ELEC 207
Instrumentation and Control

13 – Signal Filtering

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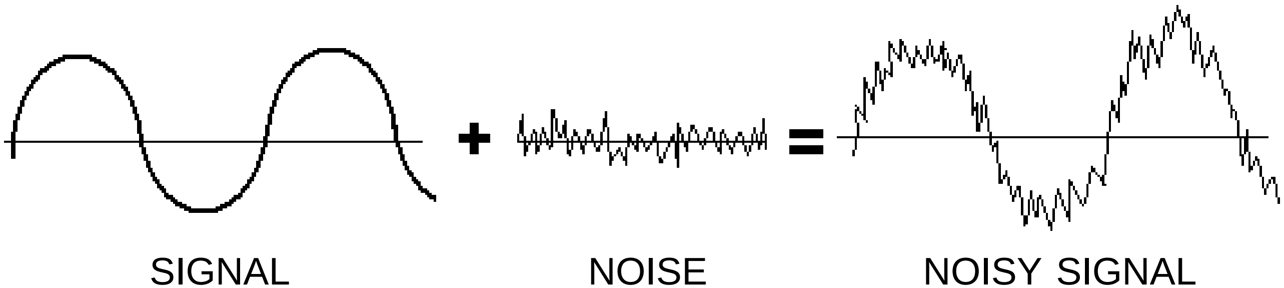
Signal and noise

Separation in the frequency domain

Often the (meaningful) measurement signal and the noise are well separated in the frequency domain:

- A typical example is high-frequency noise arising from electromagnetic interference, superimposed to a low-frequency signal;



- In this case, the noise can be removed (or at least reduced) by **filtering the signal** to **separate its different frequency components**.

Signal and noise
Filtering

A filter is a signal processing (or signal conditioning) element which (ideally) transmits only a certain range of frequencies and rejects all other frequencies:

- It can be used to separate noise from the measurement signal when they are in different frequency ranges, and/or to avoid aliasing errors when sampling a signal.

Filters can be analog or digital:

- **Analog filters** are applied to an analog signal (e.g. before the ADC) and are **electrical circuits** usually composed of resistors and capacitors (RC filters);

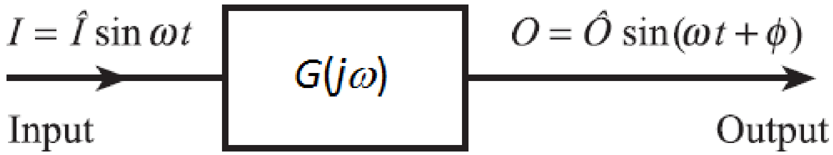
- **Digital filters** are applied to a digital signal (e.g. after the ADC) and are **algorithms** implemented in a processor (e.g., a PC or microcontroller).

Filters

Frequency response

Because of their operation in the frequency domain, filters are typically described in terms of their **frequency response**:

$$G(j\omega) = \frac{O(j\omega)}{I(j\omega)}$$



- The **magnitude** of *G*(*jω*) should ideally be 1 in the band-pass frequency range (range of frequencies to be transmitted) and 0 in the band-stop frequency range (range of frequencies to be stopped);

- The **phase** of *G*(*jω*) should ideally be 0 in the band-pass range.

Different values of magnitude and phase cause **distortions and delays**.

Filters

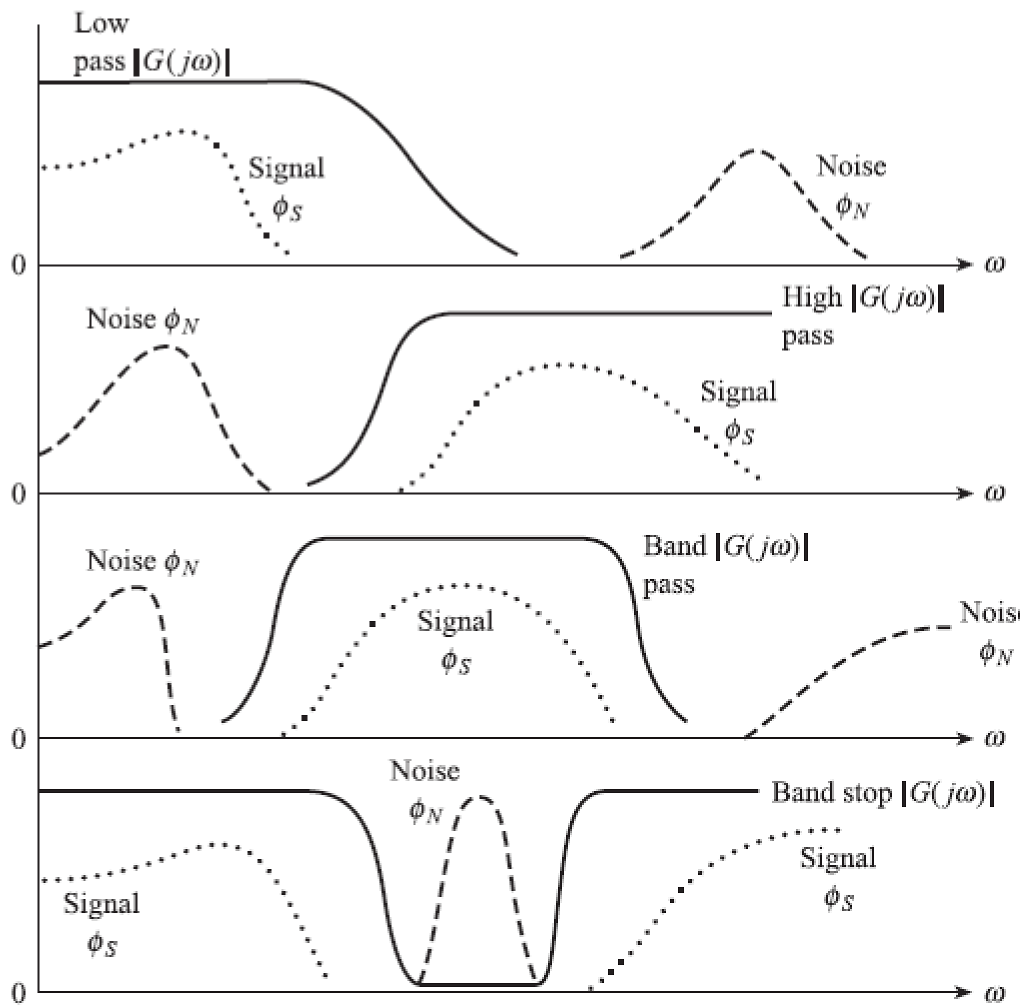
Types of filters

LOW-PASS FILTER

HIGH-PASS FILTER

BAND-PASS FILTER

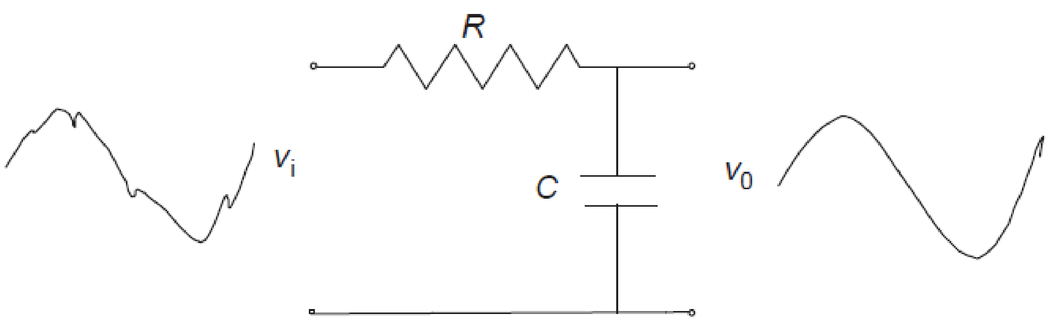
BAND-STOP FILTER



Filters

Analog vs digital filters (1)

- An example of an **analog** low-pass filter is an **RC filter**:



$$G(j\omega) = \frac{1}{1 + j\omega RC}$$

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- An example of a **digital** low-pass filter is a **moving average filter**:

$$\hat{v}_k = \frac{1}{N}\sum_{i=0}^{N-1} v_{k-i}$$

Filters

Analog vs digital filters (2)

Although analog and digital filters can have the same function and may have the same (or a similar) frequency response, they **are not equivalent**:

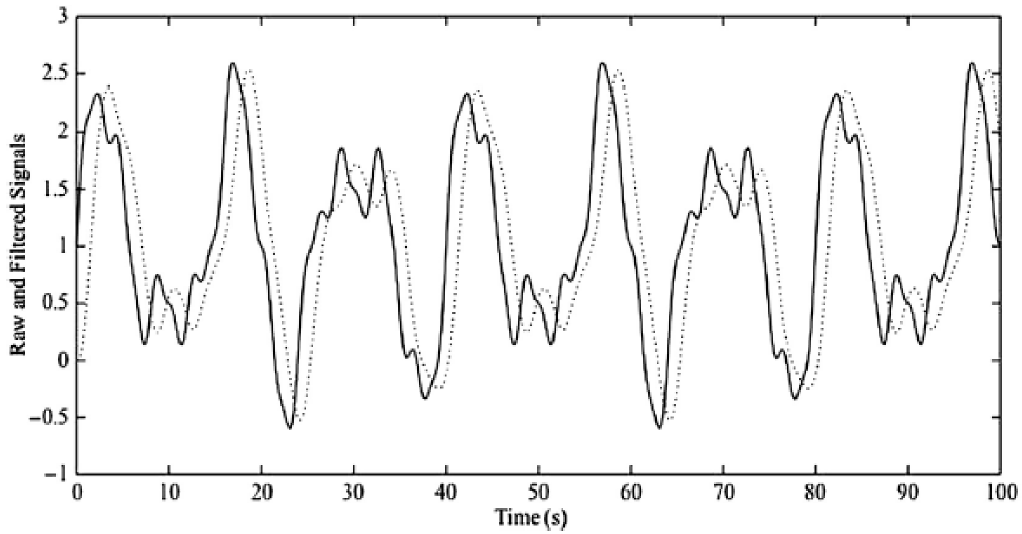
- **Analog filters** are applied before the ADC, so they can modify the bandwidth of the signal **before it is sampled**:
  - E.g., a low-pass filter can remove the noise at frequencies higher than $f_s/2$, so that the sampling condition $f_s > 2f_{max}$ is satisfied and no aliasing appears (this type of filter is called **anti-aliasing filter**);
- If a **digital filter** with the same frequency response is applied to the signal **after it has been sampled** and converted, it won't be effective because aliasing has already appeared and it is irreversible.

Limitations of signal filtering

Non-ideal frequency response

The frequency response of a real filter is different from the ideal response:

- The measurement signal (which should be transferred unchanged through the filter) may be **distorted and/or delayed**;



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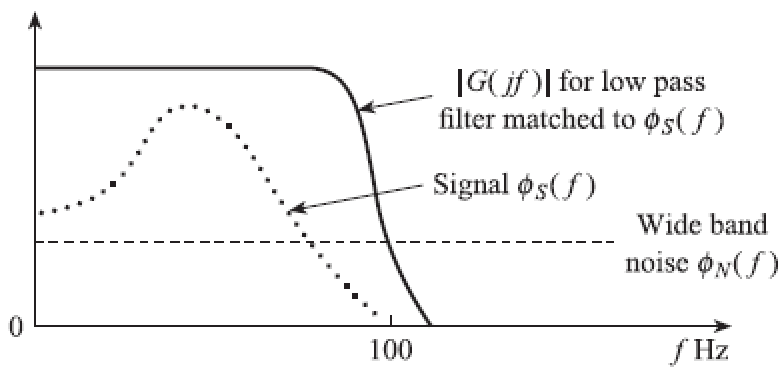
- Undesired frequency components may not be completely filtered out.

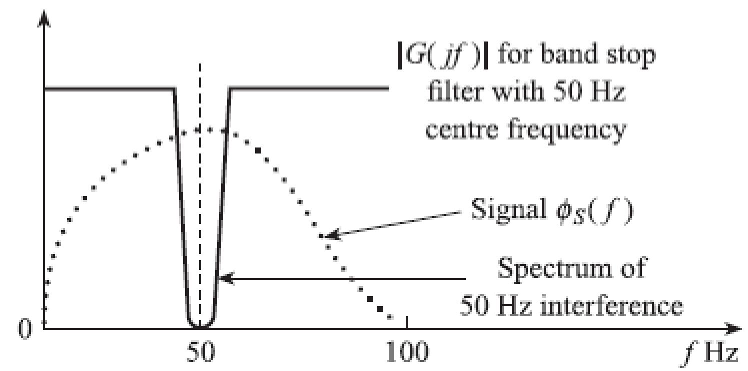
Limitations of signal filtering

Overlapping signal and noise frequency ranges

The meaningful part of the measurement signal and the noise may not be completely separated in the frequency domain. In this case, filtering cannot completely remove the noise without affecting also the measurement signal:

- Examples are a wide band noise superimposed also to the low-frequency signal, or a 50 Hz interference from the mains falling within the range of the measurement signal.





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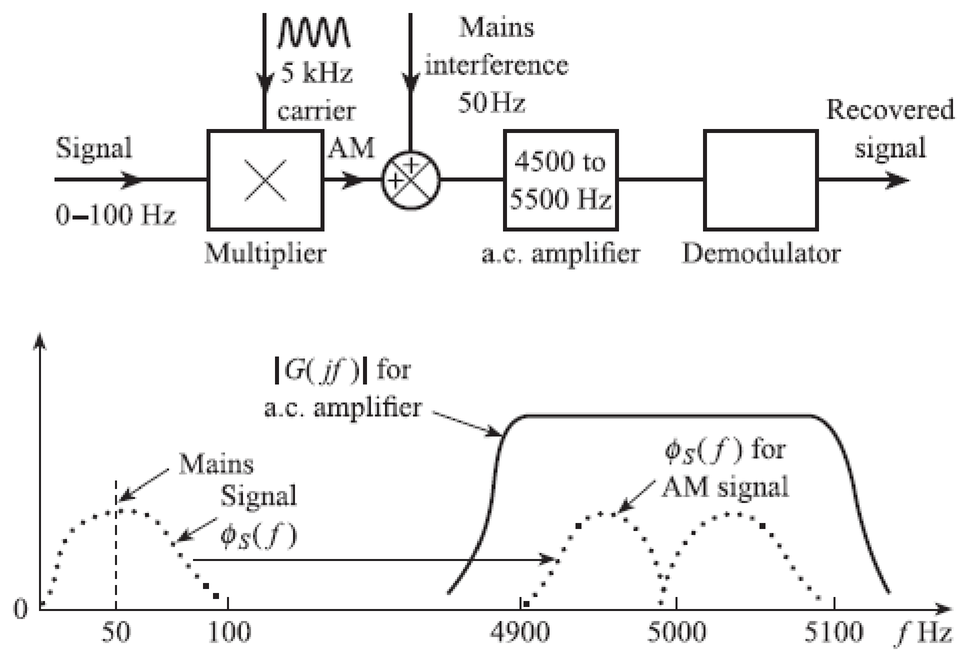
Signal modulation
Frequency shift

A possible way to avoid the overlapping frequency ranges of the signal and the noise is to shift the frequency spectrum of the signal before noise is added (e.g. when noise arises from the signal transmission):

- This is achieved by the signal **modulation**, i.e. the multiplication of the signal by a **higher-frequency carrier signal**;

- This technique is widely employed in **signal transmission** (e.g. telecommunication).



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References

Textbook: Principles of Measurement Systems, 4th ed.

For further explanation about the points covered in this lecture, please refer to the following chapters and sections in the **Bentley** textbook:

- Chapter 6, Sec. 6.5.5: **Filtering**;
- Chapter 6, Sec. 6.5.6: **Modulation**;
- Chapter 10, Sec. 10.4.2: **Dynamic digital compensation and filtering**.

NOTE: Topics not covered in the lecture are not required for the exam.

References

Textbook: Measurement and Instrumentation, 2nd ed.

For further explanation about the points covered in this lecture, please refer to the following chapters and sections in the **Morris-Langari** textbook:

- Chapter 6, Sec. 6.6: **Analog signal processing**;
- Chapter 6, Sec. 6.7: **Passive filters**;
- Chapter 6, Sec. 6.10: **Digital filters**;
- Chapter 8, Sec. 8.2.3: **Transmission using an AC carrier**.

NOTE: Topics not covered in the lecture are not required for the exam.