EEEN 462 – ANALOGUE COMMUNICATION

FREQUENCY MODULATION (FM) STUDY GUIDE & REVISION

I. FUNDAMENTAL CONCEPTS

1. WHAT IS MODULATION?

- Purpose: Efficient transmission of information (baseband signal) over a channel by shifting its frequency spectrum to a higher frequency range (carrier signal).
- Types: Analog (AM, FM, PM) vs. Digital (FSK, PSK, QAM).

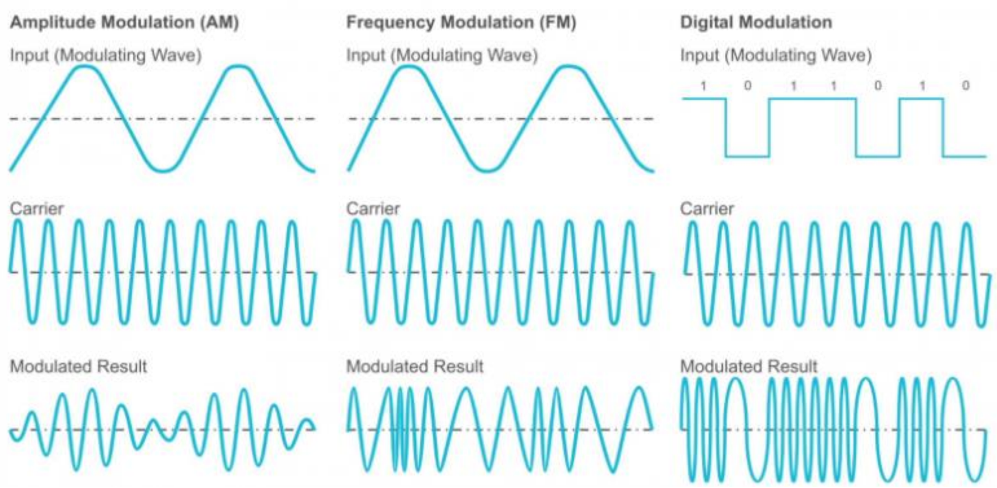

Figure 1. Types of modulation

2. ANGLE MODULATION BASICS

- General form: $s(t) = A_c * \cos[\theta(t)]$
- **Frequency Modulation (FM):** The *instantaneous frequency* $\omega_i(t)$ of the carrier is varied *linearly* with the message signal $m(t)$.
  - Instantaneous Frequency: $\omega_i(t) = d\theta(t)/dt$
  - FM Definition: $\omega_i(t) = \omega_c + k_f * m(t)$
    - ω_c = Carrier frequency (radians/sec)
    - k_f = Frequency Sensitivity (radians/sec/volt)

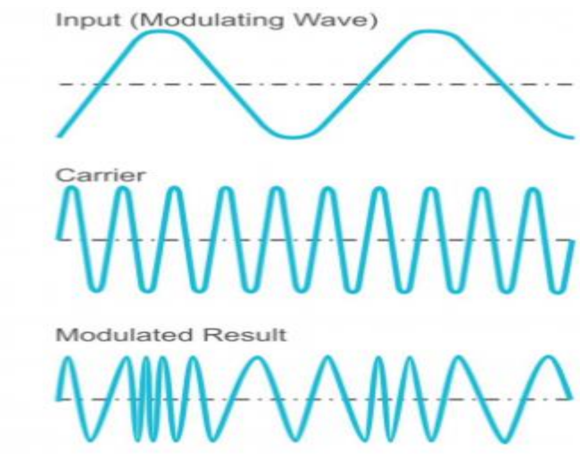

Figure 2. Principle of FM modulation

- **Phase Modulation (PM):** The *phase* θ(t) of the carrier is varied *linearly* with the message signal m(t). ($\theta(t) = \omega_c t + k_p \cdot m(t)$)
- **Relationship:** FM and PM are intrinsically linked. FM can be seen as the integral of PM (and vice-versa).

3. **THE FM WAVE EQUATION**

- Integrating the instantaneous frequency definition:
  $\theta(t) = \int \omega_i(\tau)\, d\tau = \omega_c t + k_f \cdot \int m(\tau)\, d\tau$
- FM Signal: $s_{FM}(t) = A_c \cdot \cos[\omega_c t + 2\pi \cdot k_f \cdot \int m(\tau)\, d\tau]$
  - k_f is now often expressed in Hz/Volt. Let $\Delta f = k_f \cdot \max|m(t)|$ (Peak Frequency Deviation).
  - Define Modulation Index: $\beta = \Delta f / f_m$
    - Δf = Peak Frequency Deviation (Hz) - *key parameter*.
    - f_m = Highest frequency component in m(t) (Hz).
- **Modulation Index (β):** The *single most important parameter* in FM.
  - Determines bandwidth and spectral characteristics.
  - $\beta \ll 1$: Narrowband FM (NBFM) - resembles AM spectrum.
  - $\beta \gg 1$: Wideband FM (WBFM) - many significant sidebands.

2. SPECTRUM & BANDWIDTH OF FM

1. **Single-Tone Modulation:**

- Assume $m(t) = A_m \cdot \cos(\omega_m t)$
- FM Signal: $s_{FM}(t) = A_c \cdot \cos[\omega_c t + (\Delta f / f_m) \cdot \sin(\omega_m t)] = A_c \cdot \cos[\omega_c t + \beta \cdot \sin(\omega_m t)]$

- **Bessel Function Expansion:** s_FM(t) = A_c * Σ [J_n(β) * cos((ω_c + nω_m)t)] for n = -∞ to ∞
    - J_n(β) = Bessel function of the first kind, order n, argument β.
    - Spectrum consists of a carrier component (J_0(β)) and an infinite number of sidebands spaced ±f_m, ±2f_m, ±3f_m,... away from f_c.
    - Amplitude of carrier/sideband n is A_c * |J_n(β)|.

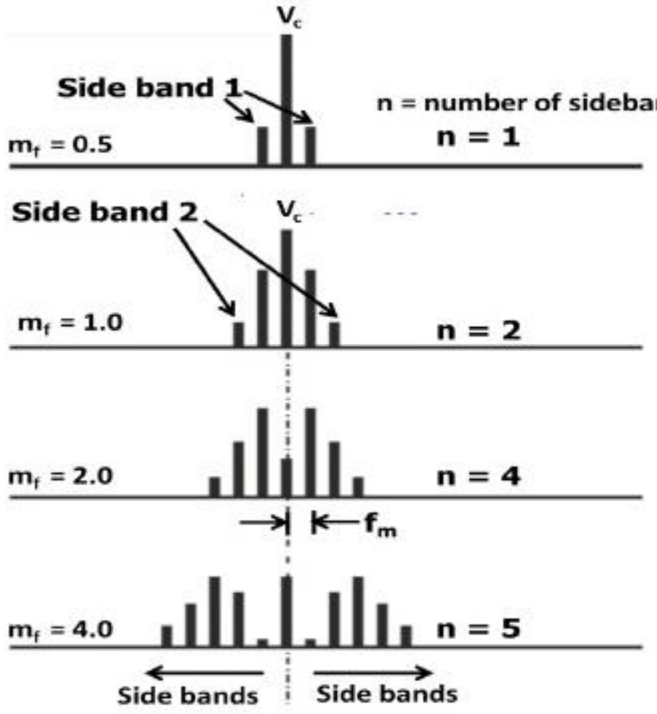

Figure 3. Frequency Modulation bandwidth

2. **Effective Bandwidth (BT)**
    - **Carson's Rule (Practical Estimate):** BT ≈ 2(Δf + f_m) = 2f_m(1 + β)
        - Captures >98% of the signal power.
        - *Memorize this!* Very important for system design.
    - **Exact Bandwidth:** Theoretically infinite. Bandwidth is defined by the number of significant sidebands (|J_n(β)| > threshold, e.g., 0.01). Rule of Thumb: n_max ≈ β + 1 --> BT ≈ 2(β + 1)f_m.
3. **Narrowband FM (NBFM) vs. Wideband FM (WBFM)**
    - **NBFM (β < 0.2 - 0.5)**
        - Bandwidth ≈ 2f_m (same as AM-DSBFC).
        - Only J0 and J1 terms significant (carrier + 1 pair of sidebands).
        - Spectrum *looks* like AM but sidebands are in *phase quadrature*.
    - **WBFM (β > 1 - 2)**

- Bandwidth >> $2f_m$ (given by Carson's rule).
- Many significant sidebands.
- Carrier amplitude ($J_0(\beta)$) can become zero at specific β values.
- Offers superior noise performance compared to NBFM/AM.

3. GENERATION OF FM SIGNALS

1. **Direct Method:**
    - **Principle:** Vary the frequency of an oscillator *directly* using the message signal m(t).
    - **Device:** Voltage-Controlled Oscillator (VCO). $f_{out} = f_{center} + k_{vco} * V_{in}$.
    - **Pros:** Simple conceptually, capable of large Δf.
    - **Cons:** Carrier frequency stability is poor (drift) - requires automatic frequency control (AFC).

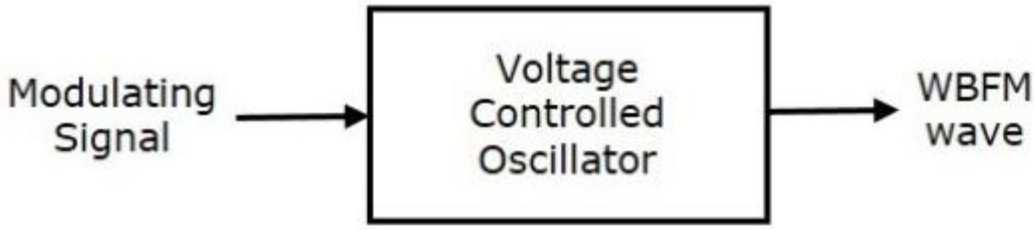

Figure 4. Direct method FM modulator

2. **Indirect Method (Armstrong Method):**
    - **Principle:** Generate NBFM first, then use frequency multiplication to increase both Δf and f_c proportionally, achieving WBFM.
    - **Steps:**
        1. Integrate m(t) -> $\int m(\tau)d\tau$.
        2. Use $\int m(\tau)d\tau$ to phase-modulate a *stable* crystal oscillator (creates NBFM/PM with small β).
        3. Pass the NBFM signal through a Frequency Multiplier (xN). This multiplies *both* f_c and Δf by N -> $\beta_{new} = N * \beta_{old}$ (WBFM).
        4. Use Mixing (Heterodyning) if necessary to shift the multiplied carrier frequency to the desired final f_c.
    - **Pros:** Excellent carrier frequency stability (uses crystal oscillator).
    - **Cons:** More complex circuitry.

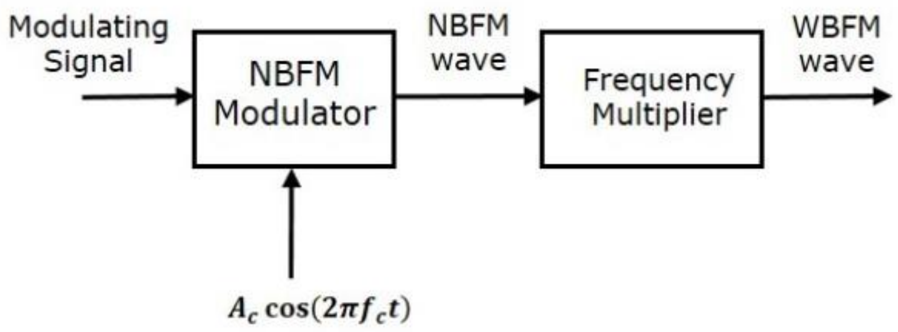

Figure 5. Direct method FM modulator

4. DEMODULATION OF FM SIGNALS (DETECTION)

- **Goal:** Recover the original message signal m(t) from s_FM(t). Convert frequency variations back to amplitude variations.
- **Key Methods:**
  1. **Slope Detector (Frequency Discriminator):**
     - **Principle:** Convert FM to AM by passing through a circuit with a linear magnitude response over the FM bandwidth (a "slope" - e.g., a tuned circuit slightly off resonance).
     - **Pros:** Simple.
     - **Cons:** Very sensitive to amplitude variations (requires a limiter beforehand), linearity is poor.

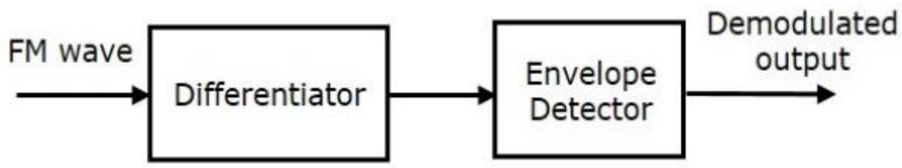

Figure 6. Direct method FM modulator

  2. **Foster-Seeley Discriminator (Phase Discriminator):**
     - **Principle:** Uses a double-tuned transformer to convert frequency variations into phase differences, then a diode detector to convert phase difference to amplitude.
     - **Pros:** Better linearity and amplitude rejection than slope detector.
     - **Cons:** Tuning critical, requires transformers.

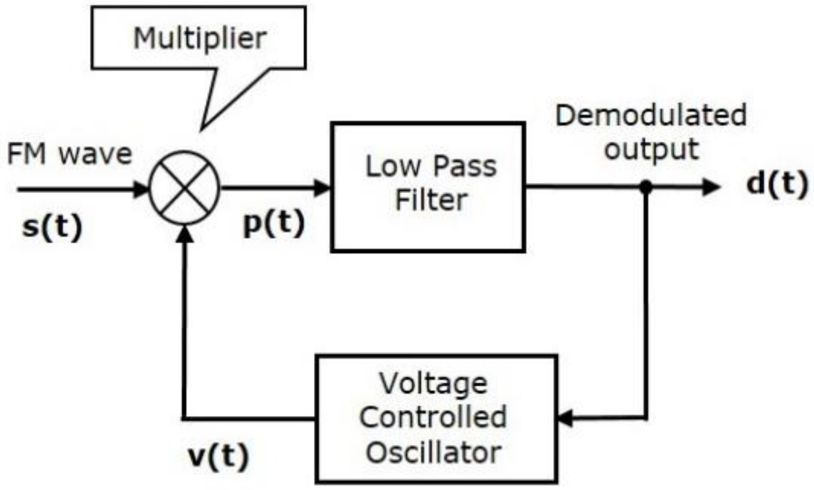

Figure 7. FM modulator phase discriminator

3. **Ratio Detector:**
   - **Principle:** Variation of Foster-Seeley designed to be inherently amplitude-limiting. Less sensitive to amplitude noise.
   - **Pros:** Built-in amplitude limiting.
   - **Cons:** More complex, tuning critical.
4. **Phase-Locked Loop (PLL) Demodulator:**
   - **Principle:** The PLL locks the VCO phase to the input FM signal phase. The VCO control voltage becomes the demodulated output m(t).
   - **Pros:** Excellent performance (linearity, noise immunity), easy to implement with ICs, very common.
   - **Cons:** Requires understanding of PLL operation. Limited lock/capture range.
5. **Quadrature Detector:**
   - **Principle:** Mixes the FM signal with a phase-shifted (90°) version of itself. The phase shift network converts frequency shift to phase shift. The mixer output is proportional to m(t).
   - **Pros:** Excellent performance, easily integrated (no coils/transformers), popular in ICs.
   - **Cons:** Requires precise phase-shift network.

- **The Limiter:** A *crucial* component preceding most FM demodulators (except Ratio Detector). It removes amplitude variations (noise, fading) by hard-clipping the signal, creating a constant-amplitude FM square wave which is then filtered. Essential for exploiting FM's noise immunity.

5. ADVANTAGES & DISADVANTAGES OF FM

- **Advantages:**
    1. **Superior Noise Immunity:** FM is much more resistant to amplitude noise (e.g., atmospheric, thermal) than AM. The limiter removes amplitude noise before detection. This is the *primary advantage*.
    2. **Capture Effect:** A stronger FM signal will "capture" the receiver and suppress a weaker co-channel signal. Allows geographically closer transmitters to reuse frequencies.
    3. **Constant Envelope:** The transmitted power is constant (A_c fixed). Allows efficient use of non-linear power amplifiers (Class C) without distortion.
    4. **Better Fidelity:** WBFM offers high signal-to-noise ratio (SNR) for high-quality audio transmission (e.g., FM radio).
- **Disadvantages:**
    1. **Larger Bandwidth:** FM requires significantly more bandwidth than AM (Carson's Rule: $BT \approx 2(\Delta f + f_m)$ vs. AM's $2f_m$).
    2. **More Complex Circuits:** Transmitters and receivers (especially demodulators) are generally more complex than AM systems.
    3. **Limited Line-of-Sight (LOS):** FM is typically used at VHF/UHF and above, which propagate mainly via line-of-sight, limiting range compared to AM MF/HF ground/sky waves.

6. APPLICATIONS

1. **FM Radio Broadcasting (88-108 MHz):** High-fidelity audio (WBFM, $\beta \approx 5$, Δf=75kHz, f_m=15kHz, BT≈180kHz).
2. **Sound in Analog Television:** FM audio subcarrier.
3. **Two-Way Mobile Radio (VHF/UHF):** Police, fire, taxi, business radio.
4. **Microwave & Satellite Communications:** Often combined with FDM.
5. **Cellular Telephony (Historical - Analog FM):** First-generation (1G) systems like AMPS.
6. **Telemetry:** Wireless transmission of sensor data.
7. **Radar:** Modulation within radar pulses.

VII. Important Relationships & Formulas

- Instantaneous Frequency: $f_i(t) = f_c + k_f * m(t)$ (Hz)
- Modulation Index: $\beta = \Delta f / f_m$
- Peak Frequency Deviation: $\Delta f = k_f * \max|m(t)|$ (Hz)
- **Carson's Rule (Bandwidth):** $BT \approx 2(\Delta f + f_m) = 2f_m(1 + \beta)$
- FM Wave (Single Tone): $s_{FM}(t) = A_c * \cos[2\pi f_c t + \beta \sin(2\pi f_m t)]$
- Bessel Expansion: $s_{FM}(t) = A_c * \Sigma [J_n(\beta) * \cos(2\pi(f_c + n f_m)t)]$ ($n = -\infty$ to ∞)

8. COMMON MISCONCEPTIONS & TROUBLESHOOTING

- **Misconception:** "FM has infinite bandwidth, so it's impractical." **Reality:** Carson's Rule gives a very practical bandwidth containing almost all the power.
- **Misconception:** "FM is completely immune to all noise." **Reality:** FM is immune to *amplitude* noise but susceptible to *phase* noise and certain types of interference (e.g., co-channel). The threshold effect exists.
- **Troubleshooting FM Demodulator**
    - Distorted Output: Check limiter function (is amplitude constant?), check discriminator linearity over the expected Δf range, check for incorrect β.
    - No Output/Weak Output: Check PLL lock, check discriminator tuning, check limiter clipping level.
    - Excessive Noise: Check signal strength (below threshold?), check limiter effectiveness.

9. STUDY TIPS & RESOURCES

1. **Focus on Concepts:** Understand *why* FM is used (noise immunity) and *how* it achieves it (constant envelope + limiter).
2. **Master the Math:** Be comfortable with the FM equation, modulation index (β), frequency deviation (Δf), and **Carson's Rule**.
3. **Visualize Spectra:** Sketch FM spectra for different β values (especially NBFM vs. WBFM). Understand Bessel nulls.
4. **Block Diagrams:** Be able to draw and explain block diagrams for FM generation (Direct, Indirect) and demodulation (Slope, Foster-Seeley, PLL, Quadrature).
5. **Compare & Contrast:** Constantly compare FM to AM and PM. Make tables of advantages/disadvantages.
6. **Practice Problems:** Do problems calculating β, Δf, f_m, BT. Analyze spectra. Design simple systems (e.g., Armstrong modulator parameters).
7. **Simulate:** Use tools like MATLAB, Python (NumPy, SciPy, Matplotlib), GNU Radio, or circuit simulators (LTspice) to visualize FM signals and spectra.
8. **Textbook:** Consult your primary textbook (e.g., Haykin & Moher, Proakis & Salehi, Lathi, Couch).
9. **Online:** Khan Academy, MIT OpenCourseWare, NPTEL lectures, reputable engineering blogs/videos (focus on core concepts).

10. ADVANCED TOPICS (BRIEF AWARENESS)

- Pre-emphasis and De-emphasis (FM Radio)
- FM Threshold Effect

- Stereo Multiplexing (FM Radio)
- FM in Digital Communications (FSK, MSK, GMSK)