QEA 3 Final Project:
Tracking Dryer Vibrations with DFT

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1 Introduction

1.1 Engineering System Overview

The system studied in this project is a residential clothes dryer drum during operation. A dryer uses an electric motor to rotate a cylindrical drum while laundry moves freely inside. The drum is supported by a suspension system that limits how vibration is transmitted to the machine frame and the surrounding environment. As the drum spins, forces generated by the motion of the laundry excite vibrations in the system.

While laundry weight is often assumed to be the main contributor to vibration, this project focuses on how the balance and distribution of the laundry load within the drum affects the system's dynamic behavior. An unevenly distributed load can introduce large periodic forces even when the total mass is relatively small.

1.2 Societal Need

Dryers and washing machines are common household appliances and must operate safely, quietly, and reliably. Excessive vibration and noise can be disruptive for users and may cause the machine to move during operation, increase mechanical wear, or damage nearby structures.

Reducing vibration improves user comfort and extends the lifetime of the appliance. Understanding how unbalanced laundry loads affect vibration allows engineers to design machines that remain stable under real-world usage, where perfectly balanced loads are rare.

1.3 Engineering Design Decisions

Engineers designing dryers must make several decisions that directly influence vibration and stability. These include the stiffness and damping of the suspension system, drum balancing strategies, allowable spin speeds, and how motor control systems respond to detected vibration.

This project shows that the balance of the laundry load plays a larger role than total weight in driving vibration. As a result, design decisions should focus on handling unbalanced loads rather than simply limiting mass. For example, engineers may need to restrict spin speeds when imbalance is detected or design suspension systems that can better tolerate uneven loading.

1.4 Physical Origin of Periodic Behavior

The dryer exhibits periodic behavior because the drum rotates at an approximately constant speed. When the laundry load is unbalanced, the center of mass of the rotating system shifts away from the axis of rotation. This creates a periodic forcing on the drum and suspension at the rotation frequency, along with higher-frequency harmonics.

Even relatively light but poorly distributed loads can generate large periodic forces. These forces can excite resonant modes of the system, leading to large vibration amplitudes. This explains why imbalance, rather than total weight alone, has a stronger effect on vibration and why identifying problematic frequencies is critical when selecting spin speeds.

2 Data Collection and Experimental Design

2.1 Experimental Objective

The objective of this experiment is to measure dryer vibration under different laundry conditions and determine how load balance affects the system's dominant vibration frequencies. Rather than focusing only on total laundry weight, the experiment examines how balanced and unbalanced loads change the frequency content and amplitude of vibration.

By analyzing these differences, the experiment aims to identify resonant behavior and inform engineering decisions related to spin speed selection and vibration control.

2.2 Physical Setup

The experiment was conducted using a residential dryer operating under normal conditions. A smartphone was placed flat on top of the dryer to record vibrations transmitted through the machine body. The phone was positioned carefully to prevent sliding or rotation during operation.

Trials were conducted using light, medium, and heavy laundry loads, with each load differing by approximately 1200 grams from the previous one. For each load level, two trials were performed: one balanced trial, where the laundry was distributed evenly throughout the drum, and one intentionally unbalanced trial, where the laundry was bundled together and tied to create a strong mass imbalance. This resulted in six load-based samples. In addition, an empty-drum trial was recorded and treated as a baseline case, since it isolates vibrations due to the machine itself without the added effects of laundry mass or imbalance.

All seven samples were collected using the same dryer settings. Each trial lasted approximately 15 seconds and captured the full operational cycle, beginning with the power-up phase, continuing through steady rotation, and ending as the dryer slowed down and stopped. External disturbances were minimized by ensuring no contact with the dryer during measurements.

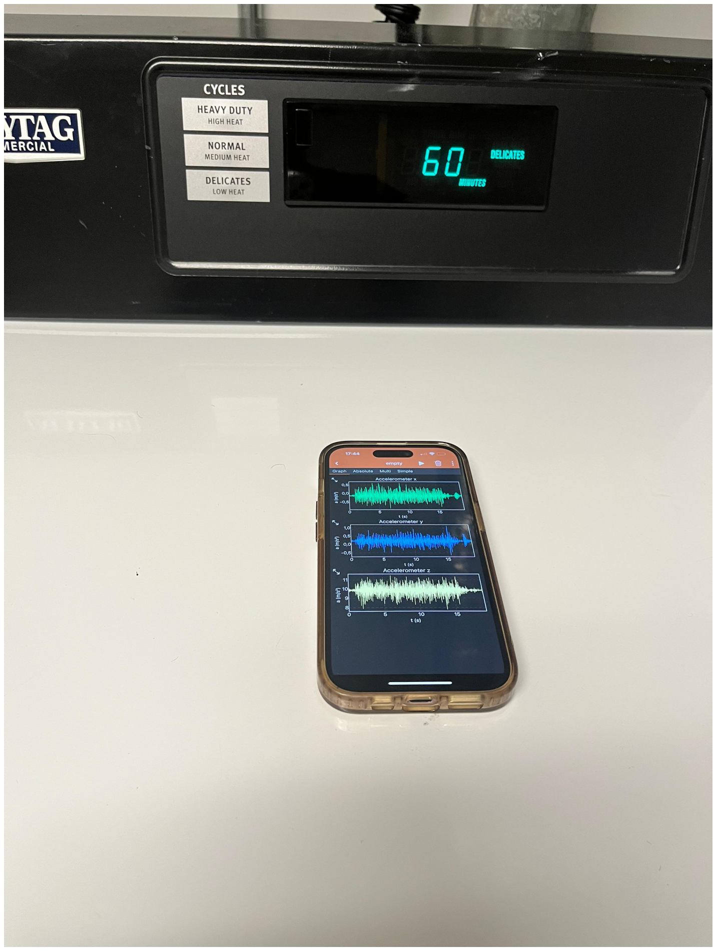

Figure 1: Experimental setup showing a smartphone placed on top of the dryer to measure vibration transmitted through the machine during operation.

2.3 Measurement Device and Sampling Parameters

Acceleration data was collected using a smartphone accelerometer and the Phyphox application. The accelerometer records acceleration along three axes, allowing vibration transmitted through the dryer structure to be measured.

Each trial was recorded for approximately 15 seconds, which provided sufficient time resolution to capture the dominant vibration frequencies during the spin cycle. The sampling rate provided by the application was high enough to capture the primary rotational frequency of the drum. The recorded acceleration data was exported as a CSV file and analyzed in MATLAB using the discrete Fourier transform.

Originally, we expected the manufacturer specifications of the dryer to define an optimal or nominal operating frequency. However, this information was not sufficient for our analysis. Instead, the empty-drum trial was used as a baseline reference to identify vibration characteristics intrinsic to the machine itself. Deviations from this baseline in the loaded trials were then attributed to the effects of laundry mass and, more importantly, load imbalance.

2.4 Recorded Load Properties

The mass of each laundry load was recorded prior to testing. For each trial, the dominant frequency observed in the DFT magnitude spectrum was identified and used for comparison across load conditions. Table 1 summarizes the recorded load masses and their corresponding mean frequencies.

Trial Type	Load Mass (g)	Balanced / Unbalanced	Mean Frequency (Hz)
Empty (Baseline)	0	Balanced	31.109
Light Load	1122	Balanced	33.045
Light Load	1122	Unbalanced	28.360
Medium Load	2486	Balanced	30.792
Medium Load	2486	Unbalanced	29.235
Heavy Load	3736	Balanced	28.105
Heavy Load	3726	Unbalanced	26.986

Table 1: Recorded laundry load masses and corresponding mean vibration frequencies extracted from the DFT for each trial.

Figure 2: Balanced laundry load in the dryer drum. Clothes are distributed evenly to minimize imbalance and reduce vibration.

Figure 3: Unbalanced laundry load in the dryer drum. Clothes are bundled to create a concentrated mass, increasing periodic vibrations and resonance effects.

3 Data Analysis Using the Discrete Fourier Transform

3.1 Data Processing

Before computing the discrete Fourier transform, the recorded acceleration data was preprocessed to ensure that the frequency-domain results reflected vibration due to the dryer system rather than artifacts of the measurement process. Acceleration data along the three axes were first extracted from the recorded CSV files. For the analysis presented here, only the vertical (z-axis) acceleration was used, as this direction most directly captures vibrations transmitted through the dryer structure to the measurement device.

Each acceleration signal was diminished by subtracting its mean value. This step removes any constant offset introduced by gravity, sensor bias, or phone orientation and prevents a large zero-frequency (DC) component from dominating the DFT magnitude spectrum. Removing the mean ensures that the frequency-domain analysis emphasizes oscillatory behavior associated with the rotating drum rather than static effects.

The time vector associated with each trial was used to estimate the sampling interval by computing the mean difference between consecutive time samples. This allowed the sampling frequency to be determined directly from the data rather than assumed a priority. No additional filtering or windowing was applied to the signal, so the calculated DFT corresponds directly to the mathematical definition of the transform and preserves the true frequency content of the measured vibration.

3.2 Discrete Fourier Transform Method

The frequency content of the measured vibration signal was analyzed using the discrete Fourier transform (DFT). For a discrete-time signal $x[n]$ consisting of N samples, the DFT is defined as :

$$X[k] = \sum_{n=0}^{N-1} x[n]e^{-j2\pi kn/N}$$

where n is the sample index in time and k is the frequency-bin index. In this experiment, $x[n]$ corresponds to the acceleration on the z-axis measured during a single dryer test, and N is the total number of samples recorded during that test.

The DFT was computed using this summation rather than a fast Fourier transform (FFT) algorithm. For each frequency index k, the acceleration signal was multiplied by a complex exponential corresponding to that frequency and summed over all time samples. This approach directly implements the mathematical definition of the DFT and allows a clear interpretation of how each frequency component contributes to the measured vibration.

The frequency associated with each DFT bin is given by:

$$f_k = \frac{kF_s}{N}$$

where F_s is the sampling frequency determined from the time data. The frequency resolution of the analysis is therefore $\Delta f = \frac{F_s}{N}$, meaning that longer time records provide finer resolution in the frequency domain.

After computing the DFT, the magnitude spectrum was formed and converted to a single-sided spectrum, since the original acceleration signal is real-valued. The zero-frequency component was excluded, and peak-finding algorithms were applied within a physically relevant frequency band to identify dominant vibration frequencies. The mean of these significant peak frequencies was then used as a quantitative measure for comparing vibration behavior across different load conditions.

3.3 MATLAB Code: DFT Analysis and Peak Detection

```
clear;
%data
files = {
    'Empty.csv'   % baseline
    'Light Balanced.csv'
    'Light Unbalanced.csv'
    'Medium Balanced.csv'
    'Medium Unbalanced.csv'
    'Heavy Balanced.csv'
    'Heavy Unbalanced.csv'
};

baselineIdx = 1;           % baseline index
useMagnitude = false;      % false = Z-axis

% peak settings
minPromFrac  = 0.05;
minPeakHzSep = 1;
fMin = 0;
fMax = 50;

%preallocate
nFiles = numel(files);
meanFreqs = nan(nFiles,1);

f_ss_all = cell(nFiles,1);
X_ss_all = cell(nFiles,1);
locs_all = cell(nFiles,1);
pks_all  = cell(nFiles,1);

% loop for DFT in all files
for i = 1:nFiles
    % load
```

```
    try
        data = readtable(files{i});
    catch
        data = readtable(files{i}, 'Delimiter', '\t');
    end

    t  = data{:,1};
    ax = data{:,2};
    ay = data{:,3};
    az = data{:,4};

    % demean
    ax = ax - mean(ax,'omitnan');
    ay = ay - mean(ay,'omitnan');
    az = az - mean(az,'omitnan');

    % signal
    if useMagnitude
        x = sqrt(ax.^2 + ay.^2 + az.^2);
    else
        x = az;
    end

    % sampling
    dt = mean(diff(t),'omitnan');
    Fs = 1/dt;
    N  = length(x);

    % DFT
    x = x(:).';
    n = 0:N-1;
    X = zeros(N,1);

    for k = 0:N-1
        X(k+1) = sum(x .* exp(-1j*2*pi*k*n/N));
    end

    % spectrum
    f = (0:N-1)*(Fs/N);
    Xmag = abs(X)/N;

    halfN = floor(N/2)+1;
    f_ss = f(1:halfN);
    X_ss = Xmag(1:halfN);
    if halfN > 2
        X_ss(2:end-1) = 2*X_ss(2:end-1);
    end

    % peak analysis
    f_use = f_ss(2:end);
    X_use = X_ss(2:end);

    band = (f_use >= fMin) & (f_use <= fMax);
    f_band = f_use(band);
    X_band = X_use(band);

    if isempty(X_band)
        meanFreq = NaN;
        locs = [];
        pks = [];
    else
        minProm = minPromFrac * max(X_band);
        [pks, locs] = findpeaks(X_band, f_band, ...
            'MinPeakProminence', minProm, ...
            'MinPeakDistance', minPeakHzSep);

        if isempty(locs)
            meanFreq = NaN;
        else
            meanFreq = mean(locs);
        end
```

```
    end

    meanFreqs(i) = meanFreq;

    f_ss_all{i} = f_ss;
    X_ss_all{i} = X_ss;
    locs_all{i} = locs;
    pks_all{i}  = pks;
end

% means
for i = 1:nFiles
    fprintf('%-12s : %.3f\n', files{i}, meanFreqs(i));
end

baselineMean = meanFreqs(baselineIdx);

% empty DFT
figure;
plot(f_ss_all{baselineIdx}, X_ss_all{baselineIdx}, 'LineWidth',1.2);
grid on; hold on;
xlim([0 fMax]);
xlabel('Frequency (Hz)');
ylabel('|X(f)|');

if ~isempty(locs_all{baselineIdx})
    plot(locs_all{baselineIdx}, pks_all{baselineIdx}, 'ro');
end
if ~isnan(meanFreqs(baselineIdx))
    xline(meanFreqs(baselineIdx), '--k');
end
title('Baseline (Empty)');

% DFT for others
figure;
tiledlayout(3,2,'Padding','compact','TileSpacing','compact');

for i = 1:nFiles
    if i == baselineIdx
        continue;
    end

    nexttile;
    plot(f_ss_all{i}, X_ss_all{i}, 'LineWidth',1.2);
    grid on; hold on;
    xlim([0 fMax]);
    xlabel('Frequency (Hz)');
    ylabel('|X(f)|');

    if ~isempty(locs_all{i})
        plot(locs_all{i}, pks_all{i}, 'ro');
    end
    if ~isnan(meanFreqs(i))
        xline(meanFreqs(i), '--k');
    end

    [~, nm, ~] = fileparts(files{i});
    title(strrep(nm,'_','\_'));
end

% comparison plots based on the baseline
labels = cell(nFiles,1);
for i = 1:nFiles
    [~, nm, ~] = fileparts(files{i});
    labels{i} = nm;
end

x = 1:nFiles;
deltaMean = meanFreqs - baselineMean;
figure;
stem(x, deltaMean, 'filled', 'LineWidth',1.5);
```

```
grid on;
xticks(x);
xticklabels(labels);
xtickangle(35);

ylabel('\Delta mean frequency vs baseline (Hz)');
yline(0,'--');
```

Listing 1: DFT and peak analysis for vibration data

4 Results & Plots

4.1 DFT Performed on Each Sample

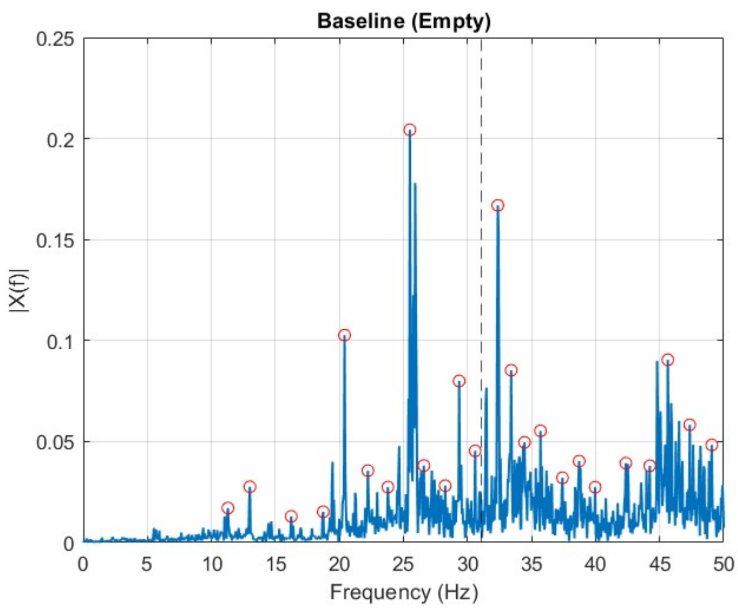

Figure 4: Discrete Fourier Transform (DFT) magnitude spectrum for the empty-drum baseline. This shows the intrinsic vibration of the dryer without laundry and serves as a reference for comparing other trials.

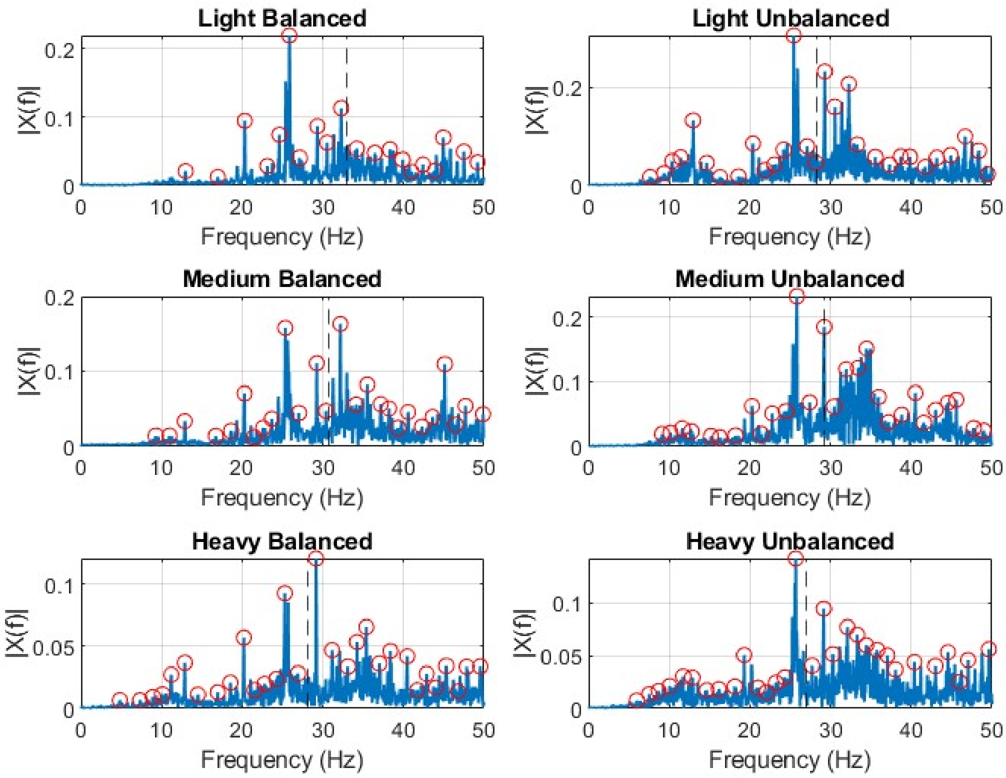

Figure 5: DFT magnitude spectra for all laundry-loaded trials. Each subplot shows how load balance and distribution affect the dominant vibration frequencies. Comparing these to the empty-drum baseline highlights the impact of load imbalance on the dryer's periodic behavior.

4.2 Baseline Comparison & Observed Trends

To understand how each laundry load affected the dryer's vibration relative to the machine itself, we plotted the baseline (empty-drum) DFT alongside a plot showing the difference between each sample and the baseline. This comparison highlights how much each load affects the system from its intrinsic vibration behavior.

From the plot, we can observe the following trends:

- The **medium balanced load** was closest to the baseline, indicating that a well-distributed load has minimal impact on the dryer's vibration characteristics.
- The **heavy unbalanced load** was furthest from the baseline, showing that large, concentrated loads induce the strongest deviations in vibration frequencies.
- Overall, **unbalanced loads consistently caused larger deviations** from the baseline than balanced loads of similar weight, confirming that load distribution is more critical than total mass in determining the machine's vibration response.

These results reinforce the importance of considering load balance when designing dryers and setting spin speed limits. Even moderate weights can create strong vibrations if distributed unevenly, while heavier but balanced loads may be less disruptive.

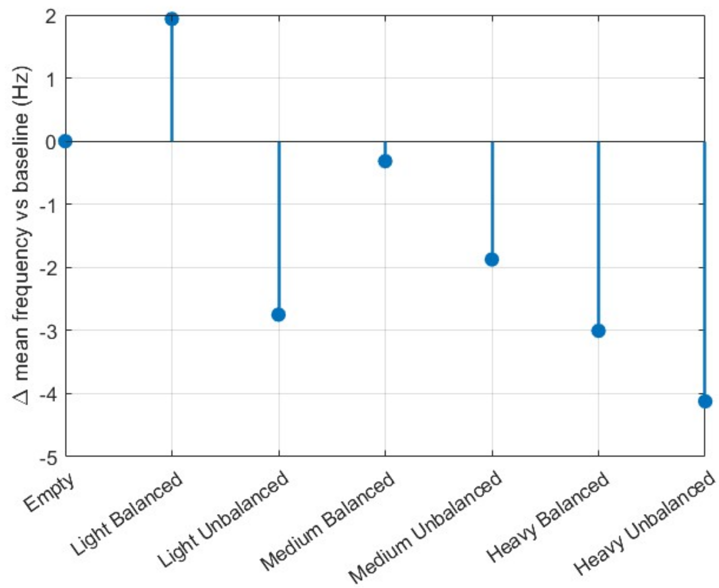

Figure 6: Comparison of baseline (empty-drum) vibration with all laundry-loaded trials. The plot shows how far each sample deviates from the baseline. Medium balanced load is closest, while heavy unbalanced load is furthest away, illustrating that unbalanced loads disturb the system more than balanced ones.

5 Conclusion

This project investigated how laundry load balance affects vibration behavior in a residential clothes dryer, with the broader goal of informing engineering design decisions related to vibration control and machine stability. Using a smartphone accelerometer placed on top of the dryer, vibration data were collected for empty, light, medium, and heavy loads under both balanced and intentionally unbalanced conditions. The vertical acceleration signal was analyzed using the discrete Fourier transform to identify dominant periodic components associated with drum rotation.

The DFT analysis revealed that changes in vibration frequency are more strongly influenced by load imbalance than by total laundry mass alone. Unbalanced loads consistently shifted the dominant vibration frequencies away from the baseline empty-drum case, even when the total load mass was relatively small. This behavior is consistent with the physical mechanism of an offset center of mass in a rotating system, which introduces periodic forcing at the rotation frequency and its harmonics.

From an engineering design perspective, these results highlight the importance of designing dryer suspension systems and control strategies that can tolerate or respond to unbalanced loads rather than simply limiting the allowable mass. Monitoring vibration frequencies relative to a baseline condition provides a practical way to detect imbalance and adjust operating parameters, such as spin speed.