Measurement and Data Driven Modeling

Assignment Report

Trade-offs in FRF Measurements

Objective

This assignment aims to explore and demonstrate the practical trade-offs between:

1. Frequency resolution
2. Measurement time
3. Signal-to-Noise Ratio (SNR)

in the context of measuring Frequency Response Functions (FRFs). This understanding is crucial when designing excitation signals for system identification.

Background

Measuring accurate FRFs requires balancing three competing factors:

1. **Frequency Resolution**: Higher resolution allows more frequency lines to be distinguished within a given bandwidth.
2. **Measurement Time**: Longer signals allow more averaging, reducing random noise.
3. **SNR**: The clarity with which excited frequency components emerge from the noise floor.

This trade-off is fundamental and unavoidable in any practical measurement setup. The trade-offs explored in this assignment assume:

- The RMS amplitude of the excitation signal is fixed to $1\,V$.
- The frequency band of interest lies between 5 Hz and 10 Hz.

Multisine Design Summary

The table below summarizes six example multisines designed to illustrate the trade-offs under different constraints:

Table 1: Example Multisine Designs for Each Trade-off Case

Trade-off Case	Excited Frequencies (Hz)	Period (s)	Notes
Fixed Resolution 1	5 to 10 Hz (30 lines)	6 s	Balanced power
Fixed Resolution 2	5 to 10 Hz (30 lines)	12 s	Higher SNR
Fixed Time 1	5 to 10 Hz (30 lines)	6 s	Baseline
Fixed Time 2	5 to 10 Hz (60 lines)	6 s	Finer resolution
Fixed SNR 1	5 to 10 Hz (30 lines)	6 s	Target SNR 40 dB
Fixed SNR 2	5 to 10 Hz (60 lines)	12 s	Same SNR, more lines

Results and Explanation

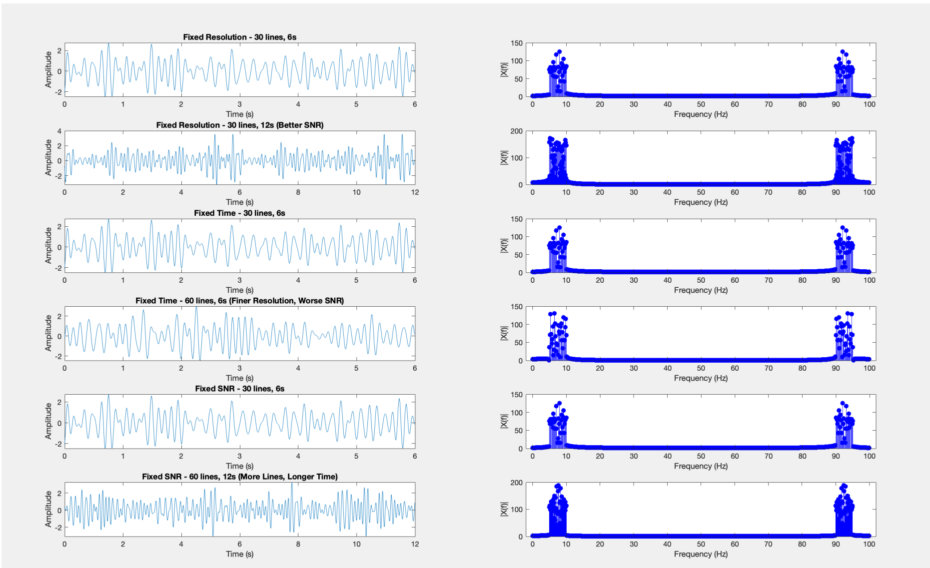

Figure 1: Time and Frequency Domain Plots for Different Multisine Designs Illustrating Trade-offs

Overview

Figure 1 displays the time domain and frequency domain representations of all six multisines. The left column shows the time-domain signals, while the right column shows the corresponding magnitudes of the Discrete Fourier Transform (DFT).

Analysis of Trade-offs

Trade-off 1: Fixed Frequency Resolution

The first two rows represent cases where 30 equally spaced frequencies between 5 Hz and 10 Hz are excited.

- Row 1 uses a 6-second signal.
- Row 2 uses a 12-second signal.

The longer duration reduces noise variance, improving the SNR. This can be seen from the cleaner peaks in the frequency spectrum of Row 2 compared to Row 1.

Physical Reason: The longer time window allows for more averaging, which reduces the variance of noise components. This means the signal peaks become sharper and more distinguishable from the noise floor in the frequency spectrum. This is a fundamental result of Fourier analysis — longer signals lead to **narrower frequency bins** and improved ability to separate signal from noise.

Trade-off 2: Fixed Measurement Time

The third and fourth rows correspond to a fixed 6-second measurement duration.

- Row 3 excites 30 frequencies.
- Row 4 excites 60 frequencies, doubling the resolution.

Since the total power (RMS fixed to 1V) must be spread over more frequencies in Row 4, the SNR per frequency decreases. This leads to less distinct peaks in the frequency domain.

Physical Reason: The fixed measurement time limits the total energy available in the excitation signal. As more frequency lines are excited (increased resolution), the available power per frequency component decreases. As a result, the peaks in the frequency spectrum become less pronounced relative to noise — this reduces the effective SNR per frequency line. This is a direct consequence of **energy spreading** across more frequencies.

Trade-off 3: Fixed SNR

The fifth and sixth rows maintain a constant SNR.

- Row 5 excites 30 frequencies over 6 seconds.
- Row 6 excites 60 frequencies, requiring the measurement duration to increase to 12 seconds to maintain SNR.

This illustrates that improving resolution (more lines) requires a proportional increase in measurement time to maintain SNR.

Physical Reason: If SNR is fixed, but resolution is increased (more frequencies excited), the only way to maintain the same SNR is to increase the measurement time. This allows the same level of noise averaging to occur for each frequency line. This highlights a fundamental fact: **higher resolution demands longer measurements if noise suppression (SNR) must be maintained**.

Summary of Observations

The experiments confirm the core trade-off triangle:

- Increasing measurement time improves SNR at constant resolution.
- Increasing resolution reduces SNR if time is fixed.
- Maintaining SNR while increasing resolution requires longer measurement times.

This triangular trade-off directly reflects the physics of spectral analysis and how energy spreads across time and frequency when the signal RMS is fixed.

Conclusion

Understanding these physical mechanisms is essential for practical FRF measurements. We must carefully select the combination of resolution, time, and SNR to match the goals of a specific system identification experiment. This trade-off framework applies to many real-world scenarios, such as vibration testing, acoustic analysis, and electromagnetic characterization.

MATLAB Code Implementation

The MATLAB code used to generate these results is included below:

```
% Trade-offs in FRF Measurement
clc; clear; close all;

% Global parameters
fs = 100;             % Sampling frequency (Hz)
RMS_des = 1;          % Desired RMS value
f_start = 5;          % Start frequency (Hz)
f_end = 10;           % End frequency (Hz)

% Tradeoff 1: Fixed Frequency Resolution
% Multisine 1 - 30 lines, 6 seconds
N1 = fs * 6;                                 % 6 seconds worth
   of samples
frequencies1 = linspace(f_start, f_end, 30);
x1 = generate_multisine(N1, frequencies1, fs, RMS_des);

% Multisine 2 - 30 lines, 12 seconds (better SNR)
N2 = fs * 12;                                % 12 seconds worth
    of samples
x2 = generate_multisine(N2, frequencies1, fs, RMS_des);

% Tradeoff 2: Fixed Measurement Time
% Multisine 3 - 30 lines, 6 seconds
x3 = x1;  % Same as Multisine 1 (fixed time = same N)

% Multisine 4 - 60 lines, 6 seconds (worse SNR, finer
   resolution)
frequencies4 = linspace(f_start, f_end, 60);
x4 = generate_multisine(N1, frequencies4, fs, RMS_des);

% Tradeoff 3: Fixed SNR
% Multisine 5 - 30 lines, 6 seconds, fixed SNR
x5 = x1;  % Same as Multisine 1 (same power spread over
   30 lines)

% Multisine 6 - 60 lines, 12 seconds (more frequencies,
   but maintain SNR by longer time)
x6 = generate_multisine(N2, frequencies4, fs, RMS_des);

% Plot all results
```

```
multisines = {x1, x2, x3, x4, x5, x6};
titles = {
    "Fixed Resolution - 30 lines, 6s', ...
    "Fixed Resolution - 30 lines, 12s (Better SNR)', ...
    "Fixed Time - 30 lines, 6s', ...
    "Fixed Time - 60 lines, 6s (Finer Resolution, Worse
       SNR)', ...
    "Fixed SNR - 30 lines, 6s', ...
    "Fixed SNR - 60 lines, 12s (More Lines, Longer Time)
       '
};

figure;
for i = 1:6
    subplot(6, 2, 2*i-1);
    plot((0:length(multisines{i})-1)/fs, multisines{i});
    xlabel('Time␣(s)');
    ylabel('Amplitude');
    title(titles{i});

    subplot(6, 2, 2*i);
    X = fft(multisines{i});
    f = (0:length(X)-1) * (fs/length(X));
    stem(f, abs(X), 'b', 'filled');
    xlabel('Frequency␣(Hz)');
    ylabel('|X(f)|');
end

disp('All␣multisines␣generated␣and␣plotted␣successfully.
   ');

%
function x = generate_multisine(N, frequencies, fs,
   RMS_des)
    t = (0:N-1) / fs;  % Time vector
    x = zeros(1, N);   % Initialize signal

    for f = frequencies
        phase = 2 * pi * rand();  % Random phase for
            each frequency
        x = x + cos(2*pi*f*t + phase);
    end
```

```
    % Scale to desired RMS
    RMS_x = sqrt(mean(x.^2));
    x = x * (RMS_des / RMS_x);
end
```