FH JOANNEUM
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Master's Thesis

written by:
Author

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of the FH JOANNEUM – University of Applied Sciences, Austria

supervised by:
Supervisor

Graz, July 15, 2024

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Abstract

Please put the summary of your work here!

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Methods

In this very first chapter, we clarify how to add your math within the text in a proper way. Below you will find some small samples of the book *"Single Channel Phase-Aware Signal Processing in Speech Communication: Theory and Practice"* [7], may this example arouses your interest to dig more into the *Signal Processing* and it's related topic *Speech Processing*.

Listing 2.1: Adding section and subsection

```
        \section{Phase Estimation Fundamentals}
        \subsection{Background and Fundamentals}
        The problem of interest in many signal processing.......
```

2.1 Phase Estimation Fundamentals

2.1.1 Background and Fundamentals

The problem of interest in many signal processing applications including radar, spectrum estimation and signal enhancement, is to detect a signal of interest in a noisy observation. The signal of interest is often represented as a sum of sinusoids characterized by their amplitude, frequency and phase parameters. Since these parameter triplet suffices to describe the signal, the problem degenerates to the detection and estimation of the sinusoidal parameters. This topic has been widely addressed in the literature of signal detection [10] and estimation [4]. While many previous studies have been focused on deriving estimators for amplitude and frequency of sinusoids in noise (see e.g. [8] for an overview), the issue of phase estimation has been less addressed. Reliable phase estimation for practical applications has not been adequately addressed, in particular for signal enhancement.

Listing 2.2: Add citations into your text

```
......the sinusoidal parameters. This topic has been widely addressed in
    the
literature of signal detection \cite{VanTrees 1968} and estimation
\cite{Kay 1993}.
```

Do not forget to add these specific bibliography fields into your *.bib* file!

2.2 Key Examples: Phase Estimation Problem

2.2.1 Example 1: discrete-time sinusoid

To reveal the phase structure of one sinusoid's frequency response we consider the following real-valued sequence

$$x(n) = \cos(\omega_0 n + \phi), \tag{2.1}$$

with ω_0 as frequency and ϕ as phase shift. Application of the discrete-time Fourier transform (DTFT), defined as

$$X(e^{j\omega}) = \mathrm{DTFTT}\left(x(n)\right) = \sum_{n=-\infty}^{\infty} x(n)e^{-j\omega n}, \tag{2.2}$$

yields the following frequency domain representation of the sequence $x(n)$

$$X(e^{j\omega}) = \pi e^{j\phi}\delta(\omega - \omega_0) + \pi e^{-j\phi}\delta(\omega + \omega_0), \tag{2.3}$$

with $\delta(\omega)$ denoting the Dirac delta function. As the cosine function is symmetric $(\cos(\omega_0 n) = \cos(-\omega_0 n))$, only the phase shift ϕ determines the phase response of $X(e^{j\omega})$

$$\angle X(e^{j\omega}) = \begin{cases} \phi, & \omega = \omega_0, \\ -\phi, & \omega = -\omega_0 \end{cases}. \tag{2.4}$$

The left column of Figure 2.1 represents the sequence $x(n)$ along time n followed by its DTFTT representation with real $\Re\{X(e^{j\omega})\}$ and imaginary $\Im\{X(e^{j\omega})\}$ parts as well as magnitude $|X(e^{j\omega})|$ and phase $\angle X(e^{j\omega})$ response. We set $\omega = 0.1 \cdot 2\pi$ and $\phi = -\pi/8$.

The result in (2.4) is valid for an observation range of n within $n \in]-\infty, \infty[$. In practice only a subset of samples n is available for analysis. This limitation can be represented by introducing an

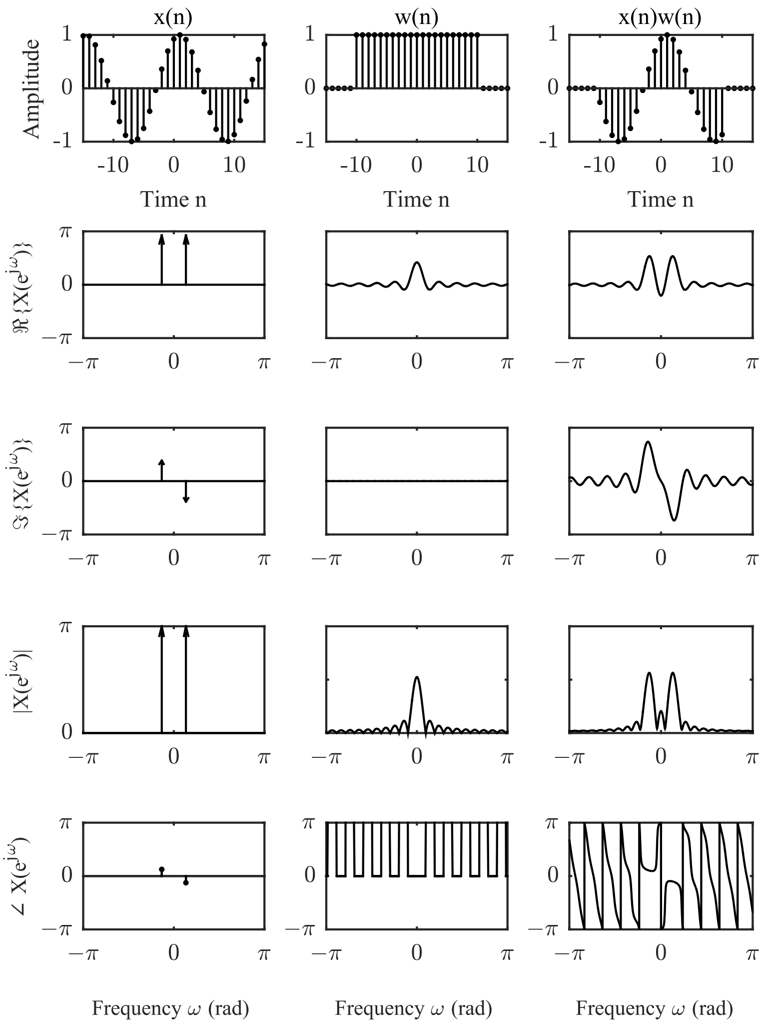

Figure 2.1: Visualization of window impact on a sinusoid $x(n) = \cos(\omega_0 n + \phi)$ in time and frequency domain with $\omega_0 = 0.1 \cdot 2\pi$ and $\phi = -\pi/8$ and a rectangular window with length $N_w = 21$. The window DTFTT $W(e^{j\omega})$ is shifted dependent on ω_0 and multiplied by $e^{j\phi}$ and $e^{-j\phi}$, respectively, as shown in the phase response of DTFTT $(x(n)w(n))$

analysis window function which is multiplied with the sequence $x(n)$. The modest analysis window is the rectangular, also known as boxcar or uniform window which has the value of one within the range of N_w and zero outside

$$w(n) = \begin{cases} 1, & |n| \leq \frac{N_w-1}{2}, \\ 0, & \text{else}, \end{cases} \tag{2.5}$$

for odd N_w. This window is symmetric ($w(n) = w(-n)$) and has the zero-phase property, yielding a real-valued DTFTT of the analysis window

$$W(e^{j\omega}) = \sum_{n=-\infty}^{\infty} w(n)e^{-j\omega n} = \sum_{n=-(N_w-1)/2}^{(N_w-1)/2} 1e^{-j\omega n} = \frac{\sin\left(\frac{N_w\omega}{2}\right)}{\sin\left(\frac{\omega}{2}\right)}, \tag{2.6}$$

also known as *Dirichlet kernel.* The middle column of Figure 2.1 illustrates a symmetric rectangular window in time and frequency domain with length $N_w = 21$ and a DTFTT length of $N = 31$ (continuous line). The real part is equal to the Dirichlet kernel and the imaginary part is equal to zero due to the symmetry of the window $w(n)$. The phase response represents the sign of $W(e^{j\omega})$ dependent on ω and is equal to zero within the mainlobe width.

The product $x(n)w(n)$ corresponds to a convolution in the frequency domain according to

$$X_w(e^{j\omega}) = \text{DTFTT}\left(x(n)w(n)\right) = \left\{X * W\right\}(e^{j\omega}). \tag{2.7}$$

Listing 2.3: Add formulars to your text

```
    \begin{equation}\label{eq:c1.7}
        X_w(e^{j\omega})=\text{\gls{DTFT}T}\left(x(n)w(n)\right)=\left\{X\ast W\right\}(e^{j\omega}).
    \end{equation}
```

By adding a label to your equation, you will be able to refer to the equation within the text!

Plugging $X(e^{j\omega})$ and $W(e^{j\omega})$, derived in (2.3) and (2.6), respectively, in (2.7) yields the following expression

$$X_w(e^{j\omega}) = \pi e^{j\phi}W(e^{j(\omega-\omega_0)}) + \pi e^{-j\phi}W(e^{j(\omega+\omega_0)}). \tag{2.8}$$

Listing 2.4: Example on how to add a figure to your text

```
\begin{figure}
  \center % 20 587 530 727
  \includegraphics{figures/figure3_2.eps}
  \vspace{-0.6cm}
  \caption{Relation of sinusoidal periods and window length and its impact
      on amplitude and phase: (a) shows a sinusoid multiplied by a boxcar
      window with a length of one period $(m=1)$. ...}\label{Figure32}
\end{figure}
```

By adding a label to your figure, you will be able to refer to the figure within the text!

This is a rather important observation as the Dirichlet kernels are shifted along the frequency axis to $\omega = \omega_0$ and $\omega = -\omega_0$. The multiplication by the constants $e^{j\phi}$ and $e^{-j\phi}$, respectively, yields a complex valued $X_w(e^{j\omega})$ as shown in the right column of Figure 2.1. The terms on the right-hand-side of (2.8) constructively add or eliminate each other, dependent on the value of ϕ and ω_0, described as *leakage effect*.

The interaction between the Dirichlet kernels is minimized if the frequency ω_0 fulfills the following requirement

$$\omega_0 = \frac{2m\pi}{N_w}, \quad m \in \mathbb{N}. \tag{2.9}$$

with m denoting the number of periods contained in one window length N_w. Figure 2.2 illustrates the impact of ω on the resulting magnitude and phase response of one sinusoid $x(n) = \cos(\omega_0 n + \phi)$ with $\phi = -\pi/8$, multiplied by a symmetric window of length $N_w = 31$. Setting $\omega_0 = 1\frac{2\pi}{N_w}$ leads to $m = 1$ and for the phase response at frequency $\omega = \omega_0$ we obtain

$$X_w(e^{j\omega_0}) = \pi e^{j\phi} W(e^{j(\omega_0 - \omega_0)}) + \pi e^{-j\phi} W(e^{j(\omega_0 + \omega_0)}) \tag{2.10}$$

As the DTFTT of the rectangular window $W(e^{j2\omega_0}) = 0$ for $m \in \mathbb{N}$, the phase response yields the true value of ϕ at frequency ω_0.

$$X_w(e^{j\omega_0}) = \pi e^{j\phi} CG \tag{2.11}$$

$$\angle X_w(e^{j\omega_0}) = \phi, \tag{2.12}$$

with defining $CG = W(e^{j0})$ as the coherent gain for the selected window[1]. The right column of

[1] Using a footnote you can associate you can give the reader the opportunity, to search for alternative sources

Figure 2.2 demonstrates the more general case of $m \notin \mathbb{N}$. The sidelobs of $W(e^{j\omega})$ interact with each other, resulting in a biased phase response at ω_0. Note, that the peak's location of the magnitude response is not at ω_0 due to the complex-valued superposition of both kernels. Therefore, any peak-picking method for obtaining a sinusoidal phase would result in a biased outcome.

In order to reduce the unpleasant impact of the sidelobe level, the choice of the window type becomes of particular interest. Basically, their behavior can be categorized by two characteristics: spectral leakage and frequency resolution. The frequency resolution is limited by the mainlobe width which corresponds to the ability to resolve two adjacent spectral lines. To increase the frequency resolution a window function with a small mainlobe width is preferred. As a smaller mainlobe width is on the expense of a reduced sidelobe level the choice of an appropriate window function is a trade-off between a high frequency resolution and a low sidelobe level. Another way of optimizing the window choice is to adjust the window length N_w to fulfill the requirement in (2.9). However, adapting N_w needs knowledge of ω_0 and is in general only possible for one single sinusoid.

Figure 2.3 shows the influence of three prominent window types on the amplitude and phase response of the sequence $x_w(n) = \sin(\omega_0 n + \phi)w(n)$ with $\omega = 3.1 \cdot 2\pi/N_w$ and $\phi = -\pi/8$. So far, only the rectangular window was discussed. Its high frequency resolution (6 dB bandwidth of the mainlobe width: $\Delta\omega_{\text{MW}} = 1.21 \cdot 2\pi/N_w$) is at the cost of rather poor sidelobe suppression level of -13 dB for the strongest neighboring sidelobe (Fig. 2.3 a)). The widely used Hamming window (b) consists of three shifted Dirichlet kernels with the purpose to minimize the sidelobe levels, achieving a suppression of -42 dB at the cost of a worse frequency resolution (6 dB bandwidth of mainlobe: $\Delta\omega_{\text{MW}} = 1.81 \cdot 2\pi/N_w$). The amplitude and phase response of the Hamming-windowed sinusoid reveal the advantage of a higher sidelobe suppression. The phase response at frequencies within the mainlobe width is determined by the true phase value $\phi = -\pi/8$. Compared to the rectangular window, the employment of a Hamming window results in a more robust phase estimation if an inaccurate frequency estimate of the sinusoid is given. Further, the magnitude's peak location is less shifted which yields a more accurate phase estimation when using peak-picking. Finally, the Blackman window is presented in (c) with a sidelobe suppression of -58 dB and a 6 dB mainlobe bandwidth of $\Delta\omega_{\text{MW}} = 2.35 \cdot 2\pi/N_w$. The neighboring phase values at ω_0 are strongly influenced by the true phase value of ϕ. However, both Hamming and Blackman windows deal with an increased mainlobe width. Once we extend our signal to multiple sinusoids, the mainlobe width plays a major role in selecting an appropriate window. If the mainlobe width contains more than one sinusoid then it is no longer possible to resolve the phase values of the sinusoids.

2.2.2 Example 2: discrete-time sinusoid in noise

So far, one sinusoid without additive noise was considered. For practical scenarios, the signal of interest is composed of multiple sinusoids corrupted with noise as shown in Figure 2.4. The problem to solve is the estimation of the sinusoidal phase ϕ_h given its amplitude and frequency denoted as A_h and ω_h, respectively. Following the harmonic model of a speech signal we assume that the sinusoidal frequency ω_h is constrained to be a multiple harmonic of a fundamental frequency, i.e. $\omega_h = h\omega_0$ with $h \in [1, \ldots, H]$ denoting the harmonic index

$$x(n) = \sum_{h=1}^{H} A_h \cos(\omega_h n + \phi_h) + d(n), \tag{2.13}$$

with $\omega_h = h2\pi f_0/f_s$ and $d(n)$ as the additive noise. Application of a window function $w(n)$, having non zero values in the range of $[-(N_w - 1)/2, (N_w - 1)/2]$, yields the windowed signal $x_w(n) = x(n)w(n)$. Similar to (2.8), the DTFTT spectrum follows as

$$X_w(e^{j\omega}) = \sum_{h=1}^{H} A_h \pi \left(e^{j\phi_h} W(e^{j(\omega-\omega_h)}) + e^{-j\phi_h} W(e^{j(\omega+\omega_h)}) \right) + D_w(e^{j\omega}), \tag{2.14}$$

where $D_w(e^{j\omega}) = \sum_{n=-(N_w-1)/2}^{(N_w-1)/2} d(n)w(n)e^{-j\omega n}$ and $W(e^{j\omega})$ is the window frequency response. To have a better insight into the phase estimation problem, we are interested in the effect of the neighboring harmonics $h \neq \bar{h}$ on the desired harmonic $\bar{h}$. We evaluate the frequency response of $X(e^{j\omega_{\bar{h}}})$ at the desired frequency $\omega_{\bar{h}}$

$$\begin{aligned} X_w(e^{j\omega_{\bar{h}}}) &= A_{\bar{h}} \pi e^{j\phi_{\bar{h}}} \cdot CG + A_{\bar{h}} \pi e^{-j\phi_{\bar{h}}} W(e^{j2\omega_{\bar{h}}}) \\ &+ \sum_{h=1, h\neq\bar{h}}^{H} A_h \pi e^{j\phi_h} W(e^{j(\omega_{\bar{h}}-\omega_h)}) + A_h \pi e^{-j\phi_h} W(e^{j(\omega_{\bar{h}}+\omega_h)}) + D_w(e^{j\omega_{\bar{h}}}). \end{aligned} \tag{2.15}$$

The additive terms on the right-hand-side of Equation (2.15) show the interaction of the adjacent harmonics to the desired phase $\phi_{\bar{h}}$ as well as the impact of the additive noise. In the following we are interested in the influence of these terms on the desired phase by re-writing (2.15) according to

$$X_w(e^{j\omega_{\bar{h}}}) = X_r(e^{j\omega_{\bar{h}}})e_c \tag{2.16}$$

where $X_r(e^{j\omega_{\bar{h}}}) = A_{\bar{h}}\pi e^{j\phi_{\bar{h}}}$ and e_c captures the phase estimation errors, given by

$$\begin{aligned} e_c \;&=\; \sum_{h=1}^{H} \frac{A_h}{A_{\bar{h}}} \left(e^{j(\phi_h - \phi_{\bar{h}})} W(e^{j(\omega_{\bar{h}} - \omega_h)}) + e^{-j(\phi_h + \phi_{\bar{h}})} W(e^{j(\omega_{\bar{h}} + \omega_h)}) \right) \\ &+\; \frac{1}{\pi A_{\bar{h}}} e^{-j\phi_{\bar{h}}} D_w(e^{j\omega_{\bar{h}}}) \end{aligned} \tag{2.17}$$

In order to get more insight on the phase error term e_c, in the following we derive its phase mean and variance.

First moment of e_c

The mean value of the phase error term is given by

$$\mathbb{E}_\phi(e_c) = \int_{-\pi}^{\pi} e_c p(\phi) d\phi \tag{2.18}$$

with $p(\phi)$ denoting the phase distribution. Applying (2.18) to (2.17) the first moment of e_c is given by

$$\begin{aligned} \mathbb{E}_\phi(e_c) = &\sum_{h=1}^{H} \frac{A_h}{A_{\bar{h}}} \mathbb{E}(e^{j(\phi_h - \phi_{\bar{h}})}) W(e^{j(\omega_{\bar{h}} - \omega_h)}) \\ &+ \sum_{h=1}^{H} \frac{A_h}{A_{\bar{h}}} \mathbb{E}(e^{-j(\phi_h + \phi_{\bar{h}})}) W(e^{j(\omega_{\bar{h}} + \omega_h)}) \\ &+ \frac{1}{\pi A_{\bar{h}}} \mathbb{E}(e^{-j\phi_{\bar{h}}}) D_w(e^{j\omega_{\bar{h}}}) \end{aligned} \tag{2.19}$$

Second moment of e_c

The second moment of the error term is given by

$$
\begin{split}
\mathbb{E}_\phi\left(e_c e_c^*\right)&=\!\sum_{h_1=1}^{H-1} \sum_{h_2=h_1+1}^H \! C_1(\bar{h},h_1,h_2) \mathbb{E}_\phi\!\left(\cos(\phi_{h_1} \!-\! \phi_{h_2} \!+\!\angle w_1(\bar{h},h_1,h_2))\right)\\
&+ \!\sum_{h_1=1}^{H-1} \sum_{h_2=h_1+1}^H\!C_2(\bar{h},h_1,h_2)\mathbb{E}_\phi\!\left(\cos(\phi_{h_1} \!-\! \phi_{h_2} \!-\!\angle w_2(\bar{h},h_1,h_2))\right)\\
&+ \!\sum_{h_1=1}^H \sum_{h_2=1}^H\!C_3(\bar{h},h_1,h_2)\mathbb{E}_\phi\!\left(\cos(\phi_{h_1} \!+\! \phi_{h_2} \!+\!\angle w_3(\bar{h},h_1,h_2))\right)\\
&+\sum_{h=1}^H C_4(\bar{h},h)\mathbb{E}_\phi\left(\cos(\phi_h-\phi_{\bar{h}}+\angle W(e^{j(\omega_{\bar{h}}-\omega_h)})D_w(e^{-j\omega_{\bar{h}}}))\right)\\
&+\sum_{h=1}^H C_5(\bar{h},h)\mathbb{E}_\phi\left(\cos(\phi_h+\phi_{\bar{h}}-\angle W(e^{j(\omega_{\bar{h}}+\omega_h)})D_w(e^{-j\omega_{\bar{h}}}))\right)\\
&+\frac{1}{\pi^2A_{\bar{h}}^2}|D_w(e^{j\omega_{\bar{h}}})|^2 + C_6(\bar{h}),
\end{split}
\tag{2.20}
$$

Listing 2.5: Add formulars to your text, splitted equations

```
\begin{equation}\label{phasevar0}
  \begin{split}
    \mathbb{E}_\phi\left(e_c e_c^*\right)&=\!\sum_{h_1=1}^{H-1} \sum_{h_2=h_1+1}^H \! C_1(\bar{h},h_1,h_2) \mathbb{E}_\phi\!\left(\cos(\phi_{h_1} \!-\! \phi_{h_2} \!+\!\angle w_1(\bar{h},h_1,h_2))\right)\\
    &+ \!\sum_{h_1=1}^{H-1} \sum_{h_2=h_1+1}^H\!C_2(\bar{h},h_1,h_2)\mathbb{E}_\phi\!\left(\cos(\phi_{h_1} \!-\! \phi_{h_2} \!-\!\angle w_2(\bar{h},h_1,h_2))\right)\\
    &+ \!\sum_{h_1=1}^H \sum_{h_2=1}^H\!C_3(\bar{h},h_1,h_2)\mathbb{E}_\phi\!\left(\cos(\phi_{h_1} \!+\! \phi_{h_2} \!+\!\angle w_3(\bar{h},h_1,h_2))\right)\\
    &+\sum_{h=1}^H C_4(\bar{h},h)\mathbb{E}_\phi\left(\cos(\phi_h-\phi_{\bar{h}}+\angle W(e^{j(\omega_{\bar{h}}-\omega_h)})D_w(e^{-j\omega_{\bar{h}}}))\right)\\
    &+\sum_{h=1}^H C_5(\bar{h},h)\mathbb{E}_\phi\left(\cos(\phi_h+\phi_{\bar{h}}-\angle W(e^{j(\omega_{\bar{h}}+\omega_h)})D_w(e^{-j\omega_{\bar{h}}}))\right)\\
    &+\frac{1}{\pi^2A_{\bar{h}}^2}|D_w(e^{j\omega_{\bar{h}}})|^2 + C_6(\bar{h}),
  \end{split}
\end{equation}
with the abbreviations
\begin{equation}
  \begin{split}
    w_1(\bar{h},h_1,h_2)&=W(e^{j(\omega_{\bar{h}}-\omega_{h_1})})W(e^{-j(\omega_{\bar{h}}-\omega_{h_2})}),\\
```

```
            w_2(\bar{h},h_1,h_2)&=W(e^{j(\omega_{\bar{h}}+\omega_{h_1})})W(e^{-j(\omega_{\bar{h}}+\omega_{h_2})}),\\
            w_3(\bar{h},h_1,h_2)&=W(e^{j(\omega_{\bar{h}}-\omega_{h_1})})W(e^{-j(\omega_{\bar{h}}+\omega_{h_2})}),
        \end{split}
    \end{equation}
```

By adding a label to your equation, you will be able to refer to the equation within the text!

with the abbreviations

$$\begin{aligned} w_1(\bar{h},h_1,h_2) &= W(e^{j(\omega_{\bar{h}}-\omega_{h_1})})W(e^{-j(\omega_{\bar{h}}-\omega_{h_2})}),\\ w_2(\bar{h},h_1,h_2) &= W(e^{j(\omega_{\bar{h}}+\omega_{h_1})})W(e^{-j(\omega_{\bar{h}}+\omega_{h_2})}),\\ w_3(\bar{h},h_1,h_2) &= W(e^{j(\omega_{\bar{h}}-\omega_{h_1})})W(e^{-j(\omega_{\bar{h}}+\omega_{h_2})}), \end{aligned} \tag{2.21}$$

and the phase independent constants

$$\begin{aligned} C_1(\bar{h},h_1,h_2) &= 2\frac{A_{h_1}A_{h_2}}{A_{\bar{h}}^2}|w_1(\bar{h},h_1,h_2)|,\\ C_2(\bar{h},h_1,h_2) &= 2\frac{A_{h_1}A_{h_2}}{A_{\bar{h}}^2}|w_2(\bar{h},h_1,h_2)|,\\ C_3(\bar{h},h_1,h_2) &= 2\frac{A_{h_1}A_{h_2}}{A_{\bar{h}}^2}|w_3(\bar{h},h_1,h_2)|,\\ C_4(\bar{h},h) &= 2\frac{A_h}{\pi A_{\bar{h}}^2}|W(e^{j(\omega_{\bar{h}}-\omega_h)})||D_w(e^{j\omega_{\bar{h}}})|,\\ C_5(\bar{h},h) &= 2\frac{A_h}{\pi A_{\bar{h}}^2}|W(e^{j(\omega_{\bar{h}}+\omega_h)})||D_w(e^{j\omega_{\bar{h}}})|,\\ C_6(\bar{h}) &= \sum_{h=1}^{H}\frac{A_h^2}{A_{\bar{h}}^2}\left(|W(e^{j(\omega_{\bar{h}}+\omega_h)})|^2+|W(e^{j(\omega_{\bar{h}}-\omega_h)})|^2\right). \end{aligned} \tag{2.22}$$

The second moment of the phase error in (2.20) provides useful insights on how the phase of the desired frequency $\omega_{\bar{h}}$ is a function of the chosen window, the additive noise and the neighboring harmonics. Subsequently the key factors are summarized as

- $W(e^{j\omega})$ the magnitude and phase response of the analysis window function
- $D_w(e^{j\omega})$ the magnitude and phase response of the additive noise
- $\frac{A_h}{A_{\bar{h}}}$ the amplitude ratio of the adjacent and desired harmonics

The impact of the selected window $W(e^{j\omega})$ can be considered for two cases: First, the harmonics are separated sufficiently which means there is no neighboring harmonic within the mainlobe width.

The window's amplitude $W(e^{j(\omega_{\bar{h}}-\omega_h)})$ for $\bar{h} \neq h$ suppresses the neighboring harmonic by its sidelobe level (see Figure 2.3) which results in a low impact of the neighboring harmonics to $\hat{\phi}$. If the harmonics are not separated, i.e., the adjacent harmonic is located within the mainlobe width then the phase error gets larger. The adjacent harmonic is not attenuated by the sidelobe level of the window thus the phase estimation gets more........

2.3 Draw graphics using TikZ & other fancy stuff

TikZ and PGF are TeX packages for creating graphics programmatically. TikZ is build on top of PGF and allows you to create sophisticated graphics in a rather intuitive and easy manner. It also could be necessary to create diagrams or graphics that should change according to variables or differing values. The resulting figures are vector graphic and can be used in different documents as well.

2.4 TikZ Example One

Listing 2.6: TikZ Example One

```
\center

\tikzstyle{arrow} = [thick,->,=>latex]
\begin{tikzpicture}

%%%%%%%%%% TIME DOMAIN %%%%%%%%%%%%%%
\coordinate (B) at (0,0);
\coordinate (Wtime) at ($(B) + (-0.5,-1.5)$);
\coordinate (Xtime) at ($(B) + (4,-2.25)$);
\draw [ultra thick] (B) to ($(B) + (6,-1)$) to ($(B) + (4.25,-3)$) to ($(B) +
    (4.25,-3) - (6,-1)$) to (B);
\filldraw [fill = black!10 ,fill opacity=1,draw opacity=1] (B) to ($(B) + (6,-1)
    $) to ($(B) + (4.25,-3)$) to ($(B) + (4.25,-3) - (6,-1)$) to (B);
\filldraw [black] (Wtime) circle (2pt);
\filldraw [black] (Xtime) circle (2pt);

%%%%%%%%%% SPEC DOMAIN %%%%%%%%%%%%%%
\coordinate (A) at (0,1.75);
\filldraw [fill = white,fill opacity=1,draw opacity=1] ($(A) + (6,-1)$) to ($(A)
     + (4.25,-3)$) to ($(A) + (4.25,-3) - (6,-1)$) to (A);
\draw [ultra thick] (A) to ($(A) + (6,-1)$) to ($(A) + (4.25,-3)$) to ($(A) +
    (4.25,-3) - (6,-1)$) to (A);
\node (domain) at ($(A) + (3.25,-1.7)$) [ellipse, very thin, fill = black!5,
```

```
    draw, minimum width = 3cm, minimum height = 2cm]{};

\coordinate (WSpec) at ($(A) + (0.5,-1)$);
\coordinate (GW) at ($(A) + (2,-1.2)$);
\coordinate (XSpec) at ($(A) + (4,-1.6)$);
\coordinate (GWTwo) at ($(A) + (2.75,-2.12)$);

\filldraw [black] (WSpec) circle (2pt);
\filldraw [black] (GWTwo) circle (2pt) node[black, yshift=0.25cm, xshift=0.125cm
    ]{$\widetilde{X}$};
\filldraw [black] (XSpec) circle (2pt);

\node (domain) at ($(A) + (3.25,-1)$) {$\mathcal{W}$};

\draw [ultra thick] (WSpec) edge[very thick, out=180.5,in=145.5,arrow, shorten
    >=0.1cm] (Wtime) node[black, yshift=0.25cm, xshift=0.125cm]{${X}$};
\draw [ultra thick] (Wtime) edge[out=80,in=135.5,arrow, shorten >=0.1cm] (GWTwo)
     node[black, yshift=-0.25cm, xshift=0.125cm]{$\widetilde{x}$};
\draw [ultra thick] (GWTwo) edge[out=180,in=45,arrow, shorten >=0.1cm] (Wtime);
\draw [arrow, thick, shorten >=0.1cm, dashed] (XSpec) to (WSpec);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
\draw [ultra thick] (Xtime) edge[out=202.5,in=195.5,arrow, shorten >=0.1cm] (
    XSpec) node[black, yshift=-0.275cm, xshift=0cm]{$y$};
\draw [ultra thick] (XSpec) edge[out=-45.5,in=45,arrow, shorten >=0.1cm] (Xtime)
     node[black, yshift=0.125cm, xshift=0.3cm]{$Y$};
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
\node [rotate = -10] (stftdom) at ($(A) + (4.5,-0.6)$) {STFT-Spectrograms};
\node [rotate = -10] (timedom) at ($(A) + (2,-4.2)$) {Time-domain signals};
%%%%%%%%%%%%%%%%%%%%%%55
\node (stftY) at ($(A) + (5,-3)$) {iSTFT};
\node (istftY) at ($(A) + (2.9,-3.25)$) {STFT};
%%%%%%%
\node (stftX) at ($(A) + (0.75,-1.6)$) {STFT};
\node (istftX) at ($(A) + (1.25,-2.05)$) {iSTFT};
\end{tikzpicture}
```

2.5 TikZ Example Two

Listing 2.7: TikZ Example Two

```
\begin{circuitikz}
  % \draw [help lines] (-1,-2) grid (12,5);

  % electrical equivalent circuit
  \draw (0,3) to[V, v_=$U_R$] (0,0);
  \draw (0,3) to[R, i>^=$I_A$, l=$R_A$] (3,3);
```

```
    \draw (3,3) to[L, l=$L_A$] (4,3);

    \draw (4,3) -- (5,3);
    \draw (5,3) to[V, v_=$U_i$] (5,0);
    \draw (0,0) -- (5,0);

    % drive
    \draw[fill=black] (4.85,0.85) rectangle (5.15,2.15);
    \draw[fill=white] (5,1.5) ellipse (.45 and .45);

    % transmission gear one
    \draw[fill=black!50] (6.7,1.49)
    ellipse (.08 and 0.33);
    \draw[fill=black!50, color=black!50] (6.7,1.82)
    rectangle (6.5,1.16);
    \draw[fill=white] (6.5,1.49)
    ellipse (.08 and 0.33);
    \draw (6.5,1.82) -- (6.7,1.82);
    \draw (6.5,1.16) -- (6.7,1.16);

    % shaft drive -> transmission
    \draw[fill=black] (5.45,1.45) rectangle (6.5,1.55);

    % momentum arrow of drive -> transmission
    \draw[line width=0.7pt,<-] (5.8,1) arc (-30:30:1);

    % transmission gear two
    \draw[fill=black!50] (6.7,0.40)
    ellipse (.13 and 0.67);
    \draw[fill=black!50, color=black!50] (6.7,1.07)
    rectangle (6.5,-0.27);
    \draw[fill=white] (6.5,0.40)
    ellipse (.13 and 0.67);
    \draw (6.5,1.07) -- (6.7,1.07);
    \draw (6.5,-0.27) -- (6.7,-0.27);

    % transmission gear three
    \draw[fill=black!50] (6.85,1.14)
    ellipse (.08 and 0.3);
    \draw[fill=black!50, color=black!50] (6.85,1.44)
    rectangle (6.65,0.84);
    \draw[fill=white] (6.65,1.14)
    ellipse (.08 and 0.3);
    \draw (6.65,1.44) -- (6.86,1.44);
    \draw (6.65,0.84) -- (6.86,0.84);

    % transmission shaft from gear two to moment of inertia
    \draw[fill=black] (6.84,0.38) rectangle (7.8,0.48);

```

```
% moment of inertia
\draw[fill=white] (8.5,0.42)
ellipse (.15 and 0.4);
\draw[fill=white, color=white] (7.9, 0.82)
rectangle (8.49, 0.02);
\draw (7.8,0.42) ellipse (.15 and 0.4);
\draw (7.8,0.82) -- (8.5,0.82);
\draw (7.8,0.02) -- (8.5,0.02);

% momentum arrow between transmission and moment of inertia
\draw[line width=0.7pt,<-] (7.2,-0.07) arc (-30:30:1);

% shaft right from moment of inertia
\draw[fill=black] (8.65,0.38) rectangle (10.9,0.48);

% brake shoe
\draw[fill=black] (9.55,{0.53+0.00})
-- +(-0.2,0.3) -- +(0.5,0.3) -- +(0.3,0.0);
\draw[fill=black] (9.55,{0.33-0.00})
-- +(-0.2,-0.3) -- +(0.5,-0.3) -- +(0.3,0.0);

% momentum arrow (left hand side of brake shoe)
\draw[line width=0.7pt,->] (9.05,-0.07) arc (-30:30:1);

% spring
\draw [domain=0:{-4.5*pi}, variable=\t, samples=200,
line width=1pt]
plot( {10.52+0.4 + 0.15*(\t*0.1)*cos(\t r)},
{0.40 + 0.15*(\t*0.3)*sin(\t r)});

% momentum arrow (left hand side of spring)
\draw[line width=0.7pt,->] (10.4,-0.07) arc (-30:30:1);

% spring wall mount
\draw[fill=black]
(10.9,{1.03-0.2}) rectangle (10.95,{1.03+0.2});
\foreach \x in {0,...,5}
\draw[line width=0.8pt]
({10.55+0.4},{1.03-0.18+\x*0.07}) -- +(0.1,0.05);

% descriptions inside graphic
\draw (5.85,2.2) node {$\omega_A, M_A$};
\draw (7.29,1.11) node {$\omega_K$};
\draw (8.25,0.44) node {$J$};
\draw (9.05,1.15) node {$M_R$};
\draw (10.4,1.15) node {$M_F$};
\draw (6.6,-0.5) node {$v$};

% descriptions of subsystems under graphic
```

```
    \draw [decorate,decoration={brace,amplitude=10pt},
    xshift=0pt, yshift=0pt]
    (5.5,-0.75) -- (-0.5,-0.75)
    node[black,midway,yshift=-20pt]
    {electromagnetic subsystem};
    \draw [decorate,decoration={brace,amplitude=10pt},
    xshift=0pt, yshift=0pt]
    (11.4,-0.75) -- (6,-0.75)
    node[black,midway,yshift=-20pt]
    {mechanical subsystem};
  \end{circuitikz}
```

2.6 How to add the blue information boxes?

Another way to highlight certain and / or important information is to use blue boxes. You may have seen some of those while skipping through this file.

> Here you can add your highlighted text!

Listing 2.8: Example for the highlighted blue box

```
      \begin{mdframed}
        Here you can add your highlighted text!
      \end{mdframed}
```

2.7 List Structures

During your writings convenient and predictable list formatting may be necessary. In this section some structures and their usage are examplified. Lists often appear in documents, especially academic, as their purpose is often to present information in a clear and concise fashion[2].

2.7.1 *Itemize* create a bullet list

- First item
- Second item
- Third item

[2] https://en.wikibooks.org/wiki/LaTeX/List_Structures

Listing 2.9: Example of an itemized structure

```
\begin{itemize}
  \item First item
  \item Second item
  \item Third item
\end{itemize}
```

2.7.2 *Enumerate* create an enumerated list

1. First item

2. Second item

3. Third item

Listing 2.10: Example of an enumerated structure

```
\begin{enumerate}
  \item First item
  \item Second item
  \item Third item
\end{enumerate}
```

2.7.3 Nested lists

1. The first item

   (a) Nested item 1

   (b) Nested item 2

2. The second item

3. The third etc ...

Listing 2.11: Example of a nested list structure

```
\begin{enumerate}
  \item The first item
  \begin{enumerate}
    \item Nested item 1
    \item Nested item 2
```

```
        \end{enumerate}
        \item The second item
        \item The third etc \ldots
    \end{enumerate}
```

2.8 How to deal with something complicated: A table

Tables are a common feature in academic writing, often used to summarize research results. Mastering the art of table construction in LaTeX is therefore necessary to produce quality papers and with sufficient practice one can print beautiful tables of any kind. Keeping in mind that LaTeX is not a spreadsheet, it makes sense to use a dedicated tool to build tables and then to export these tables into the document. Basic tables are not too taxing, but anything more advanced can take a fair bit of construction; in these cases, more advanced packages can be very useful. However, first it is important to know the basics[3]. We will now examplify the creation of one table.

Table 2.1: Sample Table One

	Gross-Pitch Error (GPE) (%)					**Fine-Pitch Error (FPE) (Hz)**				
GPE/FPE input signal	SNR (dB)					SNR (dB)				
	-6	-3	0	3	6	-6	-3	0	3	6
(UB): est. BM (PEFAC)	26.07	23.67	21.10	19.41	18.56	0.71	0.59	0.75	0.63	0.69
(UB): est. RM (PEFAC)	25.16	22.29	18.51	18.62	16.54	0.71	0.63	0.79	0.74	0.88
est. BM (PEFAC)	48.01	39.75	32.13	28.22	23.26	1.49	0.84	0.86	0.92	0.69
est. BM (proposed PE)	39.37	33.77	27.96	25.05	21.90	1.25	0.85	0.80	0.87	0.88
est. RM (PEFAC)	52.45	44.44	37.80	31.98	27.65	1.99	1.09	1.26	0.89	0.85
est. RM (proposed PE)	46.32	39.21	32.13	28.89	25.34	1.46	0.97	0.94	0.83	0.69
(LB): Mixed signal (PEFAC)	66.2	60.55	53.98	46.52	40.33	2.96	2.42	2.22	1.71	1.46

Table 2.1 shows a ruled result table. On the other hand, Table 2.2 shows a more relaxed / unlined table style. Both tables can be found in [2].

Table 2.2: Sample Table Two

	Gross-Pitch Error (GPE) (%)					**Fine-Pitch Error (FPE) (Hz)**				
GPE/FPE input signal	SNR (dB)					SNR (dB)				
	-6	-3	0	3	6	-6	-3	0	3	6
(UB): est. BM (PEFAC)	26.07	23.67	21.10	19.41	18.56	0.71	0.59	0.75	0.63	0.69
(UB): est. RM (PEFAC)	25.16	22.29	18.51	18.62	16.54	0.71	0.63	0.79	0.74	0.88
est. BM (PEFAC)	48.01	39.75	32.13	28.22	23.26	1.49	0.84	0.86	0.92	0.69
est. BM (proposed PE)	39.37	33.77	27.96	25.05	21.90	1.25	0.85	0.80	0.87	0.88
est. RM (PEFAC)	52.45	44.44	37.80	31.98	27.65	1.99	1.09	1.26	0.89	0.85
est. RM (proposed PE)	46.32	39.21	32.13	28.89	25.34	1.46	0.97	0.94	0.83	0.69
(LB): Mixed signal (PEFAC)	66.2	60.55	53.98	46.52	40.33	2.96	2.42	2.22	1.71	1.46

[3] `https://en.wikibooks.org/wiki/LaTeX/Tables`

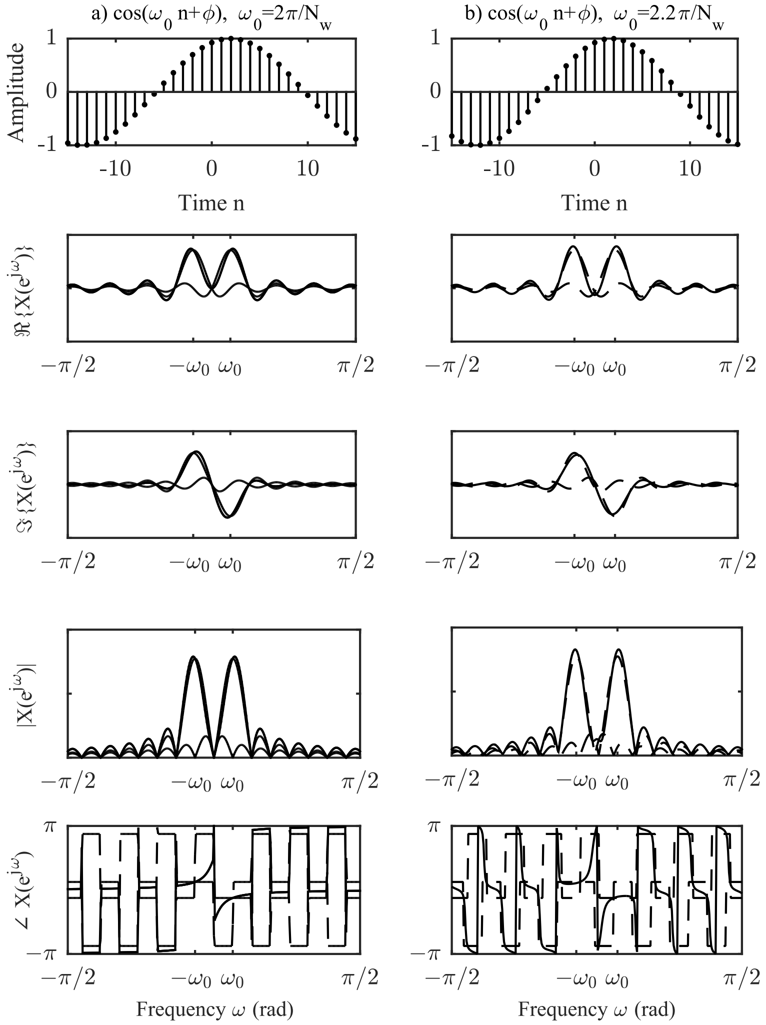

Figure 2.2: Relation of sinusoidal periods and window length and its impact on amplitude and phase: (a) shows a sinusoid multiplied by a boxcar window with a length of one period ($m = 1$). The Dirichlet kernels do not interfere at $\omega = \omega_0$ and $\omega = -\omega_0$ which yields an unbiased phase estimate of $\angle X_w(e^{j\omega_0}) = \phi$, (b) presents the more general case of a window length which does not correspond to an integer multiplier of the sinusoids period ($m = 1.1$). The amplitude as well as the phase do not approach the true value and thus, the outcome is biased.

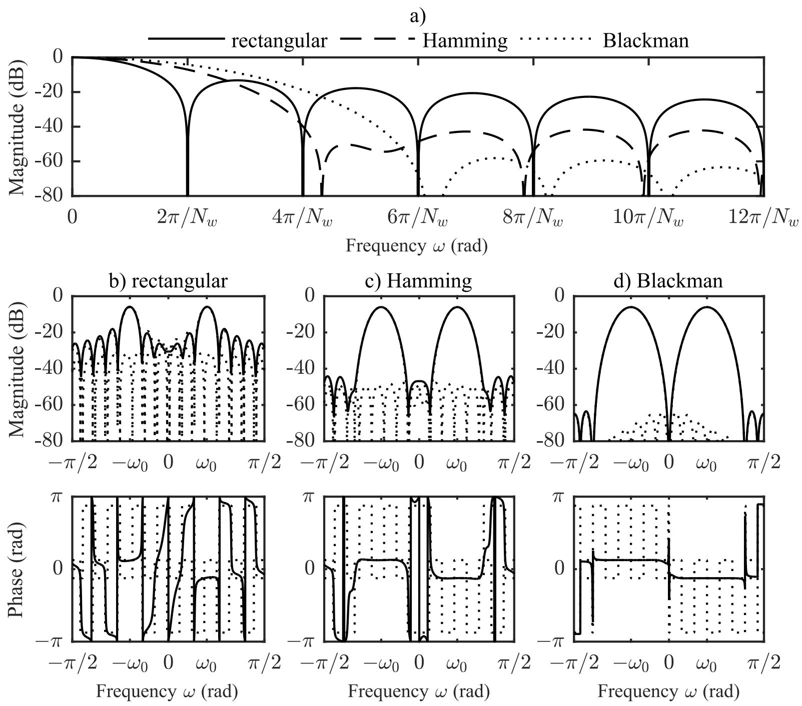

Figure 2.3: Illustration of different windows' impact on the magnitude and phase response of one sinusoid. The improved sidelobe suppression is at the cost of a higher mainlobe width resulting in a lower frequency resolution. For windows with higher sidelobe suppression, the phase response at frequency ω_0 is increasingly dominated by the phase ϕ within the mainlobe width.

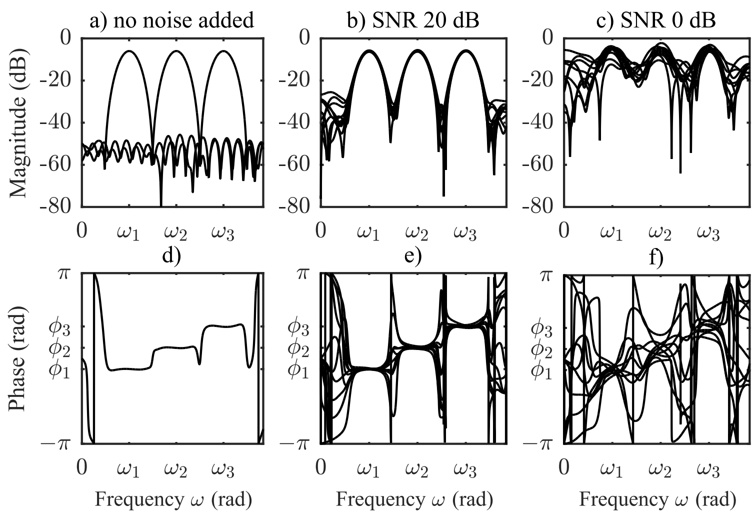

Figure 2.4: Illustration of the impact of additive white Gaussian noise on the magnitude and phase response of three neighboring sinusoids, windowed with Hamming.

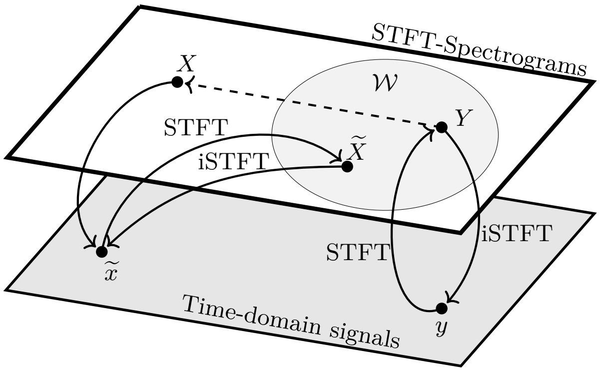

Figure 2.5: Spectrogram consistency concept used in Griffin-Lim iterative signal reconstruction. A consistent spectrogram verifies $Y = \mathcal{G}(Y)$ while for an inconsistent spectrogram $\widetilde{X} = \mathcal{G}(X)$ leading to $\mathcal{I}(X) \neq 0$.

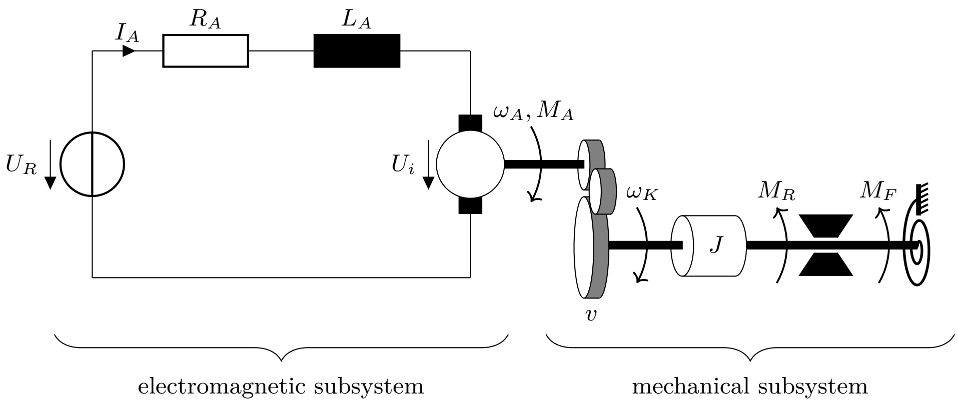

Figure 2.6: A more complex TikZ example of the *The model of a throttle valve*

3 Results

4 Discussion

A

Miscellaneous

A.1 Some Math

Again, we present you a small mathematical example. Get familiar with this syntax in order to create your own formulas[4].

$$\varpi_q(k,l) = \begin{cases} 1 \quad \quad G_q(k,l) > \rho_{\text{th}} \\ 0 \quad \quad \text{otherwise} \end{cases} \tag{A.1}$$

with ρ_{th} defined as a constant threshold. The remixing error spreading is performed as follows:

$$\begin{aligned} \hat{X}_q^{(i+1)}(k,l) &= \varpi_q(k,l)\left(\tilde{X}_q^{(i)}(k,l) + \frac{E^{(i)}(k,l)}{\sum_{q=1}^{Q}\varpi_q(k,l)}\right) \\ \tilde{\mathbf{X}}^{(i)} &= \mathcal{G}(\hat{X}_q^{(i)}), \end{aligned} \tag{A.2}$$

where $\sum_{q=1}^{Q}\varpi_q(k,l)$ accounts for the overal contributions of sources in time frequency error distribution and the remixing error $E^{(i)}(k,l)$ is defined as

$$E^{(i)}(k,l) = Y(k,l) - \sum_{q=1}^{Q}\hat{X}_q(k,l). \tag{A.3}$$

Listing A.1: The math example

```
\begin{equation}
  \varpi_q(k,l)=\begin{cases}
  &1\quad \quad G_q(k,l)>\rho_{\text{th}}\\
  &0\quad \quad \text{otherwise}\\
  \end{cases}
```

[4] `https://en.wikibooks.org/wiki/LaTeX/Mathematics`

```
    \end{equation}
    with $\rho_{\text{th}}$ defined as a constant threshold. The remixing error spreading is performed as follows:
    \begin{eqnarray}
      \hat{X}^{(i+1)}_q(k,l)&=&{\varpi}_q(k,l)\left(\tilde{{X}}^{(i)}_q(k,l)+\frac{E^{(i)}(k,l)}{\sum_{q=1}^Q{{\varpi}_q(k,l)}}\right)\nonumber\\
      \tilde{\mathbf{X}}^{(i)}&=&\mathcal{G}(\hat{X}_q^{(i)}),
    \end{eqnarray}
    where $\sum_{q=1}^Q{{\varpi}_q(k,l)}$ accounts for the overal contributions of sources in time frequency error distribution and the remixing error $E^{(i)}(k,l)$ is defined as
    \begin{equation}
      E^{(i)}(k,l)=Y(k,l)-\sum_{q=1}^{Q}{\hat{X}_q(k,l)}.
    \end{equation}
```

By adding a label to your equation, you will be able to refer to the equation within the text!

A.2 Program code / listing

Three types of source codes are supported: code snippets, code segments, and listings of stand alone files. Snippets are placed inside paragraphs and the others as separate paragraphs the difference is the same as between text style and display style formulas[5]. In the following, we will give you a short introduction on all three code listing types.

A.2.1 individual added program code

Listing A.2: Single code

```
#include <stdio.h>
#define N 10

int main()
{
int i;

puts("Hello world!");

for (i = 0; i < N; i++)
{
  puts("LaTeX is also great for programmers!");
}

return 0;
```

[5] https://en.wikibooks.org/wiki/LaTeX/Source_Code_Listings

```
}
```

Listing A.3: Example of *Single code*

```
\begin{lstlisting}[caption = {Single code}]
#include <stdio.h>
#define N 10

int main()
{
int i;

puts("Hello world!");

for (i = 0; i < N; i++)
{
puts("LaTeX is also great for programmers!");
}

return 0;
}
\end {lstlisting}
```

A.2.2 Add specific code file

Listing A.4: Same code but now we added the code file instead of copying the code into latex

```
#include <stdio.h>
#define N 10

int main()
{
int i;

puts("Hello world!");

for (i = 0; i < N; i++)
{
puts("LaTeX is also great for programmers!");
}

return 0;
}
```

Listing A.5: Example of *Adding specific code file*

```

    \lstinputlisting[language=C, caption = {Same code but now we added the code
        file instead of copying the code into latex}]{code/test.c}
```

A.2.3 Scope on specific code file

Listing A.6: Scope on specific code file

```
int i;

puts("Hello world!");

for (i = 0; i < N; i++)
{
puts("LaTeX is also great for programmers!");
}
```

Listing A.7: Example of *Scope on specific code file*

```

  \lstinputlisting[language=C, firstline=6, lastline=13, caption = {Specific
      scope on code file}]{code/test.c}
```

B

Citations

For any academic/research writing, incorporating references into a document is an important task. Fortunately, LaTeX has a variety of features that make dealing with references much simpler, including built-in support for citing references. However, a much more powerful and flexible solution is achieved thanks to an auxiliary tool called BibTeX (which comes bundled as standard with LaTeX). Recently, BibTeX has been succeeded by BibLaTeX, a tool configurable within LaTeX syntax.

B.1 Create your own bibliography

Creating your own bibliography will take you some time, but if you structure and maintane it properly you will have a powerful tool for your upcoming theses. One way to structure your bibliography is to use *JabRef*[6] or *Zotero*[7], where you can roster all resources manually or directly import existing *.bib*- or *BibTex*-Files.

B.2 How should a bibliography look like?

In this file, and during preparation of your thesis, we suggest you to use the IEEE citation standart in your bibliography. Have a look at the following listing as well at the resulting bibliography!

- An example for citing a book is [9][7]
- Example for citing a journal paper is [2]
- A Technical Standard is examplified in [1]
- Technical Report [5]

[6]`https://www.jabref.org/`
[7]`https://www.zotero.org/`

- lecture notes [6]
- An example for citing online resources [3]

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