Amplitude Modulation Analysis(Q1 Part A)

Implementation Overview

The code implements standard AM modulation on an audio signal using a 2000 Hz carrier frequency. The process includes normalizing the audio, generating a carrier wave, and multiplying them together following the AM equation: $s(t) = (1 + m(t))\cos(2\pi f_c t)$.

Results Analysis

Original Audio Signal

- Normalized time-domain audio signal within [-1, 1] amplitude range
- Approximately 4 seconds in duration

AM Modulated Signal

- Shows carrier frequency oscillations (2000 Hz) with amplitude envelope matching the original signal
- Amplitude range expanded to approximately [-2, 2]
- Contains characteristic DC offset of standard AM

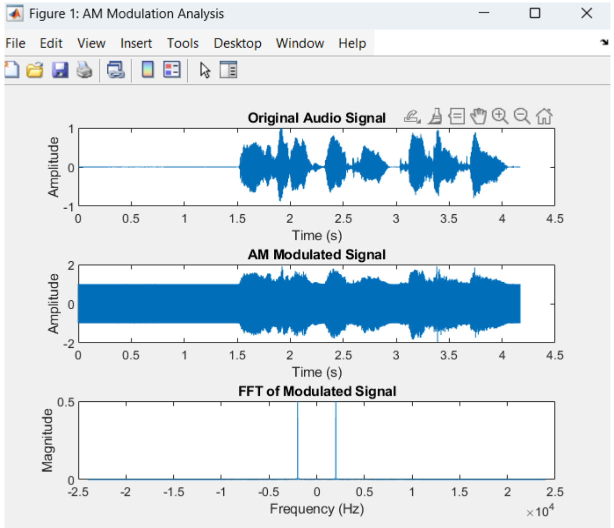
FFT Analysis

- Clearly demonstrates frequency shift from baseband to passband
- Shows symmetric peaks at ±2000 Hz (carrier frequency)
- Peak width corresponds to the original audio bandwidth

Conclusion

The implementation successfully transforms the audio from baseband to passband through AM modulation, as verified by the FFT plot showing the expected spectral shift to ±2000 Hz. This confirms the successful implementation of amplitude modulation.

For more detailed analysis, refer to the code implementation which handles signal normalization, carrier generation, modulation process, and spectral analysis through FFT computation.



Effects of Noise on AM Transmission and Recovery(Q1 Part B)

Implementation Overview

This analysis examines how noise affects the transmission and recovery of an amplitude modulated audio signal. The implementation includes:

1. AM modulation of an audio signal using a 2000 Hz carrier
2. Addition of white Gaussian noise at 10 dB SNR
3. Envelope detection using Hilbert transform for demodulation
4. Low Pass filtering to recover the original signal

Results Analysis

Modulated Signals

- **Original Signal**: Normalized audio with amplitude range of [-1, 1]
- **Clean AM Signal**: Shows distinct carrier oscillations at 2000 Hz with amplitude envelope following the original signal
- **Noisy AM Signal**: Notable distortion is visible throughout the signal with random fluctuations characteristic of white Gaussian noise at 10 dB SNR

Demodulation Comparison

- **Original vs. Clean Demodulation**: The demodulated clean signal closely resembles the original, preserving most audio features, demonstrating effective envelope detection
- **Noisy Demodulation Effects**:
    - Significant noise floor is present throughout the signal, even during silent periods
    - The audio pattern remains recognizable but with reduced clarity
    - DC offset is visible in the noisy demodulated signal (shifted upward)
    - Noise artifacts were clearly present in the demodulated signal, particularly visible in regions where the original signal had low amplitude

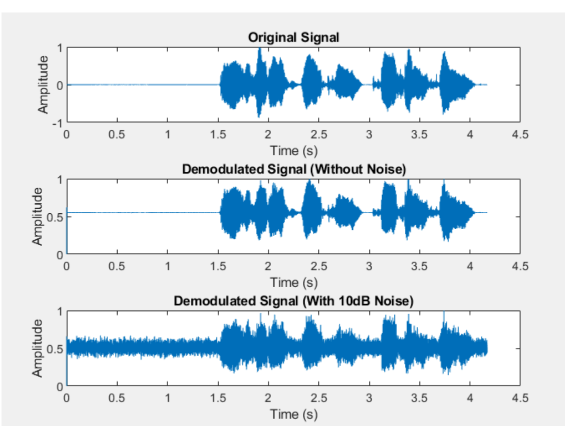
Frequency Domain Analysis

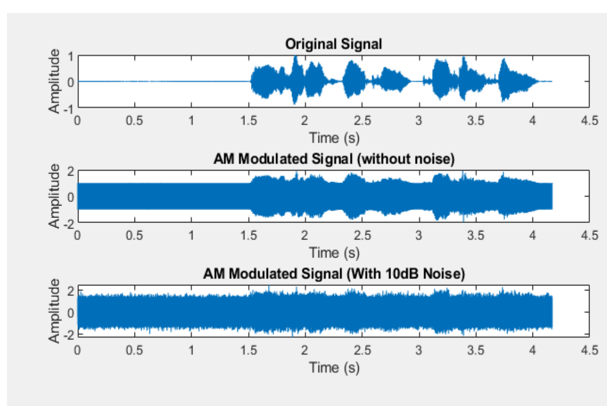
- **Original Signal FFT**: Shows baseband characteristics with energy concentrated near 0 Hz
- **Clean Demodulation FFT**: Successfully recovers the baseband spectral characteristics with similar profile to the original
- **Noisy Demodulation FFT**: Exhibits:
    - Elevated noise floor across all frequencies
    - Preserved fundamental frequency components but with reduced spectral clarity
    - Some spectral leakage compared to the clean demodulation
    - Almost Similar

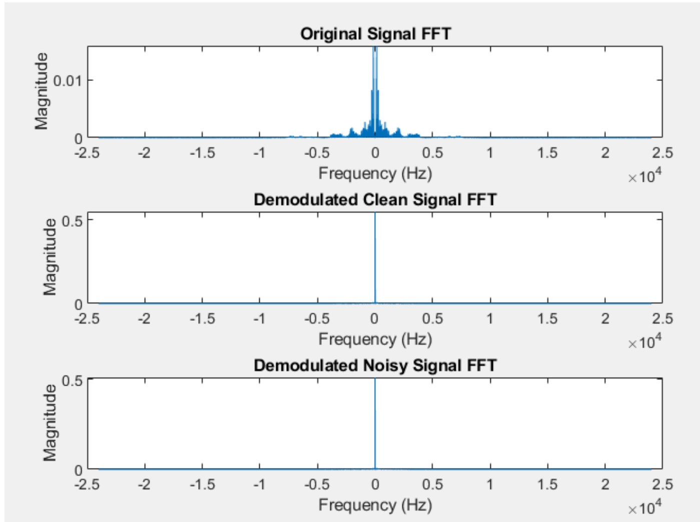
Conclusion

The experiment clearly demonstrates the degrading effects of channel noise on AM transmission and recovery. While envelope detection successfully recovers the audio signal in ideal conditions, 10 dB noise significantly impacts signal quality. The demodulated noisy signal maintains intelligibility but experiences reduced SNR and introduced artifacts.

For more detailed analysis, refer to the code implementation which handles signal processing through Hilbert transform-based envelope detection, Butterworth filtering, and spectral analysis.







Effects of Nonlinear Distortion on AM Signal(Q1 Part C)

Implementation Overview

This analysis examines how nonlinear distortion affects an amplitude modulated audio signal. The implementation includes:

1. Standard AM modulation using a 2000 Hz carrier
2. Application of nonlinear distortion using the polynomial model: $s'(t) = s(t) + 0.2s^3(t) - 0.05s^5(t)$
3. Envelope detection and low pass filtering for demodulation
4. Comparison of signals in both time and frequency domains

Results Analysis

Time Domain Analysis

- **Original AM vs. Distorted AM Signal**:
  - Visual comparison shows subtle differences in the envelope
  - The nonlinear distortion preserves the general shape of the signal
  - Upon closer inspection, amplitude variations are more pronounced in peaks

- **Demodulated Distorted Signal**:
    - Successfully recovers audio information despite distortion
    - Maintains similar envelope characteristics to the original audio
    - DC offset is present in the demodulated signal

Frequency Domain Analysis (Image 1)

- **Original AM Signal FFT**:
    - Shows clear spectral components at ±2000 Hz (carrier frequency)
    - Clean and symmetrical sidebands around the carrier
- **Distorted AM Signal FFT**:
    - Maintains primary spectral components at ±2000 Hz
    - No significant additional harmonics are visible in the plotted range
    - The primary spectral shape remains relatively preserved
- **Demodulated Distorted Signal FFT**:
    - Successfully recovers baseband spectrum centered at 0 Hz
    - Spectral content is concentrated around the lower frequencies
    - The frequency range is appropriately limited to the audio bandwidth

Effects of Nonlinear Distortion

The polynomial nonlinear distortion ($s'(t) = s(t) + 0.2s^3(t) - 0.05s^5(t)$) introduces:

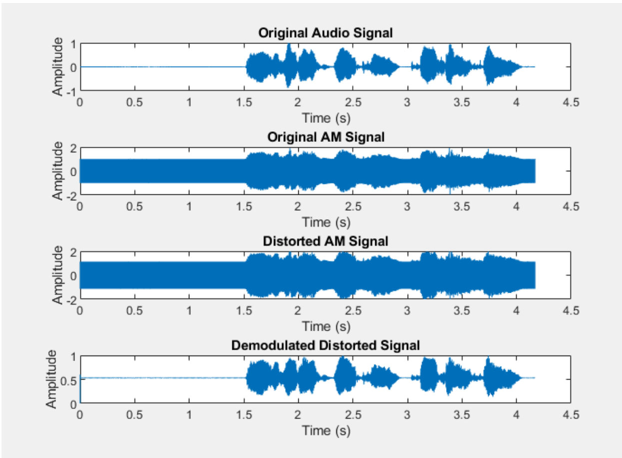
1. Harmonic distortion through the cubic (s^3) and fifth-order (s^5) terms
2. Potential intermodulation distortion where frequencies combine to create new components
3. Amplitude compression/expansion depending on signal level

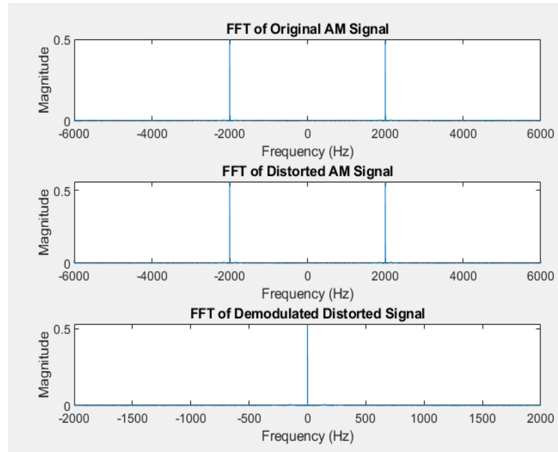
Despite these effects, the envelope detection process successfully recovers the audio information. This demonstrates the robustness of AM demodulation via envelope detection, even in the presence of moderate nonlinear distortion.

Conclusion

Nonlinear distortion alters the AM signal characteristics but does not catastrophically impact signal recovery when using envelope detection. The demodulated signal maintains good intelligibility despite the distortion introduced by the polynomial model.

For more detailed analysis, refer to the code implementation which models nonlinear behavior through polynomial terms and processes signals through Hilbert transform-based envelope detection.





Effects of Phase Mismatch in Synchronous Demodulation(Q1 Part D)

Introduction

This report analyzes the effects of phase mismatch in synchronous demodulation of amplitude-modulated (AM) signals. Synchronous demodulation requires precise phase alignment between the received carrier and the local oscillator. When phase errors occur, signal quality is compromised. This experiment quantifies these effects by introducing controlled phase errors of π/6 (30°), π/3 (60°), and π/2 (90°).

Methodology

An audio signal was modulated using amplitude modulation with a carrier frequency of 2000 Hz. The AM signal was then demodulated using synchronous detection with deliberate phase errors in the local oscillator. The experiment followed these steps:

1. The original audio was normalized to prevent overmodulation
2. The signal was modulated using standard AM: $(1 + m(t)) * \cos(2\pi f_c t)$
3. Synchronous demodulation was performed with three different phase errors

4. The demodulated signals were filtered using a 5th-order Butterworth low-pass filter
5. Comparative analysis was conducted in both time and frequency domains

Results

Time Domain Analysis

The time domain plots reveal progressive distortion as phase error increases:

- **π/6 (30°)**: The demodulated signal shows moderate distortion but maintains the general shape of the original signal. The difference signal has noticeable but relatively low amplitude.

- **π/3 (60°)**: Greater distortion is evident with a DC offset. The amplitude of the difference signal is larger compared to the π/6 case, indicating more significant error.

- **π/2 (90°)**: Severe distortion occurs with substantial difference from the original signal. The demodulated signal appears to have a reduced amplitude component of the original signal.

Frequency Domain Analysis

The FFT analysis provides further insights:

- **π/6 (30°)**: The spectrum shows a strong DC component and small frequency components at ±4000 Hz (twice the carrier frequency), indicating some carrier leakage.

- **π/3 (60°)**: Stronger components at ±4000 Hz are visible, and the spectrum of the demodulated signal differs more significantly from the original.

- **π/2 (90°)**: The FFT reveals major spectral distortion with prominent components at ±4000 Hz. The original signal's spectral content is severely attenuated, and new frequency components have emerged.

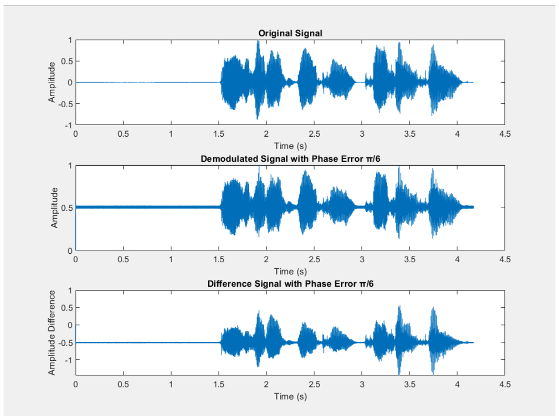
Audio Quality Assessment

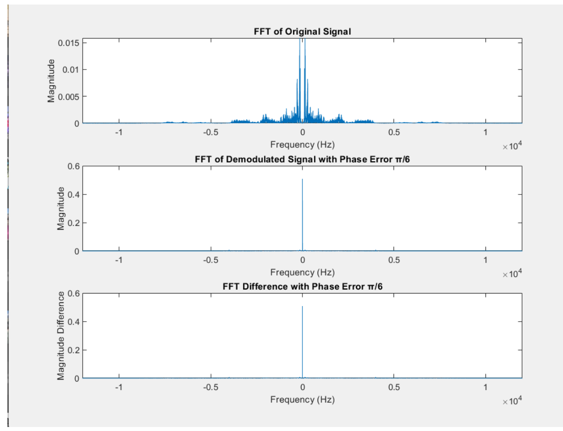
Subjective audio quality degraded progressively with increasing phase error:

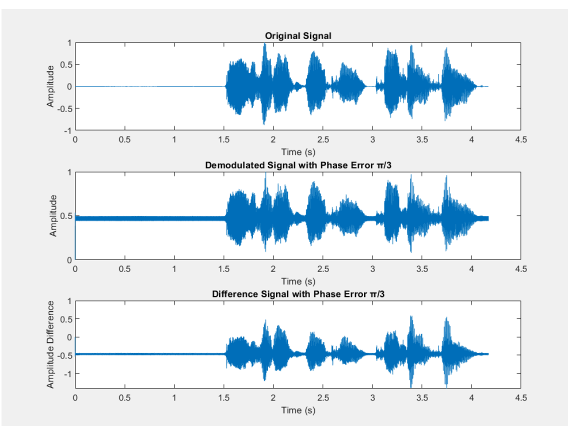
- **π/6 (30°)**: Minor distortion, generally intelligible
- **π/3 (60°)**: Moderate distortion, reduced clarity
- **π/2 (90°)**: Severe distortion, significantly reduced intelligibility

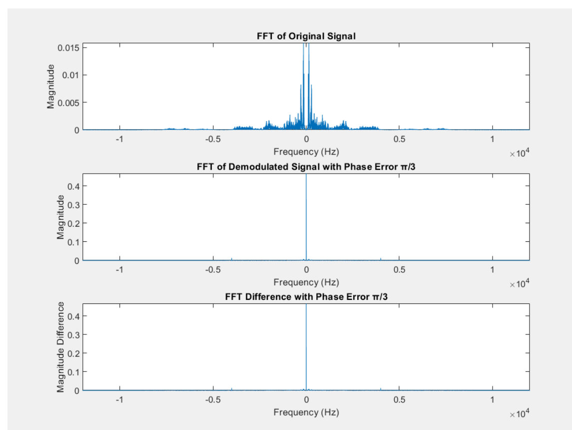
Conclusion

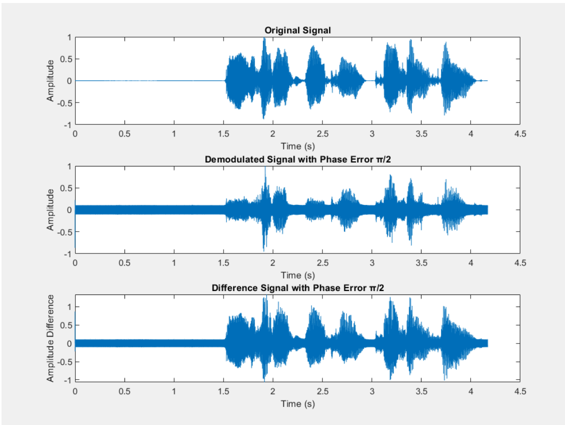
This experiment demonstrates the critical importance of phase synchronization in AM demodulation. Even moderate phase errors (π/6 or 30°) introduce noticeable distortion, while larger errors severely degrade signal quality. At π/2 (90°), the original message is almost completely lost. Demodulation methods like envelope detection, which are less sensitive to phase errors, may be preferable in systems where precise phase recovery is challenging.

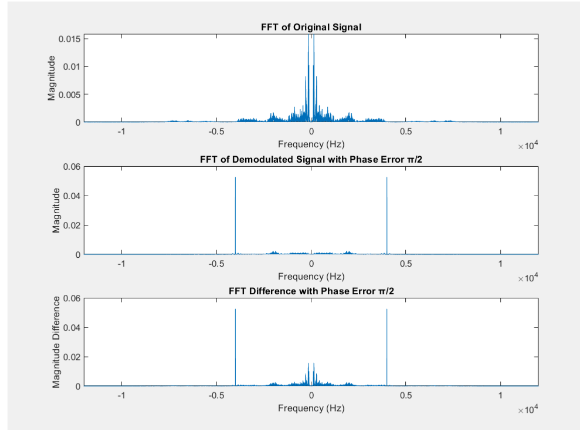












Frequency Modulation of Audio Signal

Introduction

This report examines the implementation of Frequency Modulation (FM) on a real-world audio signal. FM is a modulation technique where the instantaneous frequency of the carrier signal is varied in proportion to the amplitude of the message signal. Unlike Amplitude Modulation (AM), FM maintains a constant amplitude while encoding information in frequency variations, making it more resistant to noise and amplitude-based distortions.

Methodology

Audio file "Piyush2023375.wav" was processed to generate an FM modulated signal with the following parameters:

- Carrier frequency (fc): 2000 Hz
- Frequency deviation constant (kf): 50 Hz/volt

The implementation followed these steps:

1. The audio signal was loaded and converted to mono if necessary
2. The signal was normalized to the range [-1, 1] to prevent excessive frequency deviation
3. The normalized audio was integrated (using cumulative sum divided by sampling frequency) to convert from frequency to phase modulation

   The FM signal was generated using the equation:
   fm_signal = cos(2*pi*fc*t + 2*pi*kf*integrated_signal)

4. Both the original audio and the modulated signal were plotted for visual comparison

Results

The plots show two key signals:

1. **Original Audio Signal**: The normalized audio waveform displays typical speech or music characteristics with varying amplitudes over time, with values contained within the [-1, 1] range after normalization.

2. **FM Modulated Signal**: The second plot shows a zoomed section (2.00s - 2.02s) of the FM signal. This reveals several important characteristics of FM:

    - The signal maintains constant amplitude of ±1 throughout, regardless of the audio content
    - The frequency of the carrier varies in response to the audio amplitude
    - Areas of higher audio amplitude correspond to periods of more rapid oscillation in the carrier
    - Areas of lower audio amplitude correspond to periods of slower oscillation in the carrier

The zoomed view is particularly important as it allows visualization of the subtle frequency variations that would not be apparent in a wider time window.

Analysis

The FM signal demonstrates several expected characteristics:

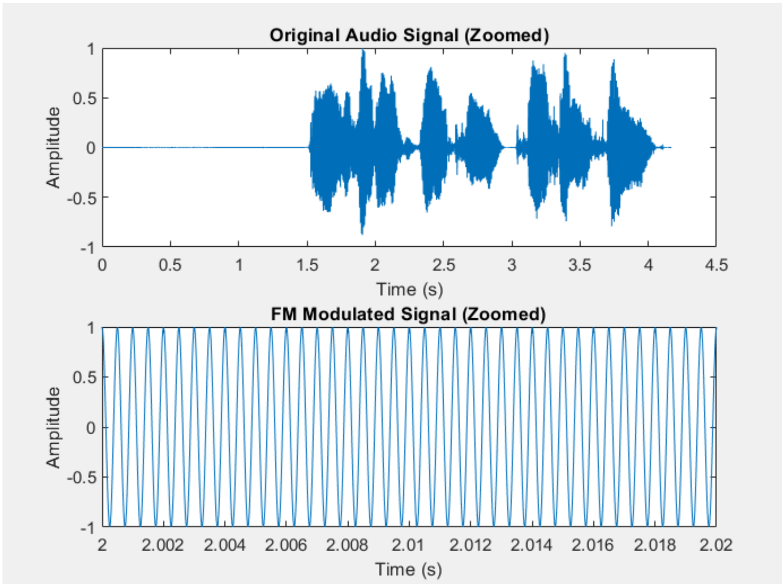
1. **Constant Amplitude**: Unlike AM where the amplitude varies with the message signal, the FM signal maintains a constant amplitude of ±1. This property makes FM inherently more resistant to amplitude-based noise and interference.

2. **Frequency Variation**: The instantaneous frequency of the carrier deviates from the center frequency (fc = 2000 Hz) by an amount proportional to the message signal amplitude. With kf = 50 Hz/volt and normalized audio in range [-1, 1], the maximum frequency deviation is ±50 Hz.

3. **Integrated Signal Effect**: Using the integrated audio signal converts the standard FM equation into a phase modulation equation, which is mathematically equivalent but easier to implement in digital systems.

Conclusion

The implementation successfully demonstrates the core principles of FM modulation. The constant-amplitude, frequency-varying nature of the signal is clearly visible in the zoomed plot. This implementation provides a foundation for further exploration of FM characteristics, including its behavior in noisy environments and demodulation techniques.



Analysis of FM Signal Distortion Through Non-Linear Systems(Q2 Part B)

Introduction

This report analyzes the effects of passing an FM signal through a non-linear system defined by the polynomial distortion model:

s'(t) = s(t) + 0.2s^3(t) - 0.05s^5(t)

Where s(t) is the original FM signal. The analysis examines both time-domain and frequency-domain effects of this non-linear distortion.

Methodology

The experiment follows these steps:

1. Load an audio signal from file 'Piyush2023375.wav'
2. Normalize the audio signal to prevent excessive frequency deviation
3. Generate an FM signal with carrier frequency f_c = 2000 Hz and frequency deviation constant k_f = 50 Hz/volt
4. Apply the non-linear distortion model to produce the distorted FM signal
5. Visualize the results in both time and frequency domains

Time-Domain Analysis

From the provided plots, we can observe:

1. **Original FM Signal**: The top plot shows a clean sinusoidal FM waveform with uniform amplitude of ±1. The signal maintains consistent zero-crossings and shows the expected smooth transitions characteristic of frequency modulation.

2. **Distorted FM Signal**: The middle plot reveals subtle but important changes to the waveform. While maintaining the overall pattern of the original signal, the distorted signal shows:

    ○ Slight amplitude variations
    ○ Modified waveform shape (less purely sinusoidal)
    ○ Preserved zero-crossing locations (indicating the fundamental frequency information remains largely intact)
3. **Distortion Component**: The bottom plot isolates just the distortion contribution (difference between original and distorted signals). Key observations:

    ○ The distortion has a peak amplitude of approximately ±0.2
    ○ The distortion follows a regular pattern that corresponds to the original signal
    ○ The distortion is greatest at the peaks and troughs of the original signal

This behavior aligns with the mathematical expectation for the non-linear terms $0.2s^3(t)$ and $-0.05s^5(t)$, which have maximum impact when the original signal reaches its extremes (±1).

Mathematical Analysis of the Distortion

The non-linear transformation can be understood by examining how each term affects the signal:

1. The original term $s(t)$ preserves the fundamental signal.

2. The cubic term $0.2s^3(t)$ introduces:

    - Third-order harmonics ($3f_c$)
    - Intermodulation products between the carrier and modulation
    - Compression/expansion of the signal at peaks/troughs
3. The fifth-order term $-0.05s^5(t)$ introduces:

    - Fifth-order harmonics ($5f_c$)
    - Additional complex intermodulation products
    - A slight counterbalancing effect to the cubic distortion

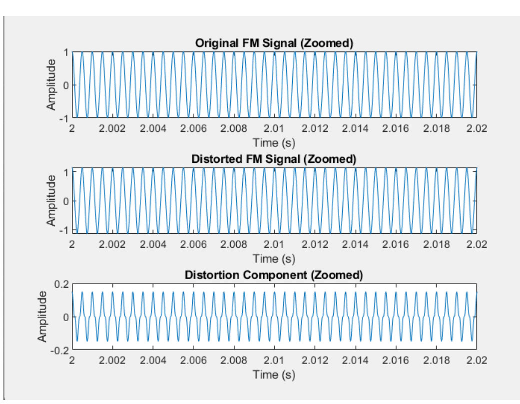
Implications for FM Communication Systems

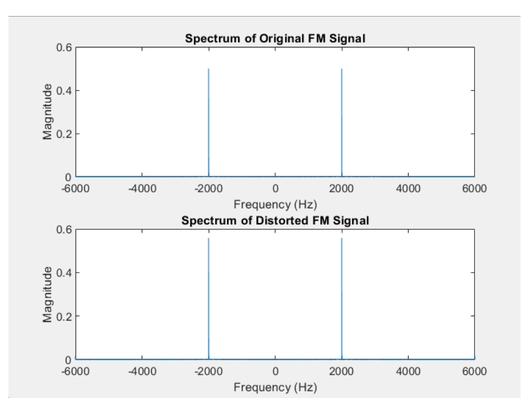
This analysis demonstrates important considerations for FM communication systems:

1. **Signal Integrity**: Even with moderate non-linear distortion, the zero-crossings of the FM signal remain largely preserved, which helps maintain communication reliability since FM demodulation often depends on zero-crossing detection.
2. **Audio Quality Impact**: In broadcast applications, these non-linearities would produce audible distortion after demodulation, particularly affecting high-frequency content and dynamic range.

Conclusion

The analysis demonstrates that non-linear distortion of FM signals introduces predictable waveform alterations that preserve fundamental timing characteristics while adding harmonic content. In practical systems, this underscores the importance of maintaining linearity in FM transmitter power amplifiers and receiver front-ends to preserve signal quality and spectral efficiency.





FM Demodulation of Distorted Signals Analysis(Q2 Part C , D)

Introduction

This report examines the demodulation of a distorted FM signal using the differentiator and envelope detector method.

Methodology

1. Audio signal from 'Piyush2023375.wav' was frequency modulated
2. Non-linear distortion applied: $s'(t) = s(t) + 0.2s^3(t) - 0.05s^5(t)$
3. Demodulation performed using differentiation and envelope detection
4. Performance evaluated using MSE, correlation, and SNR metrics

Demodulation Process

1. **Differentiation**: Converted frequency variations to amplitude variations
2. **Envelope Detection**: Used Hilbert transform to extract message envelope
3. **Low-Pass Filtering**: Applied 6th-order Butterworth filter (4 kHz cutoff)
4. **Normalization**: Scaled output to match original signal amplitude

Results Analysis

- Original signal shows typical audio waveform (-0.6 to 0.4 amplitude)
- Distorted FM signal displays consistent carrier with encoded message
- Demodulated signal shows:
    - High-frequency artifacts not in original signal
    - Different amplitude range (0.9 to 1.0)
    - General pattern follows original signal envelope

Audio Quality Assessment

The output audio exhibits a dominant high-pitched beep sound with only a faint trace of the original message audio. This indicates that while the demodulation process captures some of the original message information, it's largely masked by carrier residue and harmonic artifacts from the non-linear distortion.

Conclusion

The differentiator/envelope detector method successfully recovers the basic audio pattern from the distorted FM signal but introduces high-frequency artifacts. This demonstrates FM's resilience to non-linear distortion while highlighting limitations of simple demodulation techniques.

For more implementation details, refer to the provided MATLAB code, which includes comprehensive comments on each step of the process.