Week 1: Module introduction, lumped parameter modelling, AC circuit theory

Microphone and Loudspeaker Design - Level 5

Joshua Meggitt

Acoustics Research Centre, University of Salford

What are we covering today?

1. Introduction
2. Loudspeaker anatomy
3. Modelling loudspeakers
4. AC circuit theory
5. Complex numbers (quick detour)
6. Tutorial questions

Introduction

Introduction

1. **Who am I?**
2. What is the module about?
3. What is the structure?
4. How are you assessed?
5. Where can you get help?
6. Other useful stuff...

- *Joshua Meggitt*
- *From sunny Cornwall*
- *Did the acoustics undergrad about 11 years ago*
- *Area of research: vibro-acoustics and structural dynamics*
- *We met last year... :)*

Introduction

1. Who am I?
2. **What is the module about?**
3. What is the structure?
4. How are you assessed?
5. Where can you get help?
6. Other useful stuff...

- *Its about loudspeaker and microphone design...*
- *Understanding the physics behind loudspeaker and microphone operation*
- *Learning how to design loudspeakers and microphones for optimal performance*
- *We will also cover related concepts: cross-over design, line array modelling*
- *Some more advance concepts are not covered. E.g., horn loading, DMLs, etc.*

Introduction

1. Who am I?
2. What is the module about?
3. **What is the structure?**
4. How are you assessed?
5. Where can you get help?
6. Other useful stuff...

- *2 hour lecture each week*
- *...followed by a 1 hour tutorial session*
- *3 x 3 hour lab experiments (2 semester in 1, 1 in semester 2)*
  - **These are linked to your first assessment**
  - *Lab 1 - Electrical impedance, sensitivity, vibro-acoustic transfer function*
  - *Lab 2 - Thiele-Small parameters*
  - *Lab 3 – Crossover network design and combined system measurement*
- *Overview of module topics...*

1. Who am I?
2. What is the module about?
3. **What is the structure?**
4. How are you assessed?
5. Where can you get help?
6. Other useful stuff...

Semester	Topics
1	AC circuit theory
1	Lumped parameter/equivalent circuit modelling of loudspeakers
1	Cabinet design
1	Performance metrics
1	Some extra stuff...
2	Crossover networks
2	Line array design
2	Microphone design

Introduction

1. Who am I?
2. What is the module about?
3. What is the structure?
4. **How are you assessed?**
5. Where can you get help?
6. Other useful stuff...

- *Loudspeaker design group project (technical report) - (50%)*
  - *You are tasked with designing and prototyping a multi-driver loudspeaker (cabinetry and cross-over).*
- *Line array and microphone design challenges (commentated code submission) - (50%)*
  - *You will be given a MATLAB live-script with a series of tasks related to the simulation/ design of line arrays and microphones.*

Introduction

1. Who am I?
2. What is the module about?
3. What is the structure?
4. How are you assessed?
5. **Where can you get help?**
6. Other useful stuff...

- *Blackboard*
- *Course notes – these are pretty comprehensive but some sections need updating!*
- *Lecture presentations - I will try to record all lectures live*
- *Question board!*
- *Me - j.w.r.meggitt1@salford.ac.uk*

Introduction

1. Who am I?
2. What is the module about?
3. What is the structure?
4. How are you assessed?
5. Where can you get help?
6. **Other useful stuff...**

- *Useful books:*
  - *Acoustics – Sound Fields and Transducers, Beranek*
  - *Fundamentals of Acoustics, Kinsler and Frey*
  - *The Loudspeaker Design Cookbook, Dickason*
  - *High Performance Loudspeakers, Colloms*
- *Web stuff - don't trust everything you read!*
- *Electronics tutorials (general maths stuff)*
- *Khan Academy*
- *You will need to install MATLAB on your PC*

A weekly fact about Salford..!

Did you know...

- **Salford was the birthplace of vegetarianism!** More than 200 years ago the Reverend William Cowherd (you heard correctly!) preached the virtues of a vegetarian diet at a chapel in Salford. His followers then went on to form the Vegetarian Society. These included Joseph Brotherton who succeeded Cowherd in leading the Church and later became Salford's first MP.

Loudspeaker anatomy

Loudspeaker anatomy: what do you know about loudspeakers?

Draw and label a loudspeaker...

Loudspeaker anatomy: the driver

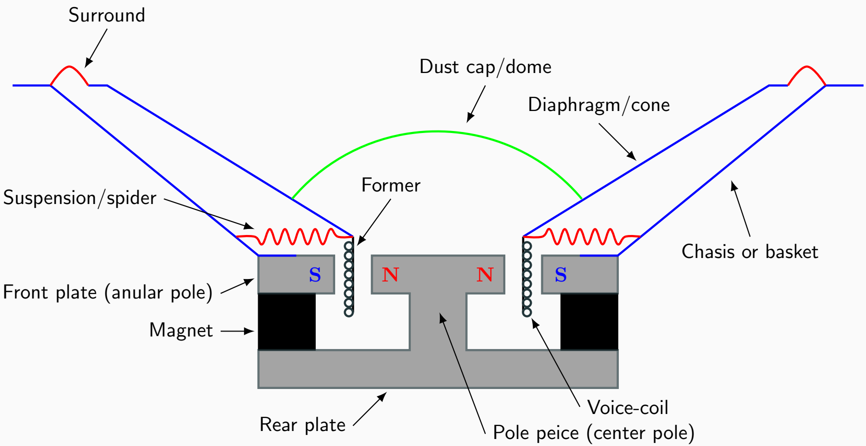


Figure 1: Schematic of a typical dynamic loudspeaker.

Loudspeaker anatomy: the cabinet

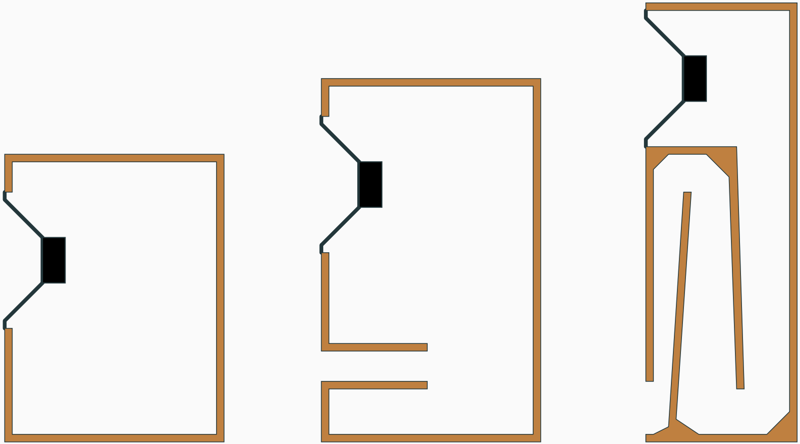


Figure 2: Typical loudspeaker systems.

Modelling loudspeakers

Modelling loudspeakers: a multi-physics problem

Electronic signal → Coil: *Electrical* → Cone: *Mechanical* → Air (in and around cabinet): *Acoustical* → **Acoustic signal**

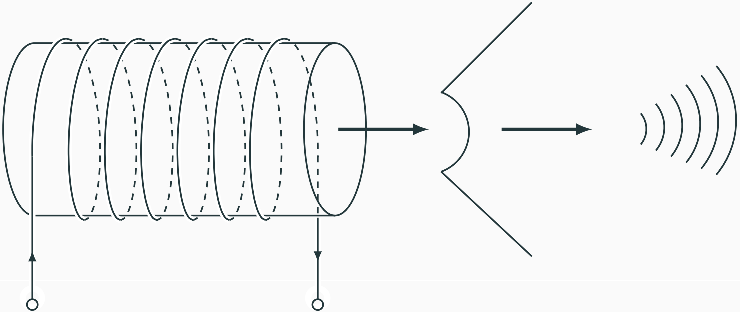


Figure 3: Operation of dynamic loudspeaker.

Modelling microphones: also a multi-physics problem

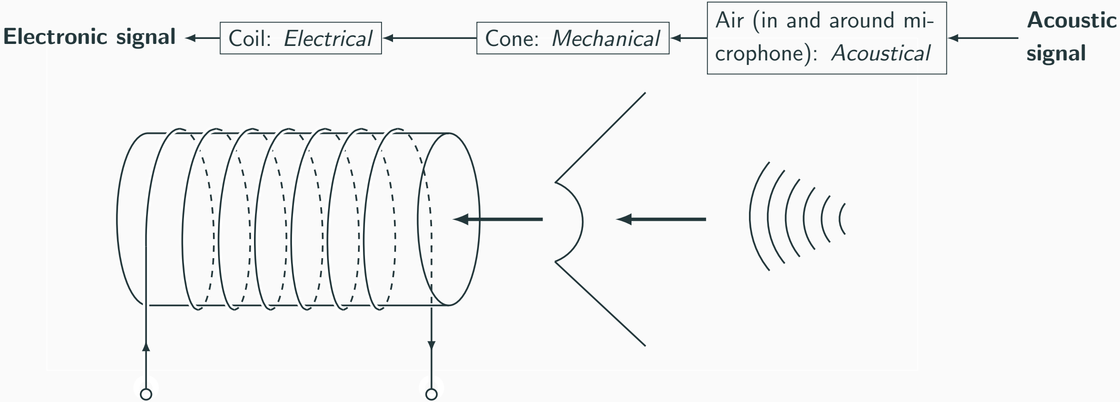


Figure 4: Operation of dynamic microphone.

Modelling methods

- Physical systems, loudspeakers included, are described by sets of differential equations. How do we solve them?
- **Analytical methods** - too complicated, especially with all the interactions!
- **Numerical methods** (e.g. finite element method) - can model complex systems, but expert knowledge/ software experience required
- **Lumped elements**:
  - Makes use of simplifications
  - Assumes components have only a single degree of freedom
  - Can be modelled using electronic circuits
  - No wave behavior within any lumps

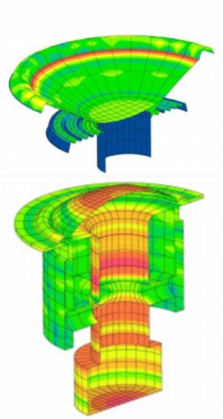


Figure 5: Example finite element model of a woofer and tweeter.

Lumped parameter assumption

- Lumped element – only independent variable is time (no spatial variation)
- Occurs when wavelength is much larger than the dimensions of the object.

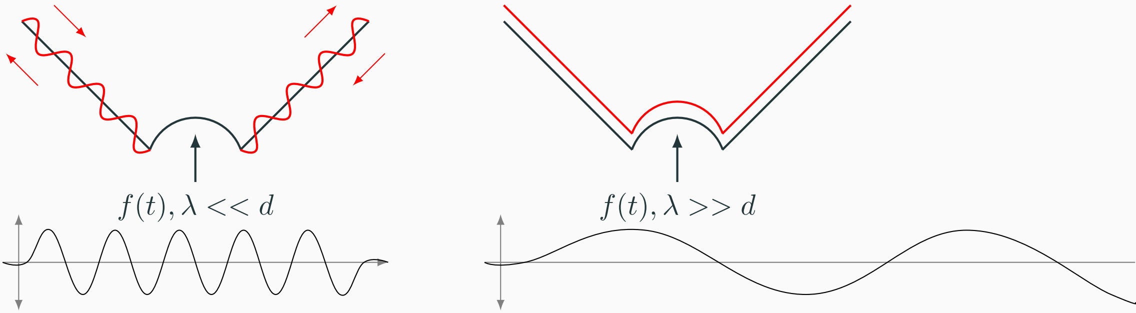


Figure 6: Lumped parameter assumptions.

Impedance: a common language

- **Electrical impedance** is the measure of the opposition that a circuit presents to a current when a voltage is applied

$$Z_E = \frac{V}{I} \tag{1}$$

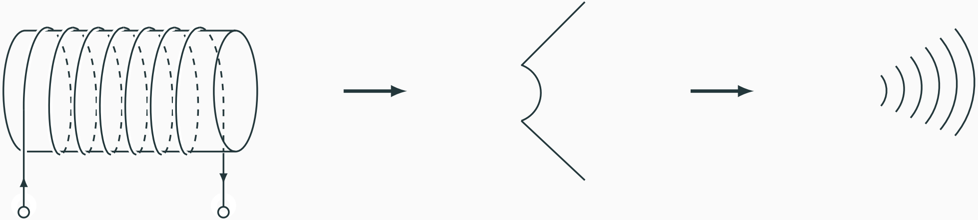
- **Mechanical impedance** is a measure of how much a structure resists motion (velocity) when subjected to a force

$$Z_M = \frac{F}{u} \tag{2}$$

- **Acoustic impedance** is a measure of the opposition that a system presents to the acoustic flow (volume velocity) when subjected to acoustic pressure

$$Z_A = \frac{p}{U} \tag{3}$$

Equivalent circuits: a tool for modelling loudspeakers (low frequency)



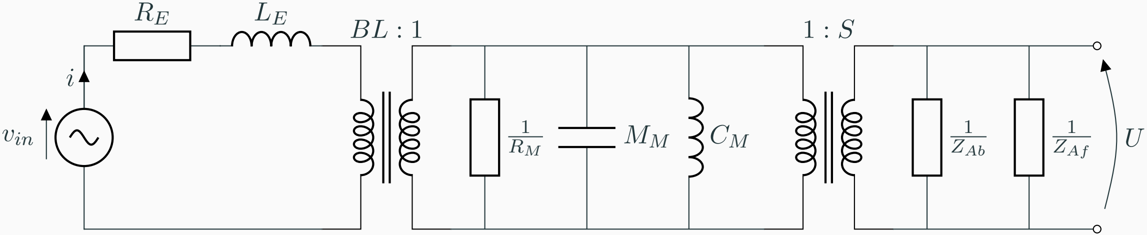


Figure 7: An equivalent electrical circuit for a dynamic loudspeaker

Equivalent circuits: a tool for modelling loudspeakers (low frequency)

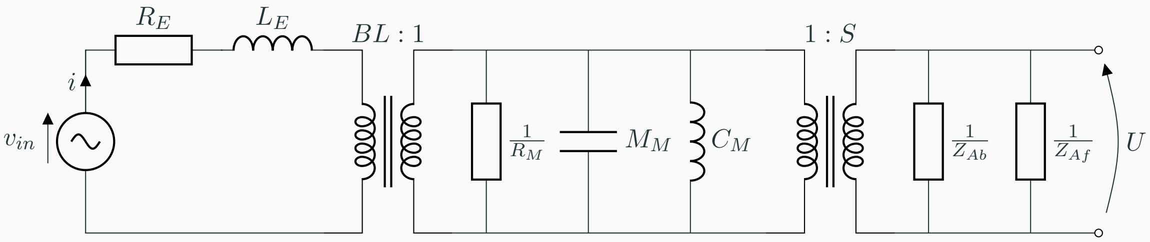


Figure 7: An equivalent electrical circuit for a dynamic loudspeaker

- To analyse complex circuits like this we need to understand:
  - Kirchhoff's laws
  - Impedance (resistance vs. reactance)
  - How to derive and analyse transfer functions

AC circuit theory

Kirchhoff's laws: electrical quantities

- **Current**
  - Is the continuous and uniform flow of electrons (which carry charge) around a circuit that are being 'pushed' by the voltage source.
- **Voltage**
  - The 'force' that pushes electrons through a conductor and the greater the voltage the greater is its ability to 'push' the electrons through a given circuit.
  - The difference in voltage between any two points in a circuit is known as the potential difference or voltage drop.
- **Impedance**
  - Is the capacity of a material to resist or prevent the flow of current or, more specifically, the flow of electric charge within a circuit.

- Voltage, current and impedance are related through the following equation,

$$V = IZ \tag{4}$$

Kirchhoff's laws: current

- **Kirchhoff's current law** states that: *'the total current or charge entering a junction or node is exactly equal to the charge leaving the node as it has no other place to go except to leave, as no charge is lost within the node'*.
- **Describes conservation of charge.**
- Mathematically, this law can be written as,

$$\sum_n I_n = 0 \tag{5}$$

where I_n is the nth current flowing into (positive I_n) or out of (negative I_n) a junction.

Kirchhoff's laws: voltage

- **Kirchhoff's voltage law** states that: *'in any closed loop network, the total voltage around the loop is equal to the sum of all the voltage drops within the same loop'* (i.e. the algebraic sum of all voltages within the loop must equal zero).
- **Describes conservation of energy.**
- Mathematically, this law can be written as,

$$\sum_n V_n = 0 \tag{6}$$

where V_n is the nth voltage drop (negative V_n) or voltage source (positive V_n) around the closed loop.

Components in series

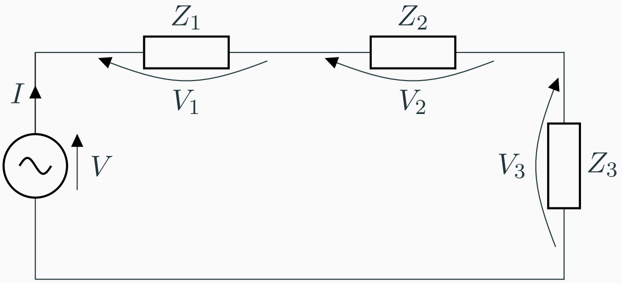


Figure 8: Three arbitrary impedances in series

- For a **series arrangement**, the total impedance Z_T presented by the circuit is,

$$Z_T = Z_1 + Z_2 + Z_3. \tag{7}$$

Components in parallel

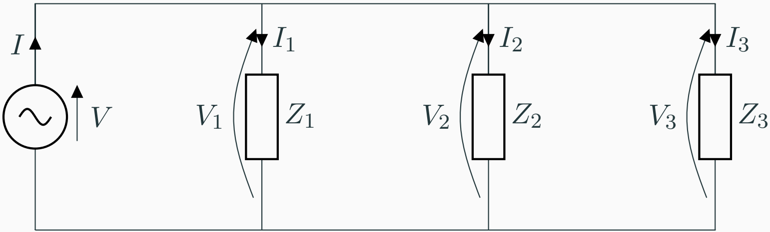


Figure 9: Three arbitrary impedances in parallel

- For a **parallel arrangement**, the total impedance Z_T presented by the circuit is,

$$Z_T = \left(\frac{1}{Z_1} + \frac{1}{Z_2} + \frac{1}{Z_3} \right)^{-1}. \tag{8}$$

- For **two elements** in parallel:

$$Z_T = \frac{Z_1 Z_2}{Z_1 + Z_2}. \tag{9}$$

Types of component

- **Resistor** - a passive electrical component that resists the flow of current.
- **Capacitor** - a passive electrical component which has the ability or ‘capacity’ to store energy in the form of an electrical charge producing a potential difference across its two ends.
- **Inductor** - a passive electrical component consisting of a coil of wire which is designed to take advantage of the relationship between magnetism and electricity as a result of an electric current passing through the coil.

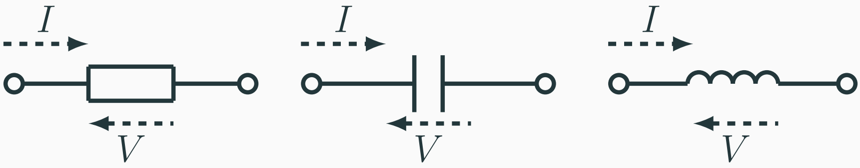


Figure 10: Symbols for resistor, capacitor and inductor.

Types of component: resistor

- **Resistor** - a passive electrical component that resists the flow of current.
- Resistance R relates voltage to current

$$V = IR \tag{10}$$

- Impedance of a resistor is

$$Z_E = \frac{V}{I} = R \tag{11}$$

Complex numbers (quick detour)

Complex numbers: quick recap

- Complex number

$$z = a + jb = |z|e^{j\theta}. \qquad (12)$$

- Magnitude and phase

$$|z| = \sqrt{a^2 + b^2}, \quad \theta = \tan^{-1}\left(\frac{b}{a}\right) \qquad (13)$$

- Very important equation: Euler's formula

$$e^{j\theta} = \cos\theta + j\sin\theta \qquad (14)$$

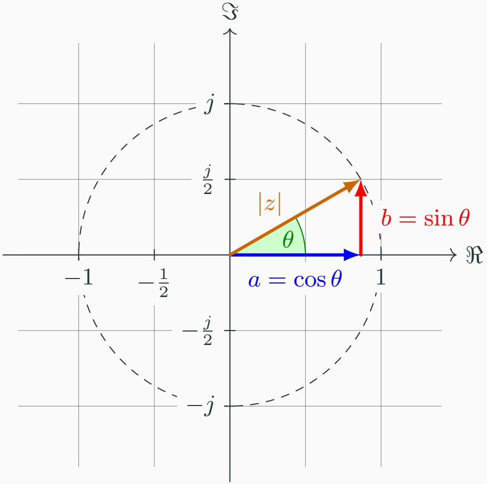


Figure 11: The complex plane

Complex numbers: quick recap

- Why use complex numbers? Convenient to represent periodic motion (please watch part one of this youtube playlist)

$$u(t) = \text{Real}\left[u_0 e^{j(\omega t+\phi)}\right] = u_0 \cos(\omega t + \phi) \tag{15}$$

- Time derivative

$$\frac{du}{dt} = j\omega u_0 e^{j\omega t} = j\omega u \tag{16}$$

- Integral wrt. time

$$\int u dt = \frac{1}{j\omega} u_0 e^{j\omega t} = \frac{1}{j\omega} u \tag{17}$$

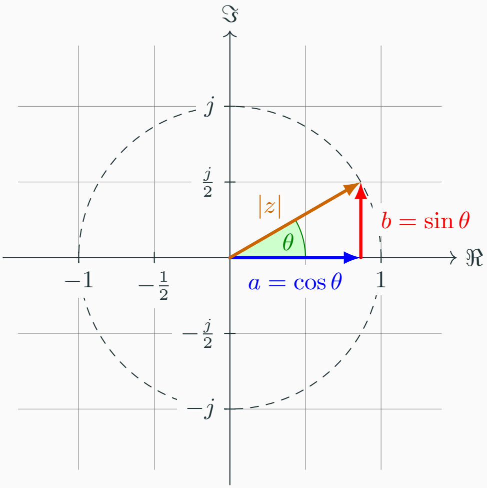


Figure 11: The complex plane

Types of component: capacitor

- **Capacitor** - a passive electrical component which has the ability or 'capacity' to store energy in the form of an electrical charge producing a potential difference across its two ends.
- Capacitance C relates voltage to charge

$$Q = CV \tag{18}$$

- Current is the time rate of change of charge

$$I = \frac{dQ}{dt} = C\frac{dV}{dt} = j\omega CV \tag{19}$$

- Impedance of a capacitor is

$$Z_E = \frac{V}{I} = \frac{1}{j\omega C} \tag{20}$$

Types of component: inductor

- **Inductor** - a passive electrical component consisting of a coil of wire which is designed to take advantage of the relationship between magnetism and electricity as a result of an electric current passing through the coil.

- Inductance L relates the time rate of change of current to voltage

$$V = L\frac{dI}{dt} = j\omega LI \tag{21}$$

- Impedance of an inductor is

$$Z_E = \frac{V}{I} = j\omega L \tag{22}$$

Types of component: summary

- Impedance is frequency dependant!
- Resistors

$$Z_{Er} = R \tag{23}$$

- Capacitors

$$Z_{Ec} = \frac{1}{j\omega C} \tag{24}$$

- Inductors

$$Z_{El} = j\omega L \tag{25}$$

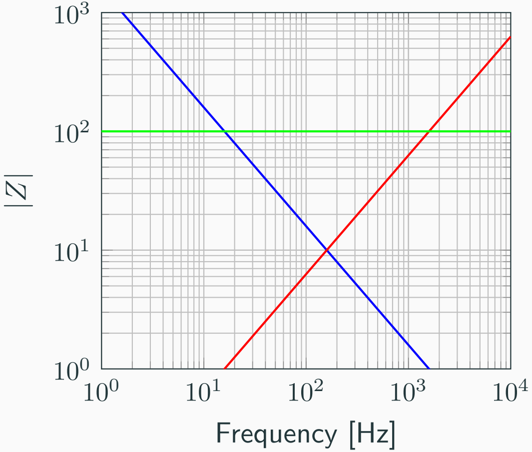
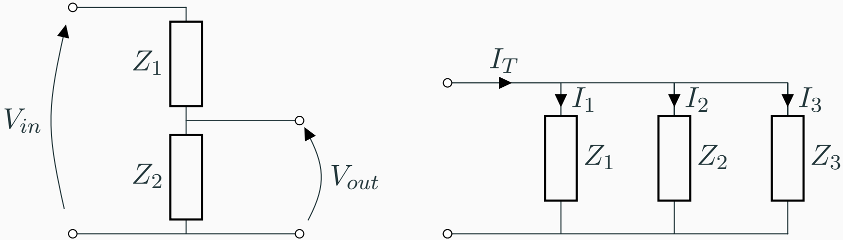


Figure 12: Impedance curves for resistor, capacitor and inductor.

Divider circuits

- By arranging collections of electrical components we can create circuits that manipulate the voltage and/or current they are being driven with.



(a) Potential divider **(b)** Current divider

Figure 13: Voltage and current divider circuits

Voltage divider

- Input voltage

$$V_{in} = IZ_T \rightarrow I = \frac{V_{in}}{Z_T} \tag{26}$$

- Output voltage

$$V_{out} = IZ_{out} \rightarrow V_{out} = \frac{Z_{out}}{Z_T} V_{in} \tag{27}$$

- We define the transfer function

$$H = \frac{V_{out}}{V_{in}} = \frac{Z_{out}}{Z_T} \tag{28}$$

- Special case when just two elements are present

$$H = \frac{Z_2}{Z_1 + Z_2} \tag{29}$$

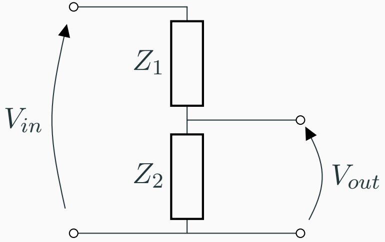


Figure 14: Potential (voltage) divider circuit

Current divider

- Total current

$$V = I_T Z_T \tag{30}$$

- The current though branch n

$$I_n = \frac{V}{Z_n} \rightarrow I_n = \frac{Z_T}{Z_n} I_T \tag{31}$$

- We define the transfer function

$$H_n = \frac{I_n}{I_T} = \frac{Z_T}{Z_n} \tag{32}$$

- Special case when just two elements are present

$$H_2 = \frac{Z_1}{Z_1 + Z_2} \tag{33}$$

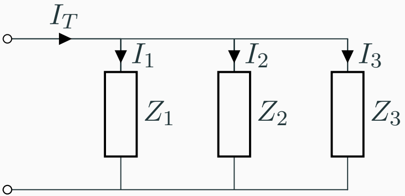


Figure 15: Current divider circuit

Next week...

- Electrical filters (high pass, low pass, resonators, Q-factor)
- The mechanical domain (mechanical impedance)

- Reading:
  - AC circuit theory: lecture notes, ch. 3, pg. all
  - Mechanical domain: lecture notes, ch. 4, pg. 28-31