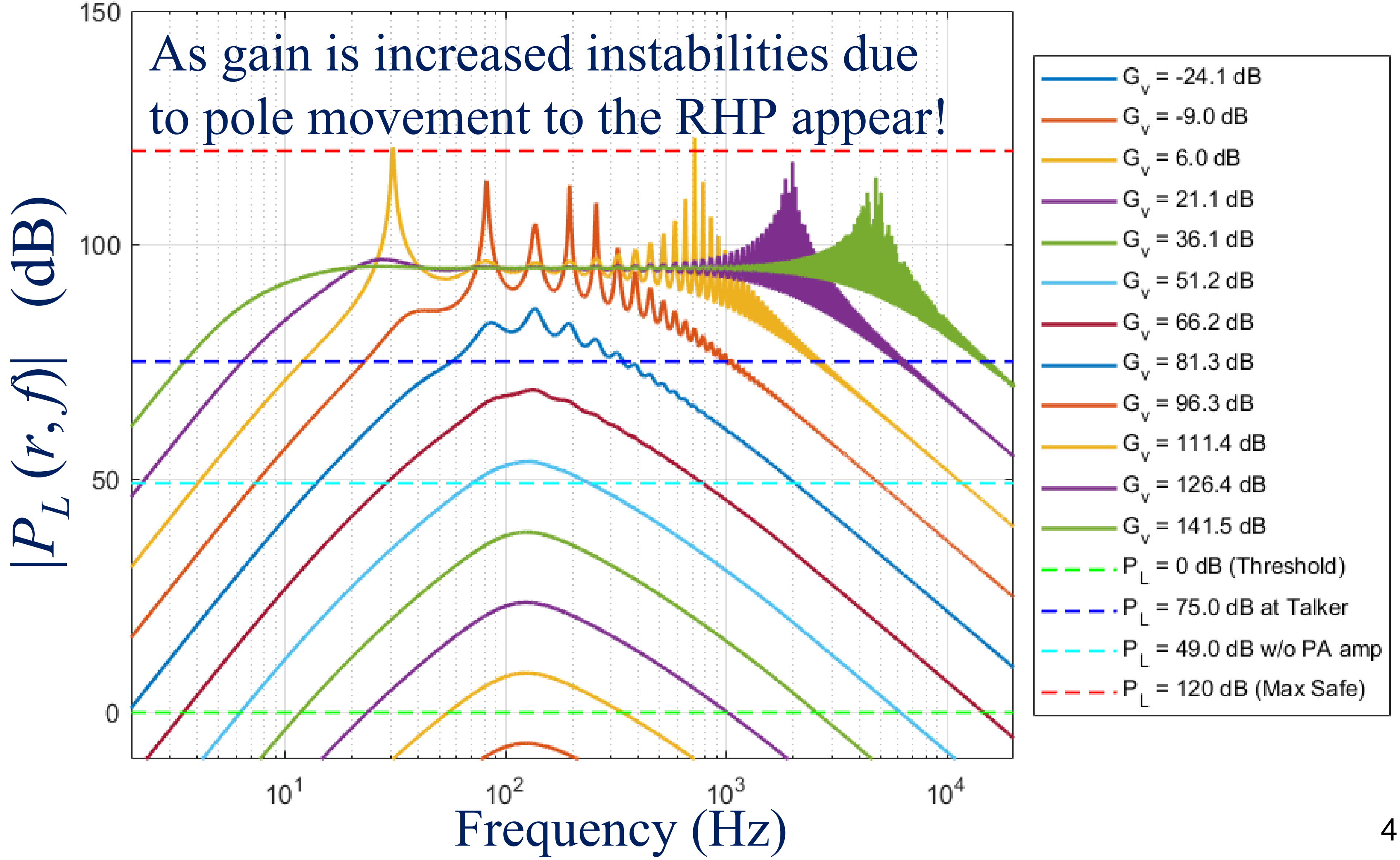
Public Address TF $T_{LA}(j\omega)$ w/o Feedback

Plotted below is $|P_L(j\omega)| = |T_{LA}(j\omega)P_A(j\omega)|$ in dB for various G (also in dB) at $r = 5$ m without considering feedback, assuming $P_A = 75$ dB (a normal human voice at a typical microphone distance of 20 cm):



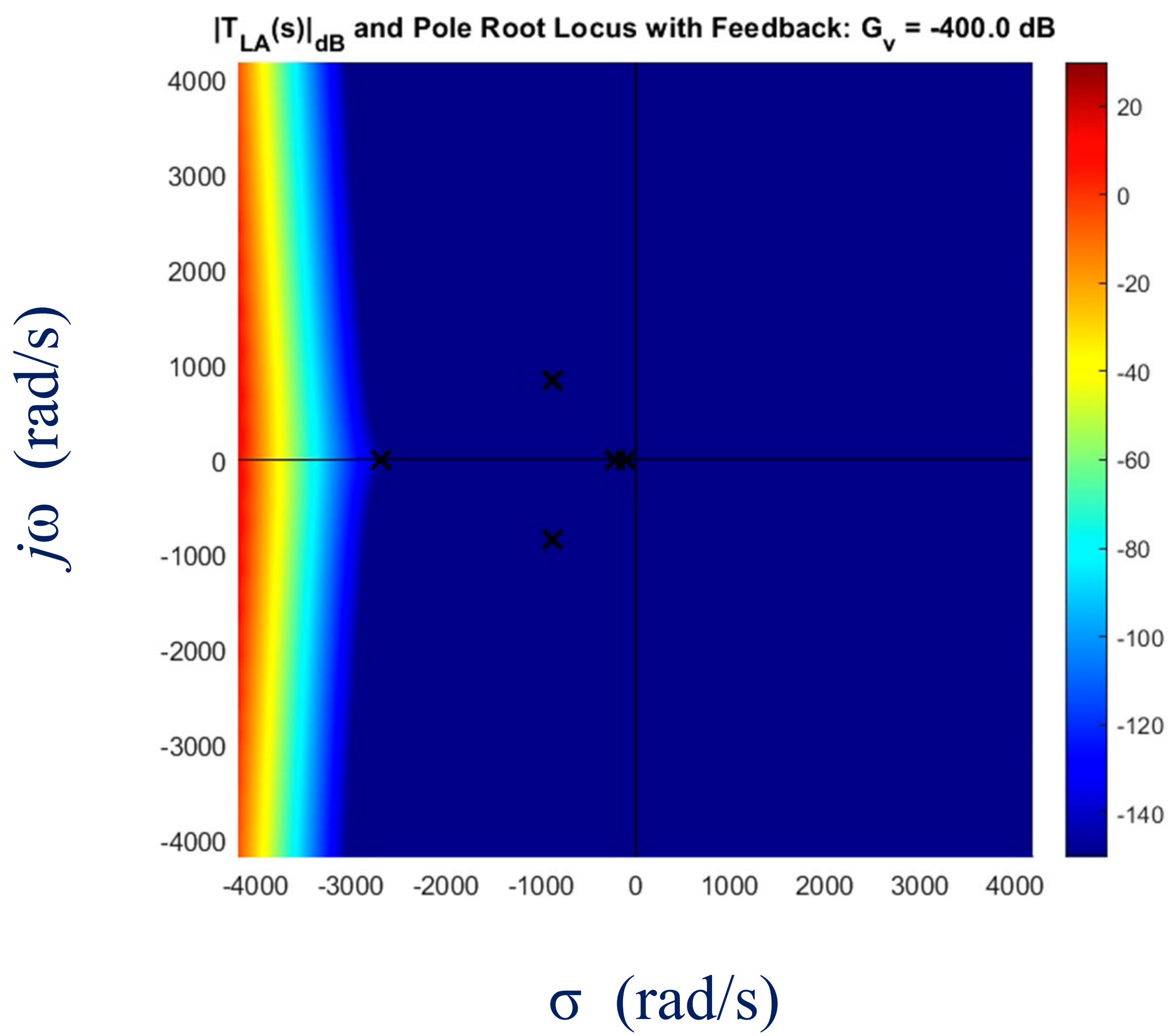
Public Address Transfer Function $T_{LA}(j\omega)$

Below is the same plot but with feedback, assuming that the microphone and speaker have an additional 20 dB of isolation due to radiation pattern rejection (i.e., directing them away from each other):



Public Address Transfer Function $T_{LA}(s)$

Below is a movie depicting feedback of the magnitude of $T_{LA}(s)$ evaluated over the complex s-plane as the gain G is increased. Note the approach of a line of singularities toward the RHP as G increases!



Note that as G increases the impact of the five original poles (i.e., w/o feedback, "×" symbols) becomes *negligible* compared to that of the advancing line of feedback-induced singularities.

Next Lecture

- Fourier series
- Series coefficients
- Examples

Reading: TRT 13-1 to 13-2

Have a healthy, safe, restful, and enjoyable break!

Key Technical Attributes of the Slide Set

- Text: Times New Roman. One font only!
- Math: Italics, standard and consistent symbology
- No more than two colors for text
- Clear graphic titles, axes, labels
- Use of all slide area, balance the material
- Simple titles that connect ideas
- Cartoons – no more complex than needed
- Use equations as a language
- Intro slide, administration slide, last lecture, this lecture, next lecture slides
- Topic separation slides
- No more that about 20 complex slides per 50-minute lecture
- Preperation time of about 15-20 minutes per slide (on average)

Consistency, consistency, consistency…

The Online Studio

Top Ten List

Top ten things to consider when setting up a home studio for remote instruction:

1. A quiet area closed to foot-traffic, kids, pets, leaf blower noise, etc…
2. A comfortable seat and uncluttered desk (rolling seats are good for extended sitting)
3. Diffuse, warm lighting (e.g., a ring light)
4. A reliable wide bandwidth internet connection (wired or near a wireless router)
5. An uninterruptible power supply for your PC, lights, etc… (500-800W, e.g., APC)
6. A green screen backdrop (unless your machine can key on the existing background)
7. A good quality web camera (e.g., Logitech, but could be the one in your laptop)
8. A good microphone (e.g., Yeti, although most laptop microphones are too bad)
9. A tablet (e.g., Wacom, if you use one) or overhead camera for real-time annotations
10. A GPS synchronized clock with seconds (ideally not your phone)

Foremost: You want an uninterrupted high-fidelity presence with your students for the entire period of your class.

A Few More…

A few more things to consider when setting up a home studio for remote instruction:

…

11. Acoustic tiles if the room reverberates (absorbing material in the corners also helps)
12. A check list to refer to before the start of each lecture
13. A comb and small mirror (at least pretend to be a TV star)
14. A course notebook and pencil (for taking notes during lecture – minimize lapses)
15. A spill-proof place for your coffee, tea, etc…
16. A space heater in case room temperature fluctuates

Forecast: It looks like we'll be using home studios for the foreseeable future. Probably a good investment.

My Spring 2020 Checklist

Here is my checklist before going live on Zoom:

- Disconnect phone in room 8:45 (-15 minutes)
- Check internet connection
- Check microphone audio
- Adjust backdrop screen
- Turn on lights and adjust
- Open clock app, phone on silent mode
- Comb hair, etc…
- Start Zoom video recording at 8:59:30 (-30 seconds)
- Start Zoom video and audio at 8:59:45 (-15 seconds)

After each lecture:

- Entertain any questions out to ~15 minutes after the lecture period
- Correct any slide errors ASAP
- Republish final/corrected slides to Canvas
- Download Zoom video and upload to Canvas

Thanks, Stay Safe,

and

Best Wishes this Fall