MONITORING THE VIBRATION RESPONSE OF A TUNNEL BORING MACHINE: APPLICATION TO REAL TIME BOULDER DETECTION

by

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ABSTRACT

This thesis is a continuation of Bryan Walter’s dissertation work (2013), which analyzed ambient vibration of a tunnel boring machine (TBM) and proved this could be used to detect boulders. This work seeks to characterize vibration of a TBM consistent with boulder impacts. A network of accelerometers was placed on a TBM in Seattle to record the vibration response to tested impacts and machine operation (cutterhead rotation). This network was then secured in place for continuous monitoring during tunneling. The investigation was driven by the development of a boulder detection algorithm that would operate in real time. Other key goals included characterizing response to both known and unknown impacts and frequencies occurring during ambient vibration, which were intended to advance general knowledge of TBM vibration while improving the robustness of the boulder detection algorithm.

Several interesting results have been obtained from this study. Vibration is consistently best transferred in the longitudinal direction (along the axis of the TBM). Many high amplitude frequency components exist during ambient vibration, many of which were found proportional to cutterhead rotation rate by Walter (2013). A majority of these frequencies have been matched to mesh frequencies of the planetary gearboxes that drive cutterhead rotation. Knowledge of these high amplitude frequencies has allowed the development of a single boulder detection variable (BDV) which compiles the high amplitude frequencies present during an impact while avoiding the high amplitude frequencies present during ambient vibration.

Although this study is limited by lack of ground truth data (where cobbles and boulders are located), the presence of a cobble-heavy soil section in the path of the TBM allowed for calibration of the boulder detection algorithm and more reliable impact detection. No significant trends were found between the magnitude of BDV-detected impacts and the frequency response functions. However, BDV impacts were extremely well correlated to till-like deposits, where many cobbles were found exiting the TBM. No trends were found relating BDV magnitude to cutterhead rotation rate or pressure inside the TBM excavation chamber. Further investigation into ambient vibration is suggested to better characterize the relationships between vibration, operating parameters, and ground conditions, and advanced modeling of TBM components is recommended to bolster general understanding of TBM vibration.
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DEDICATION

I dedicate this work to my sister, a fearless soul always climbing a taller tree, searching for a deeper connection, expressing brilliance through her words, leaving a forceful impact in her wake. It is of her I will think as I tackle each obstacle in my journey, academic and otherwise, imbibing myself with her tenacity and obstinacy to reach greater heights.

Megan V Buckley

June 22, 2000 – May 3, 2015
CHAPTER 1: INTRODUCTION

This thesis investigates the vibration of a tunnel boring machine (TBM) and its application to an impact detection system intended to identify boulders in the path of the tunnel. Much of this work is a continuation of Walter’s work evaluating possible uses of passive vibration measurement on a TBM [1].

1.1 A Brief Introduction to Vibration Monitoring in Machinery

Vibration is used for monitoring in many machine applications. Especially in rotating machinery, there is a level of ambient vibration whenever the machine is running. A change in this vibration or a sudden spike often indicates changing conditions, such as a part that is failing or external influence. Bearing failure, for instance, can be catastrophic. However, a different frequency signature can be detected before this occurs if proper monitoring is in place, and the bearing can be replaced before other more costly elements in the assembly are damaged by complete bearing failure [2], [3]. Impacts with the external environment are likely in machines that operate outdoors, especially in unpredictable situations such as underground, underwater, in the atmosphere, or in outer space. Even if the machine is manually controlled by an operator who is physically present at the machine, all impacts will not be noticeable and certainly not measureable by an operator who is monitoring many different parameters. Airborne machinery such as helicopters are built from lightweight composite materials, and damage that threatens safe operation may not be visible. Outfitting such a machine with vibration sensors is critical to logging impacts, especially if impact magnitude and location can be determined from response. This type of instrumentation is comprised of the overlapping fields of condition monitoring (CM) and structural health monitoring (SHM), using damage prognosis after known impacts have been identified [4].

1.2 Vibration Applications in Tunnel Boring Machines

Although much more resilient to environmental interaction than indoor or airborne machinery, tunnel boring machines (TBMs) can also benefit from a combination of CM and SHM. The vibration response to both internal machinery (comprised largely of components that drive or are linked to rotation of the cutterhead, such as motors, bearings, and gears) and external interaction (with the ground, especially at the cutterhead and specific cutting tools) can be used
to develop an understanding of ambient TBM vibration and indicate when damage may be occurring.

Most current vibration applications to TBMs have been related to tunneling in hard rock and are specific to the cutting tools and rock characteristics; a study by Hong et al. uses finite element modeling to investigate the dynamic interaction of a disc cutter breaking apart rock [5]. A model for the cutterhead and its interactions with the main bearing, pinion, coupling, motors, and gearboxes for a hard rock tunneling machine was developed by Sun et al. in order to optimize cutterhead design [6]. Many complex interactions were considered for this model, including field data for external excitations in hard rock tunneling, resulting in 4 primary frequency response modes of the cutterhead combined in tangential, radial, and longitudinal directions from 112 Hz to 693 Hz. While impacts are more prevalent in hard rock tunneling, TBMs tunneling through soft ground (soil deposits) also experience impacts from encountered cobbles and boulders along the alignment, more common in certain types of soil deposits. There is little research related to soft ground tunneling, especially with regards to vibration.

Walter’s study, which forms the starting point for this thesis, investigates the response of a TBM bulkhead through passive vibration measurement, with a focus on correlating vibration response to geological conditions [1]. He used a matrix of 4 accelerometers placed on the bulkhead (shown in Figure 1.1) to measure ambient vibration while tunneling and to correlate vibration with changing operating parameters and geological compositions. His work evaluated the feasibility of a boulder detection system, but only time domain response was implemented in real time for operator use. Walter investigated many aspects of TBM vibration, evaluating the feasibility and value of many avenues of future analysis. This thesis seeks to address and further analyze some of the topics introduced in Walter to progress the understanding of soft ground TBMs and their vibratory response to both internal and external excitations.
1.3 Objectives

The primary purpose of this thesis is to further the work of Walter [1] in understanding vibration of a tunnel boring machine in soft ground. A focus was placed on detecting and characterizing impacts to the TBM, both individually and as a whole. Specific objectives to advance these goals include:

1) Improving the data collection system used by Walter, including a more expansive sensor network, a more powerful data controller, and more onboard data storage
2) Characterizing the main ambient frequency components and their relationship to cutterhead rotation rate
3) Analyzing stationary test impacts to further TBM response knowledge
4) Developing an advanced boulder detection system that can be implemented in real time to alert the operator of potential boulder impacts. The concept for this algorithm is shown in Figure 1.2.
5) Evaluating impact results along the alignment in relation to ground and operating conditions

Figure 1.1 Accelerometer Locations and TBM Layout in Walter’s Study [1]
This work was largely driven by the development of the boulder detection system. The other analyses were able to improve the robustness of the algorithm while contributing to general understand of TBM vibration.

Figure 1.2 Boulder Detection Algorithm Flowchart. Flow during quiet periods with no impacts is described in blue, with the response to a boulder impact indicated in red.
CHAPTER 2: PROJECT BACKGROUND

This chapter presents all relevant information to the Seattle tunneling project and vibration monitoring system. Emphasis will be placed on the field site, key functions of the TBM including motors that drive the cutterhead rotation, equipment installed for vibration monitoring, and testing procedure.

2.1 Field Site

All data and analysis in this thesis is based on the N125 tunneling project in Seattle, Washington. Twin tunnels have been commissioned by Sound Transit to extend the existing light rail network from the University of Washington to Northgate. The project is contracted by JCM Joint Venture (comprised of Jay Dee Contractors, Coluccio Construction, and Michels Corporation). Jay Dee has been the primary contact for this research. Although both the northbound and southbound tunnels are under construction, all data presented and analyzed in this thesis is related to the northbound tunnel. The soil in this area is glacially overridden, as with most of the Pacific Northwest, and often includes boulders of various sizes. The glacial action in the past compressed and overconsolidated the soil, giving it a high density and creating highly pressurized conditions. There are four main soil types that lie in the path of the tunnel: cohesionless sand and gravel (CSG), cohesionless silt and fine sand (CSF), cohesive clay and silt (CCS), and till-like deposits (TLD). These soil types are indicated by orange, green, blue, and purple in Figure 2.1 below, respectively. Soil types affect tunneling operations in different ways, such as the necessary face pressure to support the soil in front of the TBM and the torque required to remove it, based on parameters such as cohesion, pressure angle, and unit weight that change according to soil type [7]. Most soil types are fairly homogeneous with the notable exception of till, which is by definition a heterogeneous mixture of debris, soil, and cobbles and boulders that is deposited directly by the glacier [8]. Geology along the alignment is presented in Figure 2.1, and a plan view of the alignment is shown below in Figure 2.2. The launch site of the project, the Maple Leaf Portal, is shown in Figure 2.3.
Figure 2.1 N125 Geological Profile [9]. The tunnel alignment is outlined in red, with soil types within the alignment indicated.

Figure 2.2 N125 Tunnel Alignment: Plan View [9]

Figure 2.3 Maple Leaf Portal Launch Pit. The northbound tunnel is located on the left.
2.2 TBM Components

For this project, a Hitachi-Zosen TBM, 6.4 m in diameter, is being used to excavate the northbound side of the twin light rail tunnel project. A general description of the TBM and details into the cutterhead drive motors, including vibration frequencies which might result from operation, are included in this section. The general layout of the TBM is shown in Figure 2.4.

![Figure 2.4 General TBM Layout, modified from [10]](image)

**2.2.1 General Description**

The Hitachi-Zosen TBM used for this project is known as earth-pressure balance (EPB), which is designed for soft ground (as opposed to hard rock) and is able to offset the pressure of the soils and groundwater in front of the machine with the soil that has most recently been excavated, shown in Figure 2.5-a. The excavated soil is kept pressurized in the excavation or mixing chamber behind the cutterhead and controlled by the rate at which the soil is removed through the screw conveyor. Soil conditioning agents are added to the excavation chamber to maintain an optimal consistency of muck (conditioned soil that leaves the TBM), also contributing to the chamber pressure. The screw conveyor is shown in Figure 2.5-b, the cutterhead and excavation chamber are shown in Figure 2.6, and the layout of these components can be found in Figure 2.4. The TBM constructs the tunnel as it progresses in units known as...
rings, composed of 6 precast concrete segments (including one key segment) that are placed by the TBM segment erector and bolted together. The TBM can be seen with segments waiting to be placed in Figure 2.7. Once a ring is fully constructed and secured in place, 16 hydraulic thrust jacks push the TBM off of the newly constructed ring. Advance from the thrust jacks is coupled with rotation of the cutterhead, driven by 8 electric motors, in order to move the TBM forward as it removes soil. Once the TBM has advanced the full length of the push, 1.5 m or one ring width, the next ring is constructed and the process is repeated. Due to the cyclic nature of excavating and ring building, ring number along the alignment is a natural way to categorize data and will be referred to throughout this thesis. The tunnel direction is controlled by articulation jacks; the cutterhead is slightly larger than the shield to allow tunneling along a curve. The alignment is then solidified by placement of the key ring segment. Due to the confined spaces within the TBM, all operation controls, power supplies and transformers, and monitoring systems are housed in a train of cars attached to and pulled forward by the TBM.

![Figure 2.5 a) Earth-Pressure Balance. Pressure from the soil (brown) and groundwater (blue) are offset by pressurized muck in the excavation chamber (red), from [1]; b) Muck is removed from the excavation chamber through the pictured entrance to the screw conveyor.](image-url)
Figure 2.6  a) TBM Cutterhead. The nose cone projects furthest in the center of the cutterhead, aligning the TBM. Face cutters along the axis of each spoke knock material loose, while side scrapers guide loosened material into the excavation chamber. Outer cutters extend the radius in order to allow alignment jacks to control the direction of the TBM; b) Excavation Chamber. Excavated material enters the chamber through openings in the cutterhead and is conditioned for optimal support pressure. This muck is mixed in the chamber until exiting through the screw conveyor.

Figure 2.7  a) Hitachi-Zosen TBM ready to excavate northbound tunnel; b) Concrete ring segment awaiting placement by the segment erector behind the TBM
EPB TBMs have been successful in many soft ground instances, but the presence of large boulders can be problematic and costly because the teeth and scrapers on the cutterhead are designed to remove soil and are not optimized to break apart and cut through rock. Small boulders and cobbles only need to be knocked loose and can pass through the cutterhead openings, excavation chamber, and screw conveyors whole; this machine can pass boulders up to 0.46 m (1.5 ft) in diameter. Another option would be to use disc cutters, which are much more durable and experience less shear force due to their ability to rotate, but these are much more costly. If normal scrapers are chosen, the cutterhead can sometimes become gridlocked in boulders. If the boulder cannot be chipped away or knocked aside by the cutterhead, it must be broken apart by sending divers into the pressurized excavation chamber or, an even more costly and extensive solution, by drilling a shaft down from the surface. However, with immediate knowledge of boulder interaction, more options are available. Operating parameters such as cutting speed, advance rate, and thrust can be adjusted to optimize chances of breaking through the boulder. The vibration system developed for this project monitors TBM vibration and analyzes the collected data to identify impacts with a likely correspondence to boulders and cobbles in the ground. Walter’s study determined that the frequencies present during ambient vibration are correlated to cutterhead rotation rate [1], suggesting forced vibration response. However, the frequencies are roughly 10,000 times greater than the rotation rate; therefore, the cutterhead driving motors will be investigated to identify possible sources of such high forcing frequencies.

2.2.2 Cutterhead Driving Motors

As seen in Figure 2.4, the cutterhead is attached to a rotating frame which turns with the ring gear. This gear is seated by means of the main triple roller bearing and driven by 8 cutterhead drive motors. The motors and the connection of the rotating frame to the cutterhead in the excavation chamber are shown in Figure 2.8, and the arrangement of cutterhead motors around the ring gear is shown in Figure 2.9.
Figure 2.8 a) The electric motors secured in the blue cylinders are controlled by VFD and drive the cutterhead; b) This rotating frame transmits rotation from the ring gear to the cutterhead.

Figure 2.9 Layout of Cutterhead Driving Motors with respect to the Ring Gear [10]
The electric motors are known as variable frequency drive (VFD), which allows the operator to change the speed at which the cutterhead is rotating, an important factor in adjusting to tunneling conditions. Motor speed is determined by torque load and input current—without the ability to change this current, the cutterhead rotation rate could not be changed for a given load. Torque load was expected to be approximately 2000 kNm, while the combined torque capacity from the cutterhead drive system was approximately 6000 kNm. Since the torque capacity is much greater than the expected load, motors without VFD would not be limited by torque and operate at full speed [10]. VFD motors allow this current manipulation by converting the input AC signal to DC, smoothing the signal with a capacitor, and inverting it back to AC at the desired rate with a series of switches. Positive and negative or ground switch pairs are known as poles and, with the signal frequency, determine the speed of the motor. A schematic of the VFD process is presented below in Figure 2.10 [11].

![Figure 2.10 Functional Operation of a Variable Frequency Drive [11]](image)

A summary of motor specifications is shown in Table 2.1. Calculation of the motor speed is shown in Equation 2.1. Each motor is then connected to a 3-stage planetary gearbox (Figure 2.11), the output of which is coupled to one of the pinions that turns the ring gear. All gear ratios in the assembly serve to reduce speed and increase torque; therefore, the motor necessarily has the highest rotation frequency. Even with a maximum output VFD frequency, the motor is only rotating at 29.33 Hz, lower than the frequencies observed by Walter [1].
planetary gearbox will be investigated in greater detail to identify if higher frequency components are visible in gear tooth meshing.

\[ \omega_{\text{motor}}(\text{RPM}) = \frac{120 \times f_{\text{VFD}}(\text{Hz})}{\# \text{poles}} = 60 \times \omega_{\text{motor}}(\text{Hz}) \] (2.1)

Table 2.1 Cutterhead Driving Motor Specifications [10]. The variable \( i \) indicates the overall gear ratio of the planetary gearbox. The maximum frequency refers to the output of the VFD. A maximum frequency of 88 Hz corresponds to a maximum motor speed of 1760 RPM or 29.33 Hz.

<table>
<thead>
<tr>
<th>Application</th>
<th>Output axle torque (kN-m)</th>
<th>Output (kW)</th>
<th>Number of pole (P)</th>
<th>Voltage / Base Frequency (V x Hz)</th>
<th>Quantity</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutterhead</td>
<td>82.5</td>
<td>90</td>
<td>6</td>
<td>480V / 60Hz</td>
<td>8</td>
<td>i=1/88.78 Variable frequency</td>
</tr>
</tbody>
</table>

* Maximum frequency : 88Hz / Output axle torque : 43.1kN-m

Figure 2.11 a) Approximate placement of motors, gearboxes, and pinions is shown around the ring gear, which is directly coupled to the cutterhead through the rotating frame. b) Three stages of planetary gears decrease the speed and increase the torque of the pinion. Gear thicknesses (face widths) are not to scale. c) The motor serves as the gearbox input, which divides the motor speed by 88.78 before reaching the output pinion shaft.

2.2.3 Planetary Gearbox
A single planetary stage is shown in Figure 2.12. There are four components: a sun gear, multiple planet gears, an arm that connects all of the planets, and an internal ring (different than the large ring gear that rotates the cutterhead). While many configurations of a planetary gear system are possible, all of the planetary stages in the cutterhead drive gearboxes use the same configuration: a stationary internal ring. The input of the stage is the sun gear, which rotates in either direction depending on the desired rotation of the cutterhead. For explanation purposes, the sun will always rotate in the clockwise direction. The external gear interaction between the sun and the planets dictates that they will rotate in the opposite direction (counter-clockwise) as the sun gear, but the stationary internal ring will force the planets to revolve clockwise around the sun. The arm that connects the planets captures this revolution in the output for the current stage, which is input into the next stage.

![Single Planetary Gear Stage Schematic](image)

*Figure 2.12* Single Planetary Gear Stage Schematic. The sun serves as the input, which drives the planets to both rotate and revolve with a stationary ring. The revolution is captured by output arm. Although the arm is depicted as an open triangle for visibility, its center is in reality a hollow shaft, allowing concentric shaft placement throughout the entire gearbox.

The entire gear interaction for each motor, including the motor, 3-stage planetary gearbox, pinion, and ring gear, is shown as a functional schematic in Figure 2.13. The motor drives the sun input of the first stage, and the arm output of the first two stages drive the sun inputs of the following stages. The last stage arm output drives the pinion, which drives the ring gear connected to the cutterhead in conjunction with the 7 other motor, gear-train, pinion...
combinations. Although the function of each gear is shown in the schematic, some realistic considerations are ignored. Three points will now be clarified. 1) The second and third stages are much larger than the first as they have a larger module (pitch diameter / number of teeth), meaning each tooth is larger. The module must be the same for two interacting gears. 2) All central shafts are hollow and concentric, allowing them to be supported after the pinion. 3) The first two stages have 3 planets, and the third stage has 5 planets. Two planets are shown for each stage to highlight interaction, but a true cross section would show only one as each stage has an odd number of planets.

Figure 2.13 Gear Train Functional Schematic. The motor drives the input sun of the first planetary stage. The revolving planets drive the arm, which is coupled to the sun input of the next stage. This is repeated for the next 2 stages, with a final arm output coupled to the pinion. The pinion, along with the output pinions from the remaining 7 motors, rotates the ring gear output. The total gear ratio is 799, providing the cutterhead with 799 times the torque capacity of the combined 8 motors.

After understanding the functionality of the gear train, all speeds can be calculated. The motor speed was calculated previously from the VFD output, shown again here. The ratio of two gear speeds in a simple gear train is equal to the gear ratio, or the ratio between the numbers of
teeth (N), as shown in Equation 2.2. All gear-related equations were obtained or derived from [12].

\[
\omega_{motor}\text{(RPM)} = \frac{120 \times f_{VFD}\text{(Hz)}}{\#\text{poles}} = 60 \times \omega_{motor}\text{(Hz)} \quad (2.1)
\]

\[
GR = \frac{\omega_1}{\omega_2} = \frac{N_2}{N_1} \quad (2.2)
\]

In a system with more than two gears, such as the one shown in Figure 2.14, gear ratios of each interaction are multiplied by the input frequency to find the output frequency, as shown in Equation 2.3. External gears use a negative gear ratio while internal gears use a positive gear ratio, determined by transmission direction.

\[
\omega_3 = \omega_1 \times \left( -\frac{N_2}{N_1} \right) \times \left( -\frac{N_3}{N_2} \right) = \omega_1 \times \frac{N_3}{N_1} \quad (2.3)
\]

However, a simple gear train assumes that the centers of all gears are not moving. In order to calculate the rotational speeds in a planetary gear train, all speeds must be calculated relative to the arm in order to use Equation 2.3 for simple gear interaction. (All gear centers are stationary when the arm is viewed as stationary). R is used for internal rings, S is used for suns, P is used for planets, and A is used for arms. If stage is not specified, all referenced gears are assumed to be in the same stage. All internal rings are known to be stationary (Equation 2.4). Relative speeds are calculated in Equation 2.5.

\[
\omega_{R1} = \omega_{R2} = \omega_{R3} = 0 \quad (2.4)
\]

\[
\omega_S = \omega_A + \omega_{S/A} ; \quad \omega_R = \omega_A + \omega_{R/A} ; \quad \omega_P = \omega_A + \omega_{P/A} \quad (2.5 \ a - c)
\]
Rearranging the terms in Equations 2.5 (a-c), a simple gear train calculation can be computed. Equations 2.6-2.8 show the derivation of arm speed of each planetary stage from a known sun input. The sun-planet interaction is external, while the planet-ring interaction is internal. A similar derivation was computed for the planet gears, leading to a final equation based on arm speed shown in Equation 2.9.

\[
\frac{\omega_{R/A}}{\omega_{S/A}} = \frac{\omega_R - \omega_A}{\omega_S - \omega_A} = \left( -\frac{N_S}{N_p} \right) \left( \frac{N_p}{N_R} \right) \tag{2.6}
\]

\[
\omega_A = \frac{N_S}{N_R} \ast (\omega_S - \omega_A) \tag{2.7}
\]

\[
\omega_{S(n+1)} = \omega_{A(n)} = \frac{\omega_{S(n)} \ast N_{S(n)}}{N_{R(n)} + N_{S(n)}} = \frac{\omega_{S(n)}}{GR_{S(n)}} \tag{2.8}
\]

\[
\omega_{P(n)} = \omega_{A(n)} \ast \left( 1 - \frac{N_{R(n)}}{N_{P(n)}} \right) \tag{2.9}
\]

The planetary gear ratio is calculated in Equation 2.10, allowing the calculation of both the speeds of the pinion and the ring gear (Equations 2.11-2.12).

\[
GR_{planetary} = GR_{S1} * GR_{S2} * GR_{S2} = 4.286 \times 4.833 \times 4.286 = 88.781 \tag{2.10}
\]

\[
\omega_{pinion} = \omega_{A3} = \frac{\omega_{motor}}{GR_{planetary}} \tag{2.11}
\]

\[
\omega_{ring} = \omega_{pinion} \ast \frac{N_{pinion}}{N_{ring}} = \frac{\omega_{pinion}}{GR_{ring}} = \frac{\omega_{motor}}{GR_{planetary} \ast GR_{ring}} \tag{2.12}
\]

Now that speeds of all gear components are known, mesh frequencies can be calculated. The most prevalent frequencies resulting from gear interaction are the mesh frequencies closest to natural vibration modes of the components [13]. A mesh frequency is the frequency at which a tooth from one gear meshes with a tooth on an interlocked gear, which is essentially the rotation speed times the number of teeth. This is necessarily much higher than the rotation speed and may provide an explanation of the high forced frequencies observed in Walter [1]. However, the calculation is slightly more complicated for a planetary gear train, as the planets are revolving around the sun; by the time the next sun tooth has rotated in place, the planet has moved farther away. When viewed from the reference of a stationary arm, the meshing
frequency between the sun and each planet is the same as the meshing frequency between the internal ring and each planet. Speeds must again be determined relative to the arm (Equation 2.13) in order to derive the mesh frequency of each stage (Equation 2.14). The internal ring was used in calculation for its simplicity.

\[ MF(1-3) = \omega_{S/A} \times N_S = \omega_{P/A} \times N_P = \omega_{R/A} \times N_R \]  

\[ MF(n) = |(\omega_{R(n)} - \omega_{A(n)}) \times N_{R(n)}| = \omega_{A(n)} \times N_{R(n)} = \frac{\omega_{S(n)} \times N_{S(n)} \times N_{R(n)}}{N_{R(n)} + N_{S(n)}} \]  

There is an additional meshing frequency between the pinion and ring gear, calculated in Equation 2.15. The 1st mesh frequency is highest and is therefore expected to be most useful during analysis. Table 2.2 displays the numbers of teeth, gear component frequencies, and mesh frequencies calculated at maximum speed. The first mesh frequency (MF1) is in the correct range and will be investigated in the next chapter. All mesh frequencies and their harmonics could potentially be present as a gear mesh interaction does not produce a sinusoidal signal [14].

\[ MF_4 = \omega_{pinion} \times N_{pinion} = \omega_{ring} \times N_{ring} \]  

**Table 2.2 Calculated Frequencies at Maximum Motor Speed. Negative frequency indicates opposite rotational direction.**

<table>
<thead>
<tr>
<th># Gear Teeth</th>
<th>Gear Frequencies</th>
<th>Mesh Frequencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS1</td>
<td>21</td>
<td>VFDout 88.00 Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MF1 403.1 Hz</td>
</tr>
<tr>
<td>NP1</td>
<td>23</td>
<td>ωS1=ωmotor 29.33 Hz</td>
</tr>
<tr>
<td>NR1</td>
<td>69</td>
<td>ωA1 6.84 Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MF3 19.5 Hz</td>
</tr>
<tr>
<td>NS2</td>
<td>18</td>
<td>ωP1 -13.69 Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MF4 3.9 Hz</td>
</tr>
<tr>
<td>NP2</td>
<td>25</td>
<td>ωS2 6.84 Hz</td>
</tr>
<tr>
<td>NR2</td>
<td>69</td>
<td>ωA2 1.42 Hz</td>
</tr>
<tr>
<td>NS3</td>
<td>21</td>
<td>ωP2 -2.49 Hz</td>
</tr>
<tr>
<td>NP3</td>
<td>23</td>
<td>ωS3 1.42 Hz</td>
</tr>
<tr>
<td>NR3</td>
<td>69</td>
<td>ωA3=ωpinion 0.33 Hz</td>
</tr>
<tr>
<td>Npinion</td>
<td>14</td>
<td>ωP3 -0.66 Hz</td>
</tr>
<tr>
<td>Nring</td>
<td>126</td>
<td>ωring 2.20 RPM</td>
</tr>
</tbody>
</table>
2.3 Equipment and System Development

The TBM was instrumented with a series of accelerometers and a data acquisition system in order to continuously monitor vibrations. Initial testing was performed in open air to characterize vibration response to known inputs for different accelerometer locations.

2.3.1 Vibration Monitoring System

The TBM vibration monitoring system consists of 8 accelerometers, including 4 tri-axial sensors (Silicon Designs 2460-010) and 4 uniaxial sensors (Silicon Designs 2260-010) connected to a data acquisition system (DAQ).

Specifications of the accelerometers are shown in Table 2.3, with dimensions shown in Figure 2.15. The compact nature of the accelerometers allowed them to be placed in many locations throughout the TBM without interfering with operation. The output acceleration is calculated using Equation 2.16.

Table 2.3 Accelerometer Specifications [15], [16]

<table>
<thead>
<tr>
<th>Model (Silicon Designs, Inc.)</th>
<th>2460-010</th>
<th>2260-010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Range (g)</td>
<td>±10</td>
<td>±10</td>
</tr>
<tr>
<td>Output Voltage Range (V)</td>
<td>.5 - 4.5</td>
<td>.5 - 4.5</td>
</tr>
<tr>
<td>Differential Voltage (V)</td>
<td>0 - ±4</td>
<td>0 - ±4</td>
</tr>
<tr>
<td>Frequency Response (3 dB) (Hz)</td>
<td>0 - 1000</td>
<td>0 - 1000</td>
</tr>
<tr>
<td>Differential Sensitivity (mV/g)</td>
<td>400</td>
<td>400</td>
</tr>
</tbody>
</table>

Figure 2.15 Accelerometer Dimensions [15], [16]
\[ \text{acceleration (g)} = \frac{AOP (mV) - AON (mV)}{\text{Differential Sensitivity} \left(\frac{mV}{g}\right)} = f(t) \quad (2.16) \]

The DAQ consisted of a National Instruments cRIO 9024 controller used to acquire data mounted to a chassis with analog input module (16 differential channels), power supply, power strip to power all sensors, 8 female connectors (each with 8 channels: 2 for power and 6 (2) for 3 (1) differential axes), indicator light, grounding cable, ethernet port, power port, mounting system, and the box itself. Setup is shown in Figure 2.16. The cable connection schematic, along with examples of the mounted accelerometers (bolted to steel plates inlaid with rare earth magnets), are shown in Figure 2.17.
The cRIO 9024 [17] is programmed with NI LabVIEW [18] and can be controlled through an ethernet connection, either by a directly connected computer or by a computer on a connected network, or a real-time deployable program can be launched on the cRIO. The cRIO series is designed for the second alternative, but the first is useful for program development and testing. The programs and devices used were modified from those developed and selected by Walter [1]. All vibration data in open air testing and during tunneling was collected at 3000 Hz. The basic functionality of the modified program was to continuously collect 3 second blocks of data, converted to units of g, from each channel. If a channel exceeded its specified rms trigger level, 20 blocks of vibration data with DC offset removed (gravity independent) were stored in memory and saved as a 1 minute .tdms file. Once the file was saved, monitoring recommenced.

2.3.2 Open Air Testing Procedure

Testing on the TBM was performed in open air at the Maple Leaf Portal before tunneling began in June 2014. The LabVIEW program was modified to allow for optimal file length and manual triggering for each test. Testing consisted of two main phases: stationary cutterhead testing and rotating cutterhead testing. The primary layout of the accelerometers throughout testing is shown below in Figure 2.18.

![Figure 2.18 Open Air Testing Accelerometer Layout and Directions](image-url)
Impact testing was performed on the stationary cutterhead at a series of 33 specified locations (typically cutting tools) shown in Figure 2.19. Each location was struck in tangential, radial, and longitudinal directions (with respect to the central axis of the TBM), with 3 hits for each direction to allow for averaging and evaluation of usable impacts (Figure 2.20). The vibration response will be analyzed in the next chapter to determine which accelerometers show the strongest response to impacts and if this response is dependent on the impact location. An instrumented mallet hammer with a hard plastic tip was used to impact all locations; one accelerometer was removed to free a data channel in order to record the force of the impact during impact testing.

Both ambient noise and impact testing were performed on the rotating cutterhead. For ambient noise testing, vibration data was collected during five cutterhead rotation speeds: 0, 0.40, 0.71, 1.32, 1.87 and 2.22 RPM, corresponding to approximate power throttle controls of off, idle (0%), 25%, 50%, 75%, and 100%. Noise testing is essential in characterizing and understanding the forced and free vibration of the TBM. Impact testing to the rotating cutterhead was also performed to simulate the interaction of the cutterhead with boulders. The cutterhead was rotated at 1.31 RPM (approximately 50% power), and various cutting tools and surfaces were impacted as they came in range. Over 90% of the impacts were tangential to the TBM axis in accordance with the expected impacts of boulders, with the few remaining longitudinal or a combination of tangential and radial. Both ambient noise and impact tests on the rotating cutterhead were performed with both clockwise and counterclockwise rotation. Due to the similarities between directions, only 1 direction will be analyzed. All counterclockwise rotation testing data, along with all stationary cutterhead testing data, will be analyzed in the following chapter.
Figure 2.19  Layout of Stationary Cutterhead Impact Locations. Most locations are on some type of cutter, distinguished by color type. All locations were impacted in tangential, radial, and longitudinal directions (with the exception of 29, which was only impacted longitudinally).
2.3.3 Continuous Monitoring

After testing was completed, the system was set up for continuous monitoring. The accelerometers were moved and permanently placed in their final locations, shown in Figure 2.21. Mounting plates were attached with epoxy and magnets for strong coupling.

Figure 2.20 An instrumented impact hammer was used to strike the stationary cutterhead at specified locations.

Figure 2.21 Final Accelerometer Locations and Directions
Functionality was added to the governing program to store operational data such as cutterhead rotation rate and ring number, obtained from the TBM data acquisition system, referred to as the PLC (Programmable Logic Controller). The program was then deployed on the cRIO controller to enable continuous autonomous monitoring. As much of the project was performed remotely, a virtual private network (VPN) connection was used to access and download vibration data while a boulder detection algorithm was being developed. The algorithm, discussed in the next chapter, seeks to extract a single variable from the vibration data that indicates likely boulder impacts that can be sent to the TBM operator. Functionality of the continuous monitoring system is shown below in Figure 2.22.

**Figure 2.22 Continuous Monitoring Functionality**
CHAPTER 3: VIBRATION ANALYSIS

This chapter characterizes TBM vibration due to boulder and cobble impacts by analyzing field testing data before the machine began tunneling and during operation along the alignment. All analysis concerning directions will use the following coordinates: radial (R - towards the TBM axis), tangential (T – perpendicular to the radial direction), and longitudinal (L – along the TBM axis). Both R and T are in the plane perpendicular to the TBM axis (L). Any references to previous work [1] uses transverse (T – horizontal), vertical (V), and longitudinal (L) directional coordinates to maintain consistency with his work.

Figure 3.1  a) Radial, tangential, and longitudinal directional coordinates are used in this thesis.  b) Walter used vertical, transverse, and longitudinal coordinates.  This figure was obtained from his work [1].

Impact and ambient vibration testing of the TBM before drilling (outside the tunnel in open air) are integral to understanding its behavior, where outputs can be measured to known inputs. Both hammer impact testing of the cutterhead (while stationary and rotating) and ambient noise measurement while the cutterhead was rotated at different speeds provided valuable results. Such a study is limited by the open-air nature of testing; the cutterhead cannot be conventionally accessed to perform test impacts under pressurized conditions, so some differences are expected. However, results were useful in developing an impact detection algorithm. Impacts detected by the algorithm were analyzed both individually with respect to time and frequency content and as a whole over the alignment of the tunnel with respect to occurrence and distribution of the impacts themselves.
3.1 Analysis of Stationary Testing Data

Stationary impact testing gives the best opportunity to understand the response of different sensors to different impact locations and directions, as the impacts can be tightly controlled and repeated with a stationary cutterhead. A matrix of 33 impact locations on the cutterhead was chosen to represent different radial locations and surfaces. All locations were struck with an impact hammer 9 times: three impacts for each direction (T, R, and L, with the exception of location 29, which was only struck in the L direction). The impact locations, introduced in the previous chapter, are shown again in Figure 3.2.

Figure 3.2 Stationary Cutterhead Impact Locations. Different types of cutters are indicated by different colors. Tangential (T) and Radial (R) directions are indicated, with Longitudinal (L) being along the TBM axis or into the page. All locations were impacted in T, R, and L directions, except for a single impact direction (L) at location 29.
3.1.1 Stationary Testing Setup

Impacts to a stationary cutterhead provide the chance to understand the response of different sensors to different impact locations and directions. From Walter’s study [1] in which all sensors were mounted at different locations on the back of the bulkhead, it is clear that these sensors all have very similar responses, as can be seen in Figure 3.3. The transfer function is calculated in Equation 3.1 as a function of frequency \( f \), accelerometer location \( A_{\text{bulk}}(n) \) and response direction \( \text{dir} \); response at the impact location is indicated by \( A_{\text{impact}} \). While some redundancy is valuable in case a sensor is damaged while tunneling, the overarching goal is to gain as much information as possible. Therefore, sensors were placed in different locations throughout the TBM interior (in contrast to only on the back of the bulkhead) to gather possibilities for different responses.

\[
\text{Transfer Function} \ (f, A_{\text{bulk}}(n), \text{dir}) = \frac{\text{FFT}(A_{\text{bulk}}(n, \text{dir}))}{\text{FFT}(A_{\text{impact}}(\text{dir}))} \quad (3.1)
\]

![Figure 3.3](image)

*Figure 3.3 The transfer function is calculated by dividing the FFTs of sensors in the bulkhead by the FFT of the impact location sensor. The responses of 3 different sensors (accelerometers) placed on the bulkhead are indicated by differently colored lines. The directional similarity for each sensor indicates redundancy. This data was obtained from [1].*
Preliminary response analysis was done onsite to choose the final layout of the accelerometers. The layout for all testing data presented in this and the following section is shown below in Figure 3.4.

![Figure 3.4](image_url)  
*Figure 3.4 Sensor Locations during Open Air Testing. Accelerometer directions have been replaced with channel of data collection.*

### 3.1.2 Stationary Testing Time Response

All responses from hammer impacts were first analyzed in the time domain. A signal to noise ratio (SNR) provided the most straightforward approach to understand which sensors responded best to the different impacts. The raw SNR was calculated in Equation 3.2 (for each accelerometer channel, impact location, and impact direction) as the absolute maximum of the time domain signal divided by the rms of the background noise before the first impact, averaged for each of the three impacts for the given scenario. Acceleration response of any accelerometer channel (accelerometer location and direction combination) is indicated by $\ddot{x}$ for each impact (n) in units of g. Manual control of the hammer limited identical force application, so the SNR was normalized by the average maximum hammer force for the three impacts in Equation 3.3. The average input force of the hammer was 682 N, so a factor of 100 N was included in order to scale the normalized SNR to a convenient range. Figures displaying all normalized SNR responses are shown in Figures A-1 through A-3 in Appendix A, with an example of responses to tangential impacts shown in Figure 3.5. These SNR measures were created for best comparison of
vibration spikes for different impact and sensor locations and directions; they are considered relative for use in this work.

\[
SNR_{1-raw} = mean_{1-3} \left( \frac{\max (\ddot{x}_{impact}(n) (g))}{rms(\ddot{x}_{pre-impact}(n) (g))} \right) \quad (3.2)
\]

\[
SNR_{1-norm} = \frac{100 N \ast SNR_{1-raw}}{mean_{1-3} \left( \max (F_{hammer}(n) (N)) \right)} \quad (3.3)
\]

**Figure 3.5 Normalized SNR of Tangential Impacts to Stationary Cutterhead.** Results from each impact location, accelerometer location, and response direction are shown.

In order to draw useful findings from these results, several averaging schemes were used. First, responses for all impact locations were averaged to reach a single value for each combination of accelerometer channel and impact direction. This allowed two secondary averages: accelerometer location and accelerometer response direction. As can be seen in Figure 3.4, tangential responses include the x-directions of A2, A3, and A4 and A6; radial responses include the y-directions of A2 and A3, the z-direction of A4, A5, and A8; and longitudinal responses include the z-directions of A1, A2, and A3 and the y-direction of A4. The x- and y-directions of A1 were converted by Equations 3.4 and 3.5 to conform to the TRL coordinates, estimating an angle \( \alpha \) of 20° from the vertical axis. A7 is not included because it was replaced by the impact hammer for testing. Results from the first set of averaging schemes are displayed below in Table 3.1.
\[ A_{1T} = A_{1x} \cos(\alpha) + A_{1y} \sin(\alpha) \quad (3.4) \]
\[ A_{1R} = A_{1y} \cos(\alpha) - A_{1x} \sin(\alpha) \quad (3.5) \]

**Table 3.1 Stationary Impact Testing Normalized SNR (SNR\_norm) Comparison.** All impact locations averaged for each accelerometer direction, accelerometer location, and impact direction. The longitudinal direction responds best, and radial impacts are transferred worst.

<table>
<thead>
<tr>
<th>Impact Direction</th>
<th>Accelerometer Mean</th>
<th>A Total</th>
<th>Response Direction Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A1</td>
<td>A2</td>
<td>A3</td>
</tr>
<tr>
<td>T Impact</td>
<td>2.64</td>
<td>3.82</td>
<td>7.49</td>
</tr>
<tr>
<td>R Impact</td>
<td>1.79</td>
<td>2.92</td>
<td>5.79</td>
</tr>
<tr>
<td>L Impact</td>
<td>2.45</td>
<td>4.12</td>
<td>7.94</td>
</tr>
<tr>
<td>Average</td>
<td>2.29</td>
<td>3.62</td>
<td>7.07</td>
</tr>
</tbody>
</table>

Several trends can be observed from the relative SNR comparison in Table 3.1. First, the radial impact direction consistently produced lower SNRs than both tangential and longitudinal impacts, indicating these impacts are transferred less effectively. Since impacts expected during tunneling will be almost entirely tangential and longitudinal, this fact is not highly concerning. Second, longitudinal accelerometer channels had higher responses than both tangential and radial responses. Third, accelerometers A3, A4, and A8 have the highest relative responses. These last two observations will be useful in developing an impact detection algorithm and evaluating tunneling impacts in the next section.

The second averaging scheme set involved investigating impact location. All accelerometers were averaged for each location, and impact directions were kept separate. Results are shown in Figure 3.6. The first trend from the previous averaging scheme set is repeated here: radial impacts generally produce the lowest SNR. The second averages involved refining impact location: averages based on both cutter type and radial distance were computed, with results shown in Table 3.2 below. Cutter types are highlighted in Figure 3.2 and discussed in the previous chapter. Only face cutters and side scrapers were considered for the radial distance analysis, grouped as follows: inner impacts included locations 11-16, middle radius impacts included locations 17-21, and outer impacts included locations 22-28.
SNR is normalized by hammer input force and averaged for all accelerometer channels. Different locations respond differently, but radial impacts consistently result in lower magnitudes than longitudinal and tangential impacts, corroborating Table 3.1.

Table 3.2  

<table>
<thead>
<tr>
<th>Impact Surface</th>
<th>Mean SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nose Cone</td>
<td>6.4329</td>
</tr>
<tr>
<td>Side Scraper</td>
<td>4.7487</td>
</tr>
<tr>
<td>Face Cutter</td>
<td>4.785</td>
</tr>
<tr>
<td>Outer Cutter</td>
<td>3.7325</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Radial Location</th>
<th>Mean SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner</td>
<td>4.4145</td>
</tr>
<tr>
<td>Middle</td>
<td>4.2974</td>
</tr>
<tr>
<td>Outer</td>
<td>5.4161</td>
</tr>
</tbody>
</table>

Figure 3.6  

From Table 3.2, it is clear that nose cone impacts were best transferred and outer cutter impacts were worst transferred, while side scraper and face cutter impacts had similar middle-range SNRs. No significant trends were discovered based on radial location (radial distance from impact location to TBM axis) and were therefore not pursued; however, frequency response functions of all locations sorted by radius is included in Figure A-4 in Appendix A. After a thorough comparison of time domain response, the frequency response of three selected impact locations will next be considered.

3.1.3  

Stationary Testing Frequency Response

After determining the comparative normalized SNR for different impact locations, 3 locations were chosen for frequency domain analysis based on similar cutter type and strong response. The impact locations chosen were 2, 15, and 28, representing face cutters and side scrapers that have the highest likelihood of encountering boulders due to their abundance. These
locations can be referenced in Figure 3.2. The first step in entering the frequency domain was to calculate the Fast Fourier Transform (FFT) of each individual impact response. The responses to the three impacts at each location and direction were averaged after converting each to the frequency domain. The remaining variables included impact location, impact direction, accelerometer location, and response direction. Impact directions were first compared for each combination of impact location, accelerometer location, and response direction. A subset of these responses is shown below in Figure 3.7 for impact location 15. The same response directions for impact locations 2 and 28 are shown in Appendix A, Figure A-5, with the remaining response directions for all impact locations shown in Appendix A, Figures A-6 – A-8. Acceleration magnitude is normalized by the maximum frequency component magnitude in order to better compare the shape of the frequency response. As can be seen in Figure 3.7, the three impact directions produce similarly shaped frequency response functions for each given response location and direction, despite differences in specific frequency components. These findings are corroborated by the remaining locations shown in Appendix A. Since different impact directions would usually be associated with different vibration modes, this may be a result of relatively small impacts that merely excite the cutterhead structure regardless of impact direction. However, the response at each accelerometer location differs significantly, especially comparing A4 to A1-A3; this suggests that vibration response is strongly influenced by local vibration modes at each response location. Additionally, accelerometer location affects vibration response more strongly than does impact direction, most likely due to the natural vibration modes of local structures at each accelerometer location.

Since the three impact directions produce similarly shaped frequency response results, these responses are averaged for each accelerometer location, response direction, and impact location. The magnitude is not normalized in the averaging process in order to prevent a response with lower frequency amplitudes (and consequently higher noise) from obscuring clearer frequency peaks. Figure 3.8 and Figure 3.9 display the comparison of different response directions for each accelerometer location for impact locations 15 and 2, respectively. Results for impact location 28 are shown in Appendix A, Figure A-9. Longitudinal response has the greatest magnitude in all accelerometers except A4, corroborating the time domain trend of highest SNR for longitudinal response. This is likely a result of the longitudinal direction in which vibration is transferred from the cutterhead to the bulkhead. Nearly all responses at
impact location 2 have higher magnitudes for the same limited frequency range, suggesting that side scraper impacts have a greater transfer function than the face cutter impacts (at locations 15 and 28) for a limited range of frequencies. The notable exception is A4; this suggests that A4’s location across a rotary joint is not well coupled to the cutterhead.

Figure 3.7  Impact Direction Comparison in the Frequency Domain. Response for 5 different accelerometer channels are presented for impact location 15. Magnitude is normalized by the maximum value for each response in order to view the shape rather than strength of the response.
Figure 3.8 Response Direction Comparison. Average response for 3 impact directions is plotted for the response directions of each accelerometer at impact location 15.
Figure 3.9  Response Direction Comparison. Average response for 3 impact directions is plotted for the response directions of each accelerometer at impact location 2.

Figure 3.8 shows that the different response directions (for each accelerometer location and impact location) have a lower degree of similarity than the different impact directions presented in Figure 3.7; differences are noticeable in A4, more notably at impact location 15. In order to move forward towards a big picture understanding without obscuring the responses,
individual response directions will be compared for each accelerometer and impact location. The longitudinal direction is shown here as it typically responds most strongly, and the tangential direction is pictured in Appendix A. Both tangential and longitudinal impacts are expected when encountering boulders. Accelerometers A5-A8 were ignored from this study because they are on different surfaces in different locations. Different impacts for each accelerometer are compared in Figure 3.10, while different accelerometer responses for each impact are compared in Figure 3.11.

![Graphs showing longitudinal responses for different accelerometers and impact locations](image)

*Figure 3.10 The responses to different impact locations are compared for each longitudinal accelerometer response, shown as the mean of impact direction response for each scenario. Acceleration magnitude is normalized by the maximum frequency component in order to compare the shape of the impact, as the response of location 2 is greater than the other locations.*

From Figure 3.10, one can observe the similar frequency response of different impact locations in some areas, while completely different signatures are present in others. Similar components are most likely caused by local response of the sensor and the surface to which it is attached. For example, the range of frequency peaks near 250 Hz in A4 and near 500 Hz in A2
are likely to be localized structural responses near the respective sensors. The responses of A2 and A3 are similar in most locations except the 600-750 Hz range, indicating that the outer bulkhead may be well coupled to the back of the bulkhead. It is important to recognize local responses like the one present in A4, as they may occur regularly while drilling and obscure impact response. General similarities between impact locations 15 and 28 in all accelerometer channels indicate that a direct impact to a face cutter excites a broader range of frequencies than an impact to a side scraper. Similar trends for the tangential direction can be seen in Appendix A, Figure A-10.

\[ \text{Figure 3.11 The longitudinal responses of different accelerometers are compared for each impact location, shown as the mean of impact direction response for each scenario. Similar responses in all accelerometers are visible near 700 Hz for impact location 2 and 900 Hz for impact location 28.} \]

Figure 3.11 highlights similarities between different accelerometers for each impact, indicating response of the cutterhead that is transferred to different parts of the internal TBM. Impact location 2 displays the most similarities between accelerometers with peaks near 700 Hz,
although the A3 response is much greater than the others. A similar peak can be seen in location 28 near 900 Hz; all accelerometers share a frequency peak. Both of these peaks are visible in the tangential response, shown in Appendix A, Figure A-11, although the tangential response of A4 is dominant. The face cutter impacts (locations 15 and 28) excited similar response functions in all accelerometers in the 400-550 Hz range, suggesting that local response of the cutterhead is passed through to different locations inside the TBM.

3.1.4 Key Findings from Impacts Testing of the Stationary Cutterhead

Many observations were drawn from time and frequency analysis of stationary cutterhead testing data. From the time domain, radial impacts resulted in the lowest response at all accelerometer channels and impact locations. Longitudinal response was consistently greater than other response directions. A3, A4, and A8 have the highest preliminary SNR response, though this may change under tunneling conditions when many components will experience operational noise. No trends were visible based on the radial location of impacts, but face cutters and side scrapers where impacts are most likely to occur produced similar magnitude responses.

From the frequency domain, each impact direction creates a similar frequency response shape in the big picture. This is promising because impact direction will be unknown for tunneling impacts, and its cause is likely linked to the relatively small impacts exciting a very large cutterhead. Longitudinal response is again higher than other response directions for every accelerometer except A4, which is located on a thin cylindrical structure that flexes easier in the other directions. Different response directions for each accelerometer location have some similar frequency peaks, although the overall frequency response functions are far from identical. Different vibration modes for different directions may be more obvious in the smaller structures to which accelerometers are attached. Local structural response near particular accelerometers is visible for multiple impacts, most notably in A4 in the range of 200-300 Hz. A2 and A3 produce similar responses, indicating their attachment surfaces are well coupled. From the analyzed impact locations, face cutter impacts excite a broader frequency range than side scraper impacts, while a side scraper impact better transfers the cutterhead response to all accelerometers than face cutter impacts. This may change in tunneling conditions, especially once the cutterhead vibration is damped by pressurized soil on both sides, and vibration transfer from the cutterhead through the rotating frame is limited by rotation through muck in the excavation chamber.
3.2 Analysis of Rotating Cutterhead Testing Data

After thoroughly analyzing impacts to the stationary cutterhead, testing the rotating cutterhead is an important step into simulating tunneling conditions. While the effects of soil pressure and additional machine components will be neglected, much of the vibration is correlated to cutterhead rotation [1]. The cutterhead was tested both for ambient vibration and impacts while rotating. For impact testing, the cutterhead was rotated at 50% power while the chief engineer impacted cutters, scrapers and other surfaces as they rotated past. For ambient vibration testing where no impacts occurred, the cutterhead was rotated at approximately 0%, 25%, 50%, 75%, and 100% power in both clockwise and counterclockwise directions. Due to similarities between rotation directions, only counterclockwise rotation will be analyzed (from the view of the operator, clockwise if viewed from the front of the TBM). All power percentages are controlled by manual throttle and are therefore approximate.

3.2.1 Impacts to the Rotating Cutterhead

Hammer impacts to the cutterhead while the cutterhead is rotating come closest to simulating boulder impacts experienced while tunneling (Figure 3.12-a). While larger impacts can be seen in the time domain, as shown in Figure 3.12-b from 80-105 s, only 4 of the 10 impacts in this range are visible (5 when using RMS acceleration). The frequency domain provides additional insight into the response; impacts excite a wide range of frequencies. However, a joint time-frequency analysis, known as a spectrogram, is necessary to capture the short-lived impact response of the TBM. Figure 3.12-c presents a spectrogram of the impacts, in which many more are visible. Figure 3.13 looks more closely at the 80-105 s range in which most impacts occur.
Figure 3.12  a) The cutterhead was rotated at 1.31 RPM (approximately 50% power) in the counterclockwise direction (from the operator’s perspective). The cutterhead was struck with an instrumented impact hammer 15 times, 10 of which occurred between 80 and 105 seconds. The rms value of the time domain signal was calculated for a sliding time window. b) Only 4 of the impacts are visible in the time domain, as the signal is obscured by noise from the rotating cutterhead. c) By looking at the joint time-frequency spectrogram, all 15 impacts are visible.
The 10 impacts to the rotating cutterhead (at 1.31 RPM) between 80 and 105 seconds are shown in a) the time domain and b) the frequency domain. Impacts are indicated by arrows, some of which are not visible in the time domain. Typical time signals reach a maximum absolute value of 0.025 g in periods without impacts, while typical rms values for the time domain are between 0.005 and 0.008 g in non-impact windows. Therefore, SNR values of time signal divided by noise rms can be as large as 5, with any impacts in this range being obscured.

The broadband response of impacts in the frequency domain is clearly seen in Figure 3.13. While frequencies with higher amplitudes, such as those near 300 Hz and 1000 Hz in Figure 3.13-b, obscure the impact response in the time domain, the impacts are quite visible in quieter frequency ranges. This knowledge will fuel the development of a boulder detection system later in the chapter. The next section investigates the nature of the high amplitude frequencies and their sources.
3.2.2 Rotating Cutterhead Ambient Vibration

Another important aspect in understanding machine vibration is its ambient response, i.e., without impacts. Figure 3.14 below displays the response in both the time and frequency domains. As expected, the total vibration amplitude increases with the cutterhead rotation rate. The frequency domain exhibits an interesting phenomena: key frequencies (those with higher amplitudes, indicated by dark red lines) change with cutterhead speed. As described in Walter [1], these frequencies “ramp up” with cutterhead speed.

Figure 3.14 Ambient noise vibration of the rotating cutterhead is presented in a) the time domain and b) the frequency domain. This data corresponds to counterclockwise rotation of the cutterhead (from the operator’s perspective) at different power levels that resulted in rotation rates of 0, 0.40, 0.71, 1.32, 1.87, and 2.2 RPM. Ambient vibration levels increase with rotation rate in the time domain, as do the frequencies of high magnitude components.

The correlation between dominant frequencies and cutterhead speed suggests forced vibration. However, the frequencies present are over four orders of magnitude higher than the cutterhead rotation rate, bearing in mind that the maximum cutterhead speed of 2.2 RPM = 0.04 Hz. The cutterhead torque motors have a higher maximum rotational speed of 30 Hz, but this is one order of magnitude lower than many of the frequencies present. The next logical component to analyze is the gearbox; although the motor is the fastest rotational component in a gearbox
designed to reduce speed and increase torque, the individual gear interactions occur at a higher frequency, known as the mesh frequency. Specifications of the gearbox and development of mesh frequencies is presented in Section 2.2.

The mesh frequency of the first gear interaction in stage 1 of the planetary gearbox is the highest, as the gears in this stage are spinning at the highest rotation rates. The first mesh frequency will therefore be compared to the key vibration frequencies measured for each cutterhead rotation rate. To simplify the identification of these frequencies, only one accelerometer (A1) was chosen based on its proximity to all of the gear interactions. The mean of the three response directions (T, R, and L) was used to provide a full response for the location. Key frequencies observed in A1 response that resemble harmonics and are connected by visible “ramping up” periods were identified for the four highest rotational speeds of the cutterhead, shown in Figure 3.15 below, with key frequencies outlined in Figure 3.16. Nearly all key frequencies were present in all accelerometers and directions; however, they were often obscured by higher noise levels and prolonged transient response from accelerating the cutterhead. Some of the transient response is visible in Figure 3.14 above, shown as oscillating red frequency lines.

**Rotation Noise: A1 TRL Mean**

*Figure 3.15 The high magnitude frequencies are more clearly visible in the average response of A1 (TRL directions). Rotation rates of 0.71, 1.32, 1.87, and 2.22 RPM were considered.*
The frequencies identified for analysis were chosen based on continuity and visible ramping up between different cutterhead rates. Given the proportional nature of the identified frequencies, they are assumed to be harmonics of the same base frequency. Harmonics of the mesh frequency are expected because the mesh interaction cannot produce a sinusoidal signal. There are other frequencies present, as seen in Figure 3.16, but the identified frequencies are the most prominent and therefore the most valuable to explain.

![Rotation Noise: A1 Key Frequency Harmonics](image)

*Figure 3.16 The three highest magnitude frequency components for each rotation rate seem to be evenly spaced, indicated harmonics of the first frequency. These harmonics are connected between rotation rates, indicating a common forcing frequency component.*

Given the consistent signal during constant cutterhead speed ranges, an average frequency response function for each range was sufficient to numerically identify the key frequencies. These frequencies are presented in Figure 3.17, indicating different harmonic frequencies for each cutterhead speed. These frequencies can now be compared to the first mesh frequency, described more fully in Section 2.2.3. The motor speed and mesh frequency can be calculated using Equations 3.6 and 3.7, by inputting cutterhead speed, gear ratios, and numbers of teeth. These equations were rearranged from Equations 2.12 and 2.14, respectively. The ring to pinion gear ratio is 9, and the overall gear ratio of the three-stage planetary gearbox is 88.78. The 1st ring gear and 1st sun gear have 69 and 21 teeth, respectively. Comparison results are shown in Table 3.3, with percent error calculated in Equation 3.10.
Brief analysis into the remaining frequency components was conducted, focusing on frequencies below the fundamental mesh frequency. Since harmonics are by definition integer multiples of the fundamental frequency [14], these frequency components cannot have been created by the 1st mesh interaction. The second and third stages of the planetary gearbox were included by looking at the 2nd and 3rd mesh frequencies, respectively. This requires the input rotational speeds of the second and third stages, which are found by dividing the motor speed by the proper gear ratios. The first stage gear ratio is 4.29, and the second stage gear ratio is 4.83. All ring gears have 69 teeth, and the 2nd and 3rd sun gears have 18 and 21 teeth, respectively. Calculation of the second and third mesh frequencies are shown below in Equation 3.8 and 3.9, both rearranged from Equation 2.14. Results for this study are included in Figure 3.18.

\[
MF_2(Hz) = \frac{\omega_{motor}}{GR_{S1}} \times \left( \frac{N_{Ring2} \times N_{Sun2}}{N_{Ring2} + N_{Sun2}} \right) = \frac{\omega_{motor}}{4.29} \times \left( \frac{69 \times 18}{69 + 18} \right) = \omega_{motor} \times 3.33 \quad (3.8)
\]

\[
MF_3(Hz) = \frac{\omega_{motor}}{GR_{S1}GR_{S2}} \times \left( \frac{N_{Ring3} \times N_{Sun3}}{N_{Ring3} + N_{Sun3}} \right) = \frac{\omega_{motor}}{4.29 \times 4.83} \times \left( \frac{69 \times 21}{69 + 21} \right) = \omega_{motor} \times 0.78 \quad (3.9)
\]
Figure 3.17 Frequency response was calculated for four cutterhead rotation speeds in open air conditions (before tunneling began). Frequency magnitudes are normalized by the maximum component magnitude in order to highlight the peaks for each rotation speed. Key frequencies of interest are indicated by harmonic.
Table 3.3 Mesh Frequency Comparison. The frequency values highlighted in Figure 3.17 are compared to the expected mesh frequencies at each cutterhead rotation rate.

<table>
<thead>
<tr>
<th>Cutter RPM</th>
<th>1st Mesh (Hz)</th>
<th>1st Harmonic (Hz)</th>
<th>2nd Harmonic (Hz)</th>
<th>3rd Harmonic (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.71</td>
<td>152</td>
<td>152</td>
<td>305</td>
<td>457</td>
</tr>
<tr>
<td>1.32</td>
<td>283</td>
<td>281</td>
<td>568</td>
<td>850</td>
</tr>
<tr>
<td>1.87</td>
<td>401</td>
<td>404</td>
<td>803</td>
<td>1201</td>
</tr>
<tr>
<td>2.22</td>
<td>476</td>
<td>475</td>
<td>943</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Note: % Error compares harmonic frequency to equivalent mesh frequency harmonic

\[ % \text{Error} = \frac{|n \times MF_1 - HF(n)|}{n \times MF_1} \quad (3.10) \]

The identified frequencies are in excellent agreement with the computed mesh frequency and its harmonics. As expected, there is a general trend of decreasing amplitude with increasing harmonic. The degree of similarity is fortuitous, as the cutterhead speed was measured manually (timing a specified degree of rotation) and the frequency resolution of the FFT was limited to 5.9 Hz; this relationship could have produced a difference of up to 15 Hz with the given accuracy. The excellent agreement is clearly visible in Figure 3.18 by looking at frequency components normalized by cutterhead rotation speed. Mesh frequencies are presented in the form \(MF_mn\), where \(m\) indicates the gear stage and \(n\) indicates the harmonic. The 2\(^{nd}\) mesh frequencies are also indicated in the figure, although their contributions are less significant. The 3\(^{rd}\) mesh frequencies are not clearly visible in this figure.

There are 2 main normalized frequency components visible for both the 1.87 and 2.22 RPM rotation speeds that do not clearly correspond to any mesh frequency harmonics, although the factor of 2 connecting them indicates that they may be harmonics of the same phenomenon. The 100 Hz/RPM component shows 9.6% error with respect to the 2\(^{nd}\) MF2 harmonic and 4.6% error with respect to the 9\(^{th}\) MF3 harmonic. However, it is highly unlikely that only the 9\(^{th}\) harmonic of the 3\(^{rd}\) stage mesh frequency would be significant. No other gear and bearing frequencies presented in Walter suggest a reasonable cause for these unknown frequency peaks [1]. Frequency peaks present at only one rotation speed likely correspond to resonant frequencies of certain components within the TBM. It is possible that one or both of the unknown frequencies components coincidentally overlap, but this cannot be proven with the current data. A full understanding of these contributions requires detailed modeling and additional testing that is beyond the scope of this thesis.
Figure 3.18 Frequencies were normalized by cutterhead rotation rate, and magnitudes were normalized by maximum magnitude for shape comparison. Mesh frequencies from the first stage are clearly visible, and mesh frequencies from the second stage make an appearance. Two high magnitude components are unidentified but seem to be harmonics of each other.

Although other frequencies are present, the main source of vibration is clearly the first mesh frequency and its harmonics, which will be helpful in proceeding to analyze the machine vibration in tunneling conditions. This mesh frequency analysis is corroborated by tunneling data, with an example shown in Figure 3.19. The cutterhead is rotating at 1.65 RPM, and the corresponding 1st mesh frequency harmonics match high amplitude frequency components.

During tunneling, additional frequencies are present that are not correlated to cutterhead speed; these may be caused by free response of structures like the bulkhead or any of the many operations that are simultaneously performed on a TBM, such as fans used for ventilation and cooling and pumps that propel grout, soil conditioning agents, and cooling fluids. Although the 1st mesh frequencies corresponding to the rotation rate are clearly visible once the cutterhead has reached its target speed of 1.88 RPM in Figure 3.20, frequencies such as those near 300 Hz, 950 Hz, and 1000 Hz are constant through the beginning ramp up period and likely caused by a combination of free response of structures and TBM operations other than cutterhead rotation.
Figure 3.19 Mesh frequencies from the first planetary stage are visible as high magnitude frequency components in tunneling data as well as testing data.

Figure 3.20 Mesh frequencies can be seen to ramp up with cutterhead speed. Some frequency components remain constant through ramp up, likely caused by structural free response and/or other TBM operations.
3.2.3 Key Findings from Rotating Cutterhead Testing

Many observations were clear from analysis of the rotating cutterhead tests. The rotating cutterhead creates a much higher level of ambient noise than the stationary cutterhead does, making impacts much harder to detect in the time domain. Calculating SNR as the absolute value of time signal divided by rms time signal, values of up to 5 occur due to noise. Only 33% of tested impacts breached this SNR threshold. The frequency domain shows impacts much more clearly because impacts excite broad frequency ranges; joint time-frequency spectrograms clearly show impacts as sharp vertical lines through a broad range of frequencies. This phenomenon will be very useful in detecting impacts in the next section. However, there are clear high magnitude frequency components that create most of the ambient vibration noise.

Many of these high frequency components change with cutterhead rotation rate and are therefore a result of forced vibration. Mesh frequencies of the planetary gear interactions were compared to the high magnitude frequency components; the mesh frequency of the first planetary gear stage and its harmonics constituted the most significant components to ambient frequency response. Second stage mesh frequency harmonics were also visible, but additional modeling and investigation is necessary for a full characterization of the forced response. The first mesh frequency harmonics are confirmed to be the most significant components in tunneling data. Additional frequencies exist during tunneling that result from free structural response and additional pumps, fans, and motors in the TBM. Knowledge of the spectrogram response and the source of high magnitude frequency components will enable the detection and characterization of impacts during tunneling.

3.3 Impact Detection and Characterization

The primary motivation behind this research was to develop a method to identify boulder impacts based on vibration signature to alert the TBM operator. This requires the output of a single variable, Boolean or numeric, to identify the likelihood of a boulder impact. While an accurate analysis is dependent on ground truth data such as the precise time of boulder impacts and size and placement of the boulders themselves, such data is highly impractical to obtain given the surrounding soil and uncertainty where boulders will occur; the ability to obtain such accurate ground truth data would in fact quash the relevance of impact detection altogether. Only after passing through the excavation chamber and both screw conveyors can boulder pieces or cobbles first be seen on the conveyor belt, which requires the excavation of at least one
additional ring. However, frequent cobbles under 7 inches in diameter in rings 1470-1611 have enabled a refinement of the algorithm based on a prevalence of known impacts. The sensor layout was changed slightly after initial open air testing, and the final layout (shown again in Figure 3.21) has remained constant throughout tunneling to date.

**Figure 3.21 Sensor Layout during Tunneling. Accelerometer directions are replaced with data collection channels.**

### 3.3.1 Development of Impact Detection Algorithm

Open air impact testing on the TBM confirmed that impacts were more clearly visible through their broadband response in the frequency domain than they were in the time domain, making strict time domain analysis less effective to detect impacts. In order to develop a boulder detection variable (BDV), it was therefore beneficial to travel through the frequency domain via spectral analysis; a frequency response function was calculated for a series of overlapping time windows, each separated by smaller time steps. The size and spacing of the windows was modified throughout algorithm development in order to allow the major frequency components to be seen without losing them in the noise and respond quickly enough to catch all impacts, similar to focusing a camera lens. Calculation of the raw spectrogram ($S$) at each time step ($t_n$) is shown below in Equation 3.11, where $nfft$ is the length of the FFT and $f_s$ is the sample frequency of 3000 Hz. $\ddot{x}_{ChanAvg}$ is the raw acceleration in the time domain (g) with DC offset removed, averaged for the chosen channels. The first version of the algorithm had a time step of
.05 s (150 samples), a time window of .1 s (300 samples), FFT length of 512, and all accelerometer channels (A1-A8, all directions). The power spectral density (PSD) calculated in Equation 3.12 allows an equivalence of energy between the time and frequency domains and returns the magnitude of the spectrogram (S), also incorporating the default Hamming windowing function ($\omega(n)$) [19].

$$S_{tn}(f) = \text{fft}_{nfft}\left(\ddot{x}_{\text{ChanAvg}}\left(\frac{n \ast \text{step}}{f_s} < t_n < \frac{n \ast \text{step} + \text{window}}{f_s}\right)\right)$$ (3.11)

$$PSD_{tn}(f) = \frac{2}{f_s \sum_{\text{window}+1}^{\omega(n)} |\omega(n)|^2} \ast |S_{tn}(f)|^2$$ (3.12)

Once this PSD function is calculated for all frequencies (0 to the Nyquist Frequency of 1500 Hz), PSD frequency components can be combined via summation to return a single value to the time domain. Although all frequency components can be included, the clarity of this value strongly depends on avoiding the highest amplitude frequency components caused by mesh frequencies and other TBM components; these frequencies contribute significantly higher amplitudes than the remaining frequencies. Additionally, taking the sum of all frequency amplitudes merely returns the magnitude of the time domain signal. The value of using the frequency domain lies in the frequency bands that are typically quiet, allowing for a more distinct impact and simplifying the choice of an adequate threshold. In initial testing, manually selecting a “quiet period” between high frequency components was sufficient, as indicated by $BDV_1$ (initial form of BDV) in Equation 3.13. As $S$ has units of g, PSD and therefore $BDV_1$ have units of $g^2s^2$.

$$BDV_1(t_n) = \sum_{f_{\text{low}}}^{f_{\text{high}}} PSD_{tn}(f)$$ (3.13)

However, many high amplitude frequency components are correlated to cutterhead speed, so this quiet period must constantly be scaled to current conditions. An incorrectly chosen quiet period is detrimental to impact detection, as can be seen in Figure 3.22. From the spectrogram plot, there is a clear vibration spike near 28 s and another faint spike near 55 s. The 600 - 800 Hz frequency range, which was ideal for testing, includes a high amplitude mesh frequency; no spike is visible in the BDV. The use of all frequencies (0-1500 Hz) leads to a small BDV spike in line with the first vibration spike, but it is indistinguishable from surrounding spikes in the
noise. Choosing a frequency range of 525-650 Hz enabled both spikes to be clearly visible above the surrounding noise. However, a similar spike is visible during the ramp up period when the machine began; mesh and other high amplitude machine frequencies change rapidly, obscuring the quiet period and resulting BDV.

Figure 3.22 All frequency amplitudes for the provided frequency range are summed for the spectrogram image, located at the top. The 525-650 Hz range most clearly shows impacts. The ramping up period falsely triggers the algorithm.
While a complete understanding of key (high amplitude) frequency components would allow this process to be automated with an input of cutterhead speed, unexpected frequencies from non-routine work or delays in cutterhead speed information could also influence the output variable. The second version of the BDV implemented log scaling, which clarified the vibration spikes enough to use the entire frequency range, shown in Equation 3.14. An intermediate spectral sum ($SS$) was included, replacing the PSD sum in $BDV_1$ (Equation 3.15). The variable $low_{bound}$ was used to eliminate periods when active tunneling was not present (the cutterhead was stationary). By including a moving average for the previous 200 time steps (Equation 3.17), $BDV_2$ could be compared to the surrounding area (Equation 3.16). One possible benefit of this SNR-style calculation was the absence of an absolute threshold that may not be adequate for all tunneling conditions (geological and operating alike). Additionally, a ratio is more easily understood than units that become obscure in the real world. All parameters were kept constant from the first BDV algorithm. This version of the BDV was used for false positive testing in the next section.

$$PSD_{t_n log}(f) = 10 \times \log \left( 1000 \times PSD_{t_n}(f) \right) \quad (3.14)$$

$$SS(t_n) = \text{mean}(PSD_{t_n log}(f) > low_{bound}) - \text{min}(\text{mean}(PSD_{t_n log}(f) > low_{bound})) \quad (3.15)$$

$$BDV_2(t_n) = \frac{SS(t_n)}{\text{mean}(SS(t_i) : SS(t_n))} \quad (3.16)$$

$$t_i(t_n) = \begin{cases} t_0 & n \leq 199 \\ t_{n-199} & n > 199 \end{cases} \quad (3.17)$$

After ground truth cobble data was obtained (in a region of ground where many cobbles passed through the machine with likely impacts to different parts of the cutterhead and TBM), the algorithm could be much better refined. Many modifications in the second algorithm were deemed unnecessary. A straightforward approach that allowed the choice of lower amplitude frequency bands without requiring knowledge of all key frequency components was to automatically choose only frequency components below a certain magnitude, also eliminating the need for log scaling. This magnitude was scaled to 3 times the mean PSD for the 60 s range (the length of a single file) for comparability at different cutterhead speeds. The frequency components used in BDV calculation are indicated by Equation 3.18, with the updated BDV calculation shown in Equation 3.19. $BDV_3$ has been modified to have units of g (easily applicable to real tunneling experience), with $df$ calculated in Equation 3.20 as a function of
sample frequency and FFT length. The time step was modified to .01 s (30 samples) in this version, while other spectrogram parameters did not change from the first version. Initial analysis of vibration data in the cobble-heavy ground suggested that an absolute vibration threshold was promising, although SNR calculation was considered an option for further development. Spikes in the BDV above an absolute vibration threshold were considered BDV impacts as they emulate the response of an impact but could not be corroborated by a known input; the term BDV impact will be used throughout the remainder of analysis, in conjunction with its respective vibration threshold. It is important to note that the vibration threshold does not indicate the total vibration of the system at the chosen accelerometer location(s), as the high amplitude frequencies are not included. A summary of the differences between BDV versions is shown in

\[
\begin{align*}
    f_{\text{keep}}(t_n) &= f \left( PSD_{t_n}(f) < 3 \times \text{mean}(PSD_{t_n}(f)) \right) \quad (3.18) \\
    \text{BDV}_3(t_n) &= \sqrt{\sum_{f=f_{\text{keep}}(t_n)} PSD_{t_n}(f) * df} \quad (3.19) \\
    df &= \frac{f_s}{nfft + 2} \quad (3.20)
\end{align*}
\]

*Table 3.4 BDV Development Parameters.* All versions use data with a sample frequency of 3000 Hz and 512-point FFTs.

<table>
<thead>
<tr>
<th>BDV</th>
<th>Window</th>
<th>Step</th>
<th>Frequency Selection</th>
<th>Channels</th>
<th>Manipulation</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.1 s (300)</td>
<td>.05 s (150)</td>
<td>manual quiet f band</td>
<td>A1-A8</td>
<td>PDF Summation</td>
<td>g²s⁻²</td>
</tr>
<tr>
<td>2</td>
<td>.1 s (300)</td>
<td>.05 s (150)</td>
<td>0-1500 Hz</td>
<td>A1-A8</td>
<td>PDF Log SNR</td>
<td>none</td>
</tr>
<tr>
<td>3</td>
<td>.1 s (300)</td>
<td>.01 s (30)</td>
<td>&lt;3*mean(PDF(f))</td>
<td>A1</td>
<td>√(PDF Summation*df)</td>
<td>g</td>
</tr>
</tbody>
</table>

A quasi real time algorithm is currently in place that downloads and analyzes files as they are created and sends alert emails in intervals where impacts are detected. This algorithm uses the mean response of A1, the determination of which will be explained in the next two subsections. Results from the algorithm during development are shown below in Figure 3.23 and Figure 3.24, which respectively have a high and low density of BDV impacts above the lower (.15 g) threshold. The governing algorithm can be converted into a fully real time program which alerts the operators directly whenever there is a BDV impact. BDV impacts repeated at 6 times the cutterhead speed are of most concern to the operator because they indicate an obstacle such as a boulder that is not dislodged by the cutterhead teeth and impacts each cutterhead spoke
as it passes. Another possible avenue lies in audio detection; the machine vibration can be converted to an audio signal, in which impacts can literally be heard as if the operator were inside the machine near the excavation chamber.

**Figure 3.23** Many BDV impacts are visible above the 0.15 g threshold, with few over 0.25 g.

**Figure 3.24** This figure is further along in the development, when .4 g was determined to be a more appropriate threshold. Only one impact breaches the lower .15 g threshold.
3.3.1.1 False Positive Testing

Before ground truth cobble data was obtained, a number of BDV impacts were detected using a SNR threshold of 4.0 ($BDV_2$). This BDV calculation is shown in Equation 3.16, referencing previous equations. After analyzing 465 rings of data obtained up to ring 715 (some data was not collected due to system malfunction, development, and maintenance), 77 BDV impacts were identified with the 4.0 threshold. BDV impacts detected during ring building (when the cutterhead is stationary and the TBM is not advancing) were visually identified and discounted. As no cobbles or boulder pieces were seen in the excavated material, these were all assumed to be false positive impacts. A summary of the detected false positives is seen below in Figure 3.25. Possibilities for false positives during excavation include noisy work or unexpected impacts inside or near the TBM and impacts with objects in the excavated ground, such as cobbles or rocks too small to be easily detectable in the muck. In order to investigate possible false positives, testing was performed inside the TBM to understand the response certain types of impacts would create.

Figure 3.25 A BDV impact was counted whenever the boulder detection variable ($BDV_2$) exceeded a SNR threshold of 4 and was corroborated by visual inspection of the spectrogram. Out of 465 analyzed rings, the algorithm identified 77 impacts, 67 of which were visually confirmed, an average of 1 false positive impact every 7 rings.
The bolt shown in Figure 3.26-1 was first dropped and then struck against all of the surfaces shown in locations 2-5 to simulate different possible occurrences during tunneling. The locations of the impacted surfaces inside the TBM are clarified in Figure 3.27. The process was performed both while the TBM was stationary and excavating. Spectrogram results for the stationary test are shown in Figure 3.28, and spectrogram and BDV results for the excavating test are shown in Figure 3.29. Time domain responses are calculated in Equation 3.21 as maximum SNR for each channel (sensor location and direction combination), and results are summarized in Table 3.5 and Table 3.6. Since rms is employed in SNR calculation, values up to approximately 5 may be obtained in noise. The quiet period (noise) was visually identified in the time response.

\[
SNR_{2-max}(n, \text{channel}) = \frac{\max(|\ddot{x}_{\text{impact}(n,\text{channel})}(g)|)}{\text{rms}(\ddot{x}_{\text{quiet}(n,\text{channel})}(g))} \quad (3.21)
\]

Figure 3.26 False Positive Testing Impact Locations. Location 2 is near A4 and A5; Location 3 is near A3; Location 4 is near A2 and A5; and Location 5 is near A8.
Figure 3.27 False Positive Testing Impact Locations with respect to Sensor Layout

Figure 3.28 False Positive Testing Response, Cutterhead Stationary (TBM Ring Building)
Figure 3.29 False Positive Response (with BDV2), Cutterhead Rotating (TBM Excavating)

As would be expected, all impacts are much clearer when the TBM cutterhead is stationary than when it is rotating. Most impacts, in fact, are indiscernible in the frequency domain while the cutterhead is rotating. The notable exception is impact 5 to the support structure to which A8 is attached; this relatively thin structure is able to respond to many impacts, especially when it is directly excited. Interestingly, the highest mean SNR seen in Table 3.5 while the TBM is excavating is in response to impact 2 to the arm axle near the central axle; however, several accelerometers are in close proximity to this location with clearly well-coupled surfaces. According to Table 3.6, A4, A5, and A8 had the highest mean SNR response to tested false positive impacts while excavating. They are also the only responses above an SNR value of 5, determined as a preliminary threshold in the time domain to detect impacts in Section 3.2.1. Two of these sensors, A4 and A8, also had the highest mean response in stationary impact testing. The next section will look more deeply into individual channel responses, but these sensors may be too sensitive to impacts to provide useful feedback. In addition, after taking a subset of files triggered during ring building, the response of A8 was an average of 5.8 times greater than the next highest response, A5, and 16.3 times higher than the average responses of the other sensor channels. A8’s high sensitivity to all impacts inside, behind, and ahead of the TBM suggest that it should not be used for future analysis. Of the test locations chosen, impact location 2 has the highest mean SNR, causing a high response in many different locations. This location is therefore likely to falsely indicate a boulder impact regardless of which accelerometer channels are chosen.
Table 3.5 False Positive Testing Results. SNR was calculated in Equation 3.21 (SNR\textsubscript{2-max}).

<table>
<thead>
<tr>
<th>Impact Location</th>
<th>Mean SNR</th>
<th>Highest SNR</th>
<th>2nd Highest SNR</th>
<th>3rd Highest SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stationary</td>
<td>1</td>
<td>A1R 16.2</td>
<td>A5 9.94</td>
<td>A8 8.64</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>A5 156</td>
<td>A2R 145</td>
<td>A2T 94.0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>A3L 162</td>
<td>A3T 112</td>
<td>A7 112</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>A4T 170</td>
<td>A2L 163</td>
<td>A2T 160</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>A6 126</td>
<td>A1L 72.0</td>
<td>A7 68.3</td>
</tr>
<tr>
<td>Excavating</td>
<td>1</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>8.50</td>
<td>A4L 29.5</td>
<td>A3T 12.93</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2.50</td>
<td>A7 4.15</td>
<td>A6 3.35</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3.13</td>
<td>A1R 4.14</td>
<td>A4T 3.94</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>3.70</td>
<td>A8 12.9</td>
<td>A6 4.67</td>
</tr>
</tbody>
</table>

Table 3.6 Mean SNR response of all false positive impacts was calculated for each accelerometer. SNR calculation is shown in in Equation 3.21 (SNR\textsubscript{2-max}).

<table>
<thead>
<tr>
<th>Sensor Location</th>
<th>Stationary Impacts</th>
<th>Excavating Impacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>42.67</td>
<td>3.14</td>
</tr>
<tr>
<td>A2</td>
<td>71.54</td>
<td>4.98</td>
</tr>
<tr>
<td>A3</td>
<td>68.81</td>
<td>3.28</td>
</tr>
<tr>
<td>A4</td>
<td>38.74</td>
<td>6.20</td>
</tr>
<tr>
<td>A5</td>
<td>75.06</td>
<td>5.19</td>
</tr>
<tr>
<td>A6</td>
<td>46.82</td>
<td>3.66</td>
</tr>
<tr>
<td>A7</td>
<td>79.06</td>
<td>3.91</td>
</tr>
<tr>
<td>A8</td>
<td>16.19</td>
<td>5.79</td>
</tr>
</tbody>
</table>

3.3.1.2 Accelerometer Channel Response using Cobble Impact Data

After preliminary channel analysis with data from false positive testing performed inside the TBM, different accelerometer locations and directions could be evaluated with real cobble data in order to focus on the impacts caused by cobble interaction. Five impacts from two files were evaluated for channel response, shown in Figure 3.30 and Figure 3.31. These files were chosen while BDV\textsubscript{2} was in operation. Accelerometer locations are shown above in Figure 3.21.
Figure 3.30 Two BDV impacts are picked out of the spectrogram, neither of which are not clearly identified by BDV₂.

Figure 3.31 Three impacts are picked out of the spectrogram.
The maximum SNR was calculated using Equation 3.21 for each impact in each channel (accelerometer location and direction) to compare the time domain responses of each accelerometer. The impact window was then visually identified (from \( t_{\text{start}} \) to \( t_{\text{stop}} \)) to calculate the FFT, in order to simulate the process followed by the impact detection algorithm in the frequency domain. \( BDV_{\text{chan}} \) was then calculated in Equation 3.22 by summing the frequency components separately for each channel and impact \((n)\). This diverges slightly from \( BDV_1 \) because 1) as an impact, all frequency components have high magnitudes and are not considered quiet and 2) PSD is not considered. However, values are comparable between different channels, allowing different sensors to be evaluated.

\[
BDV_{\text{chan}}(\text{channel}, n) = \sum_{f_{\text{low}}=0}^{f_{\text{high}}=1500} \text{fft} \left( \ddot{x}_{\text{impact}(n)}(\text{channel}, t_{\text{start}}: t_{\text{stop}}) \right)
\] (3.22)

\( BDV_{\text{chan}} \) for each channel is presented in Figure 3.32 below, separated by response direction. Other than the overly sensitive A8 which has the strongest response in impact 5, A1 in all directions stands out for most impacts. This is corroborated by the findings in Table 3.7 summarizing the max SNR and mean BDV for each accelerometer; excluding A8 for its hypersensitivity, A1 in all directions is the best choice. Therefore, a mean of the T, R, and L directions of A1 was used in the latest impact detection algorithm. A spectrogram of each channel can be seen in Figure 3.33; the impacts again stand out most clearly in the A1 responses. Another observation of interest is the multitude of high magnitude frequency components between 200 and 400 Hz present in the A4 responses; this matches the open air impact testing results suggesting a strong local response seen in Figure 3.10. Although magnitudes vary, A2 and A3 seem to have similar trends, which was observed in Figure 3.11.
Figure 3.32 BDV is calculated individually for each channel. BDV for each accelerometer is plotted with respect to response direction and impact location. A1 and A8 consistently respond best. However, false positive testing showed A8 extremely sensitive.
Table 3.7 Both time domain SNR (SNR$_{2\text{--}max}$, Equation 3.21) and BDV (BDV$_{chan}$, Equation 3.22) are presented for each accelerometer. Excluding A8, A1 responds best in both categories.

<table>
<thead>
<tr>
<th>Sensor Location</th>
<th>Impact SNR Avg</th>
<th>Impact BDV Avg (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>20.83</td>
<td>0.120</td>
</tr>
<tr>
<td>A2</td>
<td>7.69</td>
<td>0.029</td>
</tr>
<tr>
<td>A3</td>
<td>9.65</td>
<td>0.022</td>
</tr>
<tr>
<td>A4</td>
<td>7.09</td>
<td>0.025</td>
</tr>
<tr>
<td>A5</td>
<td>6.48</td>
<td>0.066</td>
</tr>
<tr>
<td>A6</td>
<td>3.63</td>
<td>0.066</td>
</tr>
<tr>
<td>A7</td>
<td>10.61</td>
<td>0.055</td>
</tr>
<tr>
<td>A8</td>
<td>6.80</td>
<td>0.234</td>
</tr>
</tbody>
</table>

After choosing A1 as the best accelerometer response, all rings could be retroactively analyzed with the modified algorithm ($BDV_3$). Again assuming all BDV impacts prior to ring 1470 were false positives, 72 BDV impacts in 1156 rings were detected by the algorithm, an average of 1 false positive every 16 rings. This is a significant improvement over $BDV_2$, which averaged 1 false positive every 7 rings. Some internal impacts will trigger the algorithm regardless; the goal is to minimize rather than altogether avoid this phenomenon. The response of A1 to individual impacts caused by cobble interaction will be further analyzed and characterized in the following section.
Figure 3.33 Spectrograms for each accelerometer and direction. All plots indicate vibration magnitude with respect to frequency (y-axis, Hz) and time (x-axis, s). Impacts indicated by vertical red lines are most clearly visible in all 3 response directions of A1. Low frequency components predominate in A4, which was suggested by impact testing to the stationary cutterhead. Data was collected when excavation began on ring 1479.
3.3.2 Impact Characterization

After developing the boulder detection algorithm with corroborated cobble presence, several BDV impacts were detected along the alignment. BDV impacts in this section are focused on ring 1470-1611, which are known to contain many cobbles and likely cobble impacts. While the magnitudes of impacts are known from the impact detection algorithm (BDV3 (g)), more can be learned by investigating individual impacts.

The damage a boulder can cause to the TBM is proportional to its size: cobbles (below 1 ft in diameter) and boulders up to 1.5 ft in diameter can pass through the machine whole; a medium-sized boulder can possibly be shifted in the soil enough to slowly move out of the way or break into pieces passable through the TBM; and large boulders are often immovable if not unbreakable. Therefore, knowing the size of an encountered boulder would be highly valued. A hypothesis is presented that larger boulders will induce higher magnitude acceleration in the machine. This is reasonable because a larger boulder will rebound less, imparting greater energy into the impact; a comparable scenario would be a stationary cutterhead with variously-sized boulders approaching at the same speed. The greater mass of the larger boulder would impart a greater impact force, under the reasonable assumption that all boulders have similar compositions. Therefore, a greater BDV will be assumed to indicate a larger cobble impact, although there is no way to directly match certain impacts to their respective cobble sizes. Additional complications arise as impacts can not only occur at the cutterhead, of most concern to the TBM operator, but also in the excavation chamber and in the screw conveyor. Figure 3.34 displays a prolonged impact from 15-17 seconds, which likely corresponds to a cobble scraping against the side of the excavation chamber or screw conveyor, in contrast to the other impacts which better resemble single impacts to the cutterhead or other internal TBM surfaces.
Figure 3.34 The modified boulder detection variable (BDV₃) focuses on the sum of low frequency component amplitudes for the mean of A1 directions (Equation 3.19). The continuous BDV impact from 15-17 seconds is likely a response to scraping, which may occur if a cobble is wedged against the wall of the excavation chamber or screw conveyor.

A subset of 30 BDV impacts was chosen from different points throughout the alignment for further analysis. These BDV impacts were chosen to be as sharp as possible in order to optimize comparability. Three ranges were chosen to compare different magnitude impacts, presumably correlated to different size cobbles. The low magnitude BDV impacts had a BDV between 0.25 and 0.3 g, the medium magnitude BDV impacts had a BDV between 0.45 and 0.6 g, and the high magnitude BDV impacts had BDVs above 0.73 g. The highest sharp impact available was analyzed, with a BDV of 1.16 g. These impacts were analyzed in both the time and frequency domains.

3.3.2.1 Time Domain Analysis

After determining that A1 provided the best responses in the previous section, its response directions were used throughout the following analysis. The time domain response of the chosen impacts is shown below in Figure 3.35 for the A1L direction.
Figure 3.35 A1L Time Response of Chosen BDV Impacts shown by Magnitude Range. Impacts are concatenated in time and distinguished by color. Some impacts have multiple spikes. Low magnitude BDV impacts clearly show a low frequency oscillation coupled with higher frequency oscillation. This trend is not clear in the medium and high magnitude BDV impacts.
From Figure 3.35, it is clear that there is a high degree of variability in impact response. The first acceleration spike for a given impact is sometimes much greater than the remainder of impact oscillation, indicating quick decay; other times the oscillation decays very slowly. Two or more spikes are visible in some of the responses. There is an interesting trend in the low magnitude responses that clearly shows low frequency oscillation superimposed on the transient response, which could be correlated to a local resonant frequency. This trend is not clearly visible in the medium and high magnitude responses; however, there is a chance that the trend exists but is not visible when coupled with a higher magnitude transient response.

To quantify these impacts in the time domain, two SNR values were calculated: an average SNR for the length of the impact using the rms of the impact period divided by the rms value for a chosen quiet period (Equation 3.23) and a maximum SNR (Equation 3.21). The impact window and a quiet period of approximately 2 seconds were visually identified in the time domain acceleration response. The average SNR was included as a preliminary measure of the shape of the impact (a single sharp impact or a prolonged scraping or double impact). Figure 3.36 displays the average and maximum SNRs for each direction and impact, plotted as a function of BDV. As expected, SNR increases with BDV, with a few outliers, which were most likely obscured in the time domain by significant noise. The linear correlation between average SNRs is not as strong, with some of the higher BDV impacts falling below the trend; this indicates impacts occurring over a longer time period, which was the case in many of the largest impacts.

\[
SNR_{2-avg}(n,\text{channel}) = \frac{\text{rms}(\ddot{x}_{\text{impact}(n,\text{channel})}(g))}{\text{rms}(\ddot{x}_{\text{quiet}(n,\text{channel})}(g))}
\]  

(3.23)

Although these conditions cannot be confirmed in any way, ideally all impacts chosen would be impacts at the cutterhead before cobbles have been dislodged. In this scenario, larger cobbles would have larger impact magnitudes but would also be harder to dislodge, resulting in a longer duration impact as evidenced by the average rms values. Figure 3.37 displays the normalized SNR (SNR/BDV) for each impact and response direction, more clearly highlighting differences between directions. The radial direction generally has the lowest response while the best response using all measures was longitudinal, summarized in Table 3.8 and confirming impact testing results. Therefore, A1L will be used in the following frequency domain analysis.
Figure 3.36  $\text{SNR}_2$ (max and average) vs. $\text{BDV}_3$ for chosen $\text{BDV}$ impacts. These SNR values are plotted by algorithm-determined $\text{BDV}$ for different response directions. As expected, a linear trend between SNR and BDV is visible.

Figure 3.37  SNR is normalized by BDV to compare different response directions. Radial response most consistently has the lowest response, corroborating open air testing results.
Table 3.8 Mean values for all BDV impacts were calculated for both raw and normalized SNRs. The longitudinal response was highest by all measures. SNR$_2$ and BDV$_3$ are used.

<table>
<thead>
<tr>
<th>Direction</th>
<th>SNR</th>
<th>SNR/BDV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max</td>
<td>Avg</td>
</tr>
<tr>
<td>T</td>
<td>28.03</td>
<td>3.43</td>
</tr>
<tr>
<td>R</td>
<td>25.78</td>
<td>5.86</td>
</tr>
<tr>
<td>L</td>
<td>30.92</td>
<td>6.67</td>
</tr>
</tbody>
</table>

3.3.2.2 Frequency Content vs. Magnitude

Continuing with the hypothesis that larger obstacles will impart more energy and result in greater frequency amplitudes and BDVs, the frequency domain can also be analyzed. Heavier objects typically excite a lower frequency range than lighter objects; for instance, the vibration frequencies of a sledgehammer impact are lower than those of a ball-peen hammer impact, which can be heard as lower vs. higher pitch ringing as the vibration is converted to sound waves. However, the fairly constant material composition of cobbles may limit differences observed in frequency response.

A set of subset of BDV impacts were chosen based on similarity in the time response; sharp impacts with only one peak were selected to analyze in the frequency domain. Chosen impacts can be found in Appendix A, Figure A-12. The A1L frequency response was plotted for each chosen BDV impact, separated by magnitude range, in Figure 3.38 below. The comparable plot for A1T response is shown in Appendix A, Figure A-13. The low magnitude BDV impacts share a fairly shallow (not sharp) frequency peak range near 400 Hz. Both the medium and high magnitude impacts have common high frequencies in the range of 1100-1300 Hz. Tangential responses show similar shared frequency peak ranges (Appendix A, Figure A-13). Although these relationships are visible, they are relatively weak. Additionally, no impact response has the limited frequency range observed for the side scraper impact in Figure 3.11. However, the presence of soil and muck around the cobble and cutterhead likely obscures the frequency response; it would be imprudent to discount the possibility of a side scraper impact without the ability to test under tunneling conditions. The average FFT of the chosen BDV impacts for the longitudinal and tangential responses in each range is plotted in Figure 3.39. Unfortunately, no strong trends exist. Some of the larger peaks in the low frequency range are visible at a similar amplitude in the higher magnitudes (such as the low peak near 400 Hz), but they are obscured by higher peaks at other frequencies in the mid and high magnitude BDV impacts. There is an
increase in the amplitude of frequencies in the 1100-1300 Hz range as magnitude increases. This may be consistent with a smaller impact being more easily damped by soil and other components, especially in higher frequencies. The cobbles observed exiting the machine had a limited range of variability, reaching a maximum diameter of 7 inches. Therefore, differences in magnitude are likely due, at least in part, to factors other than cobble size, such as the cobble-soil interaction and the location of impact with the TBM. In addition, the common composition of cobbles may limit variation in frequency response shape. The hypothesis that BDV is proportional to the size of the cobble or boulder may still be valid, but it requires more ground truth data with large boulders to further develop. Current magnitude variation is likely tied to the location of impact and the sharpness of the impact, distinguishing a glancing blow from a head-on collision. The existing variation may also be correlated to cobble size, but the difference is not enough to create a corresponding variation in the frequency domain. Another limitation of the current study is the use of FFT on very short impacts; additional methods should be developed for further analysis.

Figure 3.38 A1L Frequency Response Functions of BDV Impacts during Cobble-Heavy Rings. Magnitude is normalized by maximum magnitude component for shape comparison.
3.3.3 Key Findings from Impact Detection and Characterization

Using knowledge obtained in Section 3.2 from testing the rotating cutterhead, namely the appearance of impacts in joint time-frequency spectrograms and the existence of high amplitude frequency components, a boulder detection algorithm could be developed. By adding the lower amplitude frequency components for a specific time step, a boulder detection variable (BDV) could be determined in units of g. An algorithm is currently in place to analyze data as it is recorded and send notifications when impacts occur.

False positive testing indicated that A4, A5, and A8 had the highest response to likely internal impacts during excavating. Both A4 and A8 were also most responsive in stationary...

Figure 3.39 Average A1 L and T Frequency Response Functions by Magnitude Range. No clear frequency trends are visible based on impact magnitude.
impact testing. A8 responds most strongly to routine work during ring building, making it overly sensitive and undesirable to use in the algorithm. Most false positive impacts tested were not visible during tunneling, but large enough internal impacts will inevitably trigger the algorithm. After analyzing individual channel response to known cobble impacts, A1 was determined to have the most consistent and visible response to true impacts.

The hypothesis was presented that larger impacts correspond to larger cobbles; a subset of A1 responses to individual impacts in different magnitude ranges were thus chosen for further analysis. The longitudinal direction had the highest response, corroborating stationary impact testing results. BDV was well correlated to SNR, indicating that a vibration magnitude rather than SNR threshold is sufficient for the current analysis. A slight trend towards higher amplitudes in higher frequency ranges was visible with increasing magnitude, but no strong trends were visible from analysis of the chosen impacts in the frequency domain. However, this alone does not invalidate the hypothesis that larger cobbles produce larger impact magnitudes. Several factors are involved: 1) frequency response of impacts to the cutterhead is impractical to test under full tunneling conditions; 2) cobble impacts can occur to many parts of the TBM, such as the cutterhead, rotating frame, shell, and screw conveyor; and 3) boulders have fairly consistent compositions, limiting the differences that may be visible in the frequency domain. More ground truth data is necessary to draw any definite conclusions about this hypothesis.

3.4 Analysis of BDV Impacts along Tunnel Alignment

This section will investigate overall trends in impacts along the tunnel alignment, with a focus on impacts during the cobble-heavy range of rings 1470-1611. Trends investigated include number of BDV impacts, magnitude and distribution of BDV impacts, and correlation between BDV and key operating parameters.

3.4.1 BDV Impacts vs. Geology: Big Picture

When a tunneling project is underway, one of the biggest concerns is the geology that will be excavated through; this will determine the necessary face pressure and soil conditioning setups in addition to the optimal combination of penetration rate and cutterhead speed. Unfortunately, knowing the precise geological composition of the entire alignment is impossible; therefore, expected composition maps are developed from a series of boring locations by geological experts that can be very helpful in preparing for excavation. The soils in Seattle are
typically very densely packed, as they were consolidated by glaciers. Four main soil types occur along the tunnel alignment: cohesionless sand and gravel (CSG, orange), cohesionless silt and fine sand (CSF, green), cohesive clay and silt (CCS, blue), and till-like deposits (TLD, purple). While each soil type has different conditions that affect operation, the two most important points are: 1) each of the first 3 layers is most likely deposited in a single process before glacial consolidation and therefore somewhat homogeneous and compact and 2) till is deposited directly by the glacier and therefore very heterogeneous with a high probability of debris [8].

In Figure 3.40 below, the number of impacts identified using the BDV algorithm in each ring is compared to the geologic composition within the excavated tunnel in b), with entire geology to the surface shown in a). The number of BDV impacts is directly proportional to the percent of TLD, in which cobbles have been most present. Figure 3.41 displays a closer view of the BDV impacts from rings 1470 to 1611 in a), highlighting the direct correlation; b) displays the magnitude and distribution of BDV impacts for rings 1470 to 1611. Assuming a fairly even distribution of cobbles within the till deposits, the expected frequency of cobbles is very well correlated with the frequency of BDV impacts.
Figure 3.40  

a) The tunnel alignment along the first 1600 rings travels through 4 main geologic compositions.  
b) The number of BDV impacts is strongly correlated to the TLD deposits, most prominently in rings 1470-1611 where many cobbles were observed.  

Geological data was obtained from the Geotechnical Baseline Report (GBR) [9].
Figure 3.41  a) Number of BDV impacts per ring has a clear trend of being proportional to till-like deposits, suggesting an even distribution of cobbles within the deposit. Geology was obtained from [9]. b) BDV impacts that occurred in rings 1470 to 1611 had a fairly constant distribution, with mean BDV impact magnitude between .3 and .4 g, although outliers are fairly common.
3.4.2 Impacts vs. Geology: Distribution of Impacts in Rings 1470-1611

The nature of analyzing BDV magnitudes above a certain threshold dictates that their distribution will not be normal, which is corroborated by Figure 3.41-b). The average magnitude of BDV impacts above 0.25 g is relatively constant between 0.3 and 0.4 g, varying slightly more in rings with fewer impacts; BDV impacts are very tightly packed close to the threshold. The impacts are condensed into a box and whisker plot in Figure 3.42, in which the blue box indicates the middle 50% of BDV impact magnitudes and the black lines (whiskers) indicate the range of the remaining BDV magnitudes. With limited exceptions, mostly in later rings with a lower total impact number, more than 75% of all BDV impacts lie below 0.4 g.

Figure 3.42 This box and whisker plot shows the distribution of BDV impact magnitudes in each ring. Although some BDV impacts reach very high magnitudes, the majority of BDV impacts above the .25 g threshold are below .4 g.

Aside from the slight aforementioned fluctuations in later rings with fewer impacts, there is a fairly consistent distribution of BDV impact magnitudes along the alignment. This would ideally be correlated to consistent sizing of cobbles throughout the alignment—the number of cobbles would changes with the proportion of till deposits, but the distribution of cobble size would not noticeably change. While cobbles were obtained in various sizes throughout rings 1470-1611, the absence of knowledge about precise number and size distribution of cobbles is a limitation of this study. A sample of the range of cobble sizes is shown below in Figure 3.43.

Figure 3.43 Many cobbles were identified in the muck from rings 1470-1611. Cobble size varies, with a maximum diameter of 7 inches.
3.4.3 Operating Parameters vs. BDV

After compiling all BDV impacts above a .25 g threshold in rings 1470-1611, it was beneficial to compare them to operating parameters. At this point, both SNR and BDV have been considered throughout the analysis and were well correlated in the impacts considered in Section 3.3.2. While the BDV has been successful at identifying impacts using a fixed amplitude threshold, it has not been clear whether information is lost by neglecting the background noise. For instance, greater impact energy is transferred when the cutterhead is rotating faster, which may create larger BDV magnitudes. Since background noise is proportional to cutterhead speed, comparing BDV with cutterhead speed is an effective way to determine the necessity of the SNR. As can be seen in Figure 3.44-a) below, no clear trends exist between cutterhead speed and BDV impact magnitude; cutterhead speeds themselves resemble a normal distribution, with magnitudes evenly distributed for all values. While the SNR is still beneficial for comparing time domain impacts, preliminary results confirm Section 3.3’s conclusion that it is not necessary for determining BDV impact magnitude.

Walter also discusses correlations between operating parameters and vibration; from his study, cutterhead speed and earth pressure, respectively, have the two highest influences on TBM vibration [1]. BDV impact magnitude is compared to average pressure of the excavation chamber in Figure 3.44-b). As with cutterhead speed, no clear trends exist, although the spread of chamber pressures is greater than that of cutterhead speeds. While BDV impact magnitude does not appear to be correlated to these parameters, other vibration characteristics may be affected by operating conditions. Further development of ambient vibration analysis is necessary to carry Walter’s findings with respect to operating conditions forward.
3.4.4 Key Findings from Impacts along Tunnel Alignment

When compared to geology along the alignment, the number of BDV impacts per ring was very well correlated to the proportion of till-like deposit in the composition. This suggests even distribution of cobbles within the TLD deposit. Additionally, the distribution of impacts within each ring was consistent and centered close to the .25 g threshold between .3 and .4 g, suggesting that cobbles sizes were also evenly distributed between rings. No clear trends were visible between impact magnitude and either cutterhead rotation rate or earth pressure. Operating parameters are more likely to influence ambient vibration characteristics; ambient vibration should be further analyzed in order to develop a better understanding of this relationship.
CHAPTER 4: CONCLUSIONS AND RECOMMENDATIONS

The primary motivation behind this thesis was to understand the vibration of a tunnel boring machine, with a central application of detecting impacts to the TBM cutterhead caused by interaction with boulders during tunneling. This study is a continuation of Walter’s work and delved further into characterization of impacts and the source of forced vibration. Specific items for improvement listed by Walter that were addressed in this measurement system and analysis included: 1) an improved data collection system, including a more expansive sensor network, a more powerful data controller, and more onboard data storage and 2) characterization of the main ambient frequency components as forced response to the mesh frequencies [1].

4.1 Specific Findings and Conclusions

Many other observations were prevalent throughout analysis of data collected from the N125 tunneling project in Seattle, Washington. More conclusive results were obtained by analyzing open air testing data, where impact locations, directions, and forces are known. Impacts to the stationary cutterhead showed that tangential and longitudinal impacts, expected during tunneling, were transferred better than improbable radial impacts, while longitudinal accelerometer channels responded best to all impacts. Frequency response is most dependent on impact location and accelerometer location; some accelerometers, such as A4, are dominated by local structural response instead of transferred cutterhead response. Likewise, certain impact locations, such as impacts to side scrapers, transfer well into most accelerometer locations. However, this clear response is likely dependent on the open air nature of testing; pressurized soil tunneling conditions are likely to induce a high degree of damping on specific impact frequency components.

Testing the rotating cutterhead proved that significant noise is introduced by cutterhead rotation, with rms vibration levels correlated to rotation rate, corroborating findings in [1]. By investigating the joint-time frequency domain spectrogram, it was apparent that most noise is generated in specific high amplitude frequency components. In relatively quiet periods, impacts were clearly visible by the broadband frequency response they produced, even though they were often obscured in the time domain. Further investigation into the high amplitude ambient frequencies revealed that some of the largest peaks were a result of the gear meshing frequency and its harmonics from the first stage of the planetary gearboxes, which reduces the speed and
increases the torque of the cutterhead driving motors to be harnessed by the rotating ring gear and cutterhead. In addition to the identified mesh frequencies, there are other high magnitude frequency components visible, both related to cutterhead speed and constant. Advanced modeling and investigation of structural and mechanical components and coupling is necessary for a complete characterization of these frequencies.

Results from rotating cutterhead tests were used to develop a boulder detection algorithm, using a summation of frequencies while avoiding the high magnitude components for each time step to output a single variable most useful to the TBM operator. False positive testing and channel response comparison with likely cobble impacts (BDV impacts during the cobble-heavy range of rings 1470-1611) were used to refine the algorithm, establishing that accelerometer A1 responded best to assumed cobble impacts without being overly sensitive to internal or posterior impacts. Assuming that no true impacts were present before ring 1470, this modification decreased the rate of false positive identification by more than 50%.

True impacts were more difficult to characterize than testing impacts because the input location, direction, and magnitude were all unknown. Not only could impacts occur to different surfaces at different locations on the cutterhead, they could also occur to different surfaces at different locations within the excavation chamber and screw conveyor. No BDV impacts detected during cobble-heavy rings were observed to repeat with spoke width, so all cobbles were assumed to be knocked loose or moved upon first impact. Under the hypothesis that impact magnitude or BDV is correlated to cobble size, a subset of BDV impacts was chosen to include three distinct magnitude ranges. BDV was well correlated to time domain SNR and confirmed testing results that the longitudinal direction possessed the best response, but no strong trends were visible in the frequency domain. Although larger boulders may excite a lower frequency range than smaller cobbles, several factors, most prominently the lack of boulders encountered along the alignment, prevented an accurate assessment of this hypothesis.

Coming from a wider perspective, the number of BDV impacts per ring was extremely well correlated to the presence of till-like deposits in the geological composition estimation. The proportionality of number of BDV impacts to % TLD in the tunnel alignment suggests that cobbles were fairly evenly distributed within the glacial deposit, and a consistent magnitude distribution suggests that cobble size was also evenly distributed within the deposit. No trends were observable from comparing impact magnitude to the operating parameters of cutterhead
rotation rate and earth pressure, identified by Walter as having the largest effect on vibration [1]; however, lack of correlation between BDV impact magnitude and cutterhead speed confirmed that SNR is not necessary when considering impact magnitude. Operating parameters are more likely correlated to ambient vibration characteristics than impact vibration characteristics.

4.2 Comprehensive Findings and Recommended Future Improvements

Results of this study have advanced the understanding of TBM vibration, which is very limited in the literature. Regardless of impact direction, the TBM responds best in the longitudinal direction. The high amplitude frequencies that predominate ambient vibration are largely forced by gear meshing frequencies. Additionally, joint time-frequency analysis is a valuable tool in detecting impacts to such a high noise application. From a geological standpoint, results suggest that even a heterogeneous deposit such as till has an even distribution of cobbles. Boulders may likely follow this pattern, although the much lower total numbers make an accurate prediction of location much more difficult. Since this thesis has been written, the BDV algorithm developed has been successfully implemented onboard the TBM with real-time feedback to the operator and positive response from both the operator and contractors.

One of the major limitations of this study is the availability of ground truth data; although boulders and cobbles are undesirable from a contracting perspective, they are necessary to develop meaningful findings from a research perspective. This study became much more valuable after the occurrence of a plethora of cobble impacts; it would likely become infinitely more valuable after encountering one or more boulders.

This study can also become more expansive by considering ambient vibration in depth and developing advanced finite element models of the TBM, with a focus on the rotating cutterhead, cutterhead drive structure, main bearing, excavation chamber, and bulkhead. In combination with a more advanced knowledge of other mechanical components, these could lead to a full characterization of the vibration response, including frequencies forced by mechanical components and free response of total and local structures. Relationships between operating parameters, geological composition, and vibration require significant ambient vibration analysis. Additionally, any testing that can be done in conditions more closely approximating pressurized tunneling conditions would be very beneficial. Impacts to the excavation chamber and screw conveyor are more attainable and may help to distinguish the impact location of tunneling impacts more clearly.
REFERENCES


APPENDIX A: SUPPLEMENTARY FIGURES FOR IMPACT ANALYSIS

Figure A-1  SNR of Tangential Impacts to Stationary Cutterhead. Results from each impact location, accelerometer location, and response direction are shown.
Figure A-2  SNR of Radial Impacts to Stationary Cutterhead.  Results from each impact location, accelerometer location, and response direction are shown.
Figure A-3  SNR of Longitudinal Impacts to Stationary Cutterhead. Results from each impact location, accelerometer location, and response direction are shown.
Figure A-4 Frequency Response of Impacts to Stationary Cutterhead. Results are sorted by radial distance of the impact location. No clear trends exist.
Figure A-5  Frequency Response of Impacts to Stationary Cutterhead, Locations 2 and 28, comparable directions. Results show FFT normalized by max frequency component for each impact direction, sorted by accelerometer location and response direction.
Figure A-6 Frequency Response of Impacts to Stationary Cutterhead, Location 2, remaining directions. Results show FFT normalized by max frequency component for each impact direction, sorted by accelerometer location and response direction.
Figure A-7 Frequency Response of Impacts to Stationary Cutterhead, Location 15, remaining directions. Results show FFT normalized by max frequency component for each impact direction, sorted by accelerometer location and response direction.
Figure A-8 Frequency Response of Impacts to Stationary Cutterhead, Location 28, remaining directions. Results show FFT normalized by max frequency component for each impact direction, sorted by accelerometer location and response direction.
Figure A-9  Frequency Response of Impacts to Stationary Cutterhead, Location 28. Results show FFT average for impact direction and response direction, sorted by accelerometer. Similar frequency peaks are visible in many accelerometers.
Figure A-10 The responses to different impact locations are compared for each tangential accelerometer response, shown as the mean of impact direction response for each scenario. Acceleration magnitude is normalized by the maximum frequency component in order to compare the shape of the impact.
Figure A-11 The tangential responses of different accelerometers are compared for each impact location, shown as the mean of impact direction response for each scenario.
Figure A-12 Time Response of Chosen BDV Impacts. A subset of 4 BDV impacts for each magnitude range to analyze in the frequency domain. All BDV impacts were chosen in the cobble-heavy range of rings 1470-1611.
Figure A-13  AIT Frequency Response Functions of BDV Impacts during Cobble-Heavy Rings. Magnitude is normalized by maximum magnitude component for shape comparison.