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Sound power ranking of three circular saws with 12 saw blades, and a blade stiffener while considering feed rate and feed force

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ABSTRACT

Permanent hearing loss and tinnitus are common among construction workers. Saws are thought to be a significant contributor to worker noise over-exposure in the woodworking industry. Many saw blades claim to have low noise and vibration; the literature claims that noise reductions of 5 to 10 dB are commonplace. To better understand the currently available noise reduction options for saw blades, sound power measurements were made in the loaded and unloaded conditions for three circular saws with 12 saw blades with and without a blade stiffener. In the loaded condition, the material cut was one-inch thick rough-cut oak. Oak was used as a hardwood. During sawing, the feed force and feed rate were measured. The sound power (watts) was divided by the feed rate (inches/second) to calculate the average sound power per unit of material cut. This feed-rate-adjusted sound power level was used to compare the performance of blades and saws. It was found that the difference in feed rate adjusted sound power level between the highest and lowest saw setups was approximately 10 dBA. The saw and blade combination with the lowest feed rate adjusted sound power used a DC motor, a thin kerf blade, and a blade stiffener.

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1 CIRCULAR SAW NOISE

Saw blades are very common in many industries including construction sites where materials from asphalt to wood are cut with saws. In many industries, saws are thought to be a significant contributor of noise (Maue 2004). Although circular saws produce noise from the saw blade, motor, gears, cooling fan, and structural acoustic radiation of the circular saw housing; the saw blade is thought to be the main noise source (Crocker 2007 p975). In particular, saws including saw blades are thought to be the main cause of worker noise over-exposure in the woodworking industry (Crocker 2007 p980). After the saw blade, the motor may be the next most important source of noise, (Babyak 2005). Circular saws using DC motors are thought to have a significantly lower sound power levels than saws using AC motors; however, this may be affected by the feed rate (Babyak 2005). The over-exposure to noise in the construction industry and the lack of proper use of hearing protection puts construction workers at an elevated risk of noise-induced hearing

loss (Garvey 2015; Neitzel 2011). Noise over-exposure can be reduced by engineering control of noise at the source (Suter 2002).

1.1 Study of saws, saw blades, and a blade stiffener

A study of the noise of three circular saws, 12 saw blades and a blade stiffener was undertaken to better understand the options for noise control of circular saws. There were concerns that the motor cooling fan may be a significant sound source, so a circular saw was manufactured using a large DC motor without a cooling fan. Several parameters effecting the sound pressure level at the workstation were estimated for circular saws and dimension saws (Groß 2009). The feed rate was found to have a nearly linear effect on the sound pressure level at the workstation using ISO 7960. There were concerns that feed rate, feed force, and downward force may be uncontrolled parameters which affect the measured sound power levels. The feed rate, feed force, and downward force were measured during the experiments.

There were concerns that a circular saw which cuts very slowly may have a lower sound power level but take so much time to complete a defined task that a circular saw with a higher sound power level that cuts faster would ultimately have a lower cumulative noise exposure for cutting a board. This concern was addressed by adjusting the sound power level using the measured feed rate. The cumulative noise exposure per unit of work accomplished provides a quantitative comparison of power tools for the purpose of selecting the power tool with the lowest available cumulative noise exposure for completing a defined task. This paper compares the feed rate adjusted sound power level for three circular saws, 12 saw blades, a blade stiffener while accounting for the effects of the feed rate and feed force.

1.2 Noise control of saw blades

Much of the literature on noise control in the woodworking industry comes from studies of large machines. This paper will relate the literature on noise control for large machines to portable circular saws. Saws radiate noise in both the unloaded and loaded conditions. In the unloaded condition saw blades make idling noise which can be a significant contributor to noise exposure (Rizica 2001; Leu 1984). In the unloaded condition, saw blades produce noise by aerodynamic sources involving the tooth and gullet area of the blade (Crocker 2007 p980). Saw blades produce noise in the loaded condition by structural vibrations related to the saw blade and workpiece (Crocker 2007 p980). There are three types of vibrations in circular saw blades aero-acoustic, forced, and resonant (Hufnagel 2010; Leu 1984). When redesigning a saw blade or selecting a noise control for a woodworking machine, it is important to consider the feed rates, depth of cut, power consumption, surface quality, tool wear and maintenance (Crocker 2007 p978).

Many of the noise problems in woodworking machines can be solved by remediating the noise produced as a result of saw blades (Crocker 2007 p975). Noise controls for saw blades generally focus on blade design and mounting. The cutter vibrations are minimized by redesigning the cutter (such as gullet height) and by adding damping to the saw blades to further reduce vibration amplitudes. Noise reductions of 5 to 10 dB in both the unloaded and loaded conditions by redesigning the gullets and added blade damping are common place (Crocker 2007 p983).

The use of cutter teeth or knives which are parallel to the axis of rotation (straight knives) is inherently noisy (Crocker 2007 p841). The blade of a circular saw can be thought of as a thin disk cutter which can have significant transverse vibrations. The helical continuously wound cutter design with many rows of knives breaks up the vibration excitations and reduces noise. In the loaded condition during cutting the helical designed knives with many rows of knives have a nearly continuous contact with the workpiece. This smooths out the time varying force and minimizes the amplitude of the periodic force components. Circular saw blades with teeth designed similar to helical cutters which break up the vibration excitations may have lower noise.

Damping the vibrations is another method of noise reduction. Outside of constrained layer damping only minor noise reductions can be achieved by other damping methods such as mounting techniques (Crocker 2007 p983). A concern is that the constrained layer may be structurally weak and may prematurely fail due to heat and stress. Often noise control strategies less effective than constrained layer damping are used due to the structural problems associated with incorporating constrained layer damping into a circular saw blade. There is software developed for analyzing viscoelastic constrained layer designs of circular saws (Wang 2012).

Previous studies of saw blade noise found that blades with additional fine slots for vibration reduction and constrained layer damped type blades reduced noise effectively (Maue 2004). Maue also found that low noise saw blades are not purchased as much as other blades partly because of not being known and being more expensive. Aerodynamic blade noise increases at a rate of 15-18 dB per doubling of cutter tip speed (Crocker 2007 p981; Reiter 1976). Aero-acoustic vibration can be minimized by reducing the blade tip speed (Leu 1984; Reiter 1976). The workpiece width and length are important factors in determining noise. The noise level increases by approximately 6 dB per doubling of width of the workpiece for straight knife cutters. As the workpiece becomes wider the noise level increases (Crocker 2007 p977). Using a cutter with non-uniform pitch can significantly reduce noise (Crocker 2007 p994). The use of slotted blades can reduce the noise from 109 dB to 90 dB (Crocker 2007 p842). The amount of noise reduction due to use of sound absorbing materials in guards is unpredictable and highly dependent on the tool conditions. Approximately 2 to 4 dB of noise reduction can be at most expected (Crocker 2007 p984).

2 SAW BLADES

In this paper, 12 saw blades are compared. The saw blades have four different manufacturers and three different purposes, Finishing, framing, and combination or all-purpose blades. The blades have several properties which are listed in Tables 1 and 2. Three of the saw blades are duplicated for assessing the repeatability of the measurements. The duplicate blades are indicated in the left column in Table 1. Blades 1-3 were made by C.M.T. Utensils SpA (Pesaro, Italy). Blades 4-5 were both made by Forrest Manufacturing Company (Clifton, NJ). Blades 6-9 were made by Freud America Inc. (High Point, NC). Blades 10-12 were made by Oldham Saw Company (West Jefferson, NC).

Table 1: Saw blades properties

| Blade Number | Manufacturer | Model Number | Number Teeth | Tooth Material | Outer Expansion Slots | Vibration Stabilizing Slots | Kerf | Coating | New/Used |
|--------------|--------------|----------------------------|--------------|----------------|-----------------------|-----------------------------|-------|---------------|-----------|
| 1 | CMT | 251.040.07 | 40 | Carbide | 4 | 4 | Thick | PTFE One-side | New |
| 2, 3 | CMT | 250.024.07 | 24 | Carbide | 4 | 4 | Thick | PTFE One-side | New |
| 4 | Forrest | Woodworker II, WW07Q307100 | 30 | Carbide | 3 | 0 | Thick | None | New |
| 5 | Forrest | Woodworker I, WW07Q607100 | 60 | Carbide | 3 | 0 | Thick | None | New |
| 6, 7 | Freud | Diablo D0740X | 40 | Carbide | 4 | 4 | Thin | Perma-Shield | New |
| 8, 9 | Freud | Diablo D0724X | 24 | Carbide | 4 | 4 | Thin | Perma-Shield | New |
| 10 | Oldham | B725-P | 140 | Steel | 0 | 0 | Thin | None | Used-Worn |
| 11 | Oldham | B725-HG | 60 | Steel | 0 | 0 | Thick | None | Used-Worn |
| 12 | Oldham | B725-4216 | 16 | Carbide | 0 | 0 | Thick | None | Used-Worn |

Table 2: Saw blades properties. Note: Industrial Thin Kerf (ITK)

| Blade Number | Blade Thickness (inch) | Kerf Thickness (inch) | Hook Angle (degrees) | ATB Angle (degrees) | Maximum Speed (RPM) | Nominal Diameter (inch) | Nominal Bore (inch) | Blade Purposes |
|--------------|------------------------|-----------------------|----------------------|---------------------|---------------------|-------------------------|---------------------|--------------------------------------|
| 1 | 0.048 | 0.071 | 20 | 30 | 8400 | 7 1/4 | 5/8 | ITK Finishing Blade |
| 2, 3 | 0.048 | 0.071 | 20 | 15 | 8400 | 7 1/4 | 5/8 | ITK Framing Blade |
| 4 | 0.074 | 0.094 | 20 | 15 | 7000 | 7 1/4 | 5/8 | All Purpose, RIP Blade |
| 5 | 0.068 | 0.094 | 20 | 30 | 7000 | 7 1/4 | 5/8 | All Purpose, Trim and Crosscut Blade |
| 6, 7 | 0.041 | 0.063 | 15 | 15 | 10000 | 7 1/4 | 5/8 | Finishing Blade, Crosscut |
| 8, 9 | 0.041 | 0.063 | 15 | 15 | 10000 | 7 1/4 | 5/8 | Framing Blade, Rip and Crosscut |
| 10 | 0.054 | 0.083 | NA | NA | 9400 | 7 1/4 | 5/8 | Finishing Blade |
| 11 | 0.068 | 0.074 | NA | NA | 9400 | 7 1/4 | 5/8 | Combination Blade |
| 12 | 0.061 | 0.102 | 15 | 15 | 9400 | 7 1/4 | 5/8 | Framing Blade, Rip and Crosscut |

Images of the blades are shown in Figures 1, 2, and 3. The saw blades have different patterns of slots. The outer slots are expansion slots to reduce warping as the blade temperature increases. The inner slots are for stabilization and vibration reduction.



Figure 1: Front view of saw blades (1), (2, 3), (4). These blades were new before testing.



Figure 2: Front view of saw blades (5), (6, 7), (8, 9). These blades were new before testing.



Figure 3: Front view of saw blades (10), (11), and (12). The Oldham blades were used and worn before testing.

3 BLADE STIFFENER AND CONSTRAINED LAYER DAMPING TREATMENT

Permatex high temperature silicone Room Temperature Vulcanizing (RTV) gasket maker was used to test whether adding a viscoelastic damping layer to the blade stiffener noise reduced the saw blade noise. The blade stiffeners were both manufactured by Forrest Manufacturing Company (Clifton, NJ). Table 3 provides details of the blade stiffeners.

Table 3: Blade stiffeners

| Manufacturer | Diameter | Thickness | Arbor | Coating | Coating Thickness (inch) |
|--------------|----------|-----------|-------|--------------|--------------------------|
| Forrest | 4 inch | 0.115 | 5/8 | None | – |
| Forrest | 4 inch | 0.121 | 5/8 | RTV Silicone | 0.006 |



Figure 4: On the left, front view of the blade stiffener without any treatment. On the right, front view of the blade stiffener with room temperature vulcanizing silicone treatment, which acts as a viscoelastic damping treatment.

4 CIRCULAR SAWS

Three circular saws were tested with the twelve saw blades. The circular saws originated from Makita, Craftsman, and a Research circular saw manufactured by Able Tool Corporation, (Cincinnati, OH). Table 4 lists basic properties of the three saws. Figures 5 and 6 show the front and side images of the three saws. The Research saw uses a DC motor model MPP1003D41-KPSN, manufacturer Parker Hannifin (Rohnert Park CA). The Research saw has a DC motor with a controller which converts three phase 208 Volt AC power to DC power to run the motor. The Research saw has a greater weight and lower speed which may affect the sound power.

Table 4: Saw information and specifications of the three saws.

| Manufacturer | Model Number | Serial Number | Weight (lbs) | Rated Speed (RPM) | Rated Power (Watts) | Dimensions Length, Width, Height (inch) |
|--------------|--------------|---------------|--------------|-------------------|---------------------|---|
| Makita | 5007F | 1039372 | 11.1 | 5800 | 1800 | 12.0 x 9.5 x 9.5 |
| Craftsman | 320-1087 | 1862 | 12.5 | 5000 | 1680 | 11.8 x 9.0 x 9.8 |
| Able Tool | 0001 | 0001 | 29.2 | 4000 | 1756 | 15.0 x 11.0 x 9.5 |



Figure 5: Front view of the Makita, Craftsman, and Research circular saws respectively from left to right.



Figure 6: Side view of the Makita, Craftsman, and Research circular saws respectively from left to right.

5 EXPERIMENTAL DESIGN

In this experiment, the A-weighted sound power level measured in accordance with ISO 3744 was the measured response. The sound power level measurements were conducted at the University of Cincinnati Sound Power laboratory using the Sound Power VI which was described by Hayden in 2009 (Hayden 2009). Sound power measurements were made in both the loaded and unloaded

conditions. For the unloaded condition, the saw was resiliently suspended from a steel frame using bungee cords and run at full speed with no load. In the unloaded condition each setup had three samples of the A-weighted sound power level. Each unloaded sound power level sample had one position of the saw and 50 seconds for time averaging. For the loaded condition, each sound power level measurement had a total of twenty samples of the A-weighted sound power level which consisted of ten slices of 5 seconds duration in two positions.

During the loaded condition measurements, the saws crosscut one-inch thick rough-cut oak boards. Oak was used as a limiting case of an available hardwood. During the loaded condition measurements, the feed rate was measured using a linear position transducer model SP2-50 manufacturer Celesco (Chatsworth, CA). The feed force was measured in three axes using a triangular force plate model HE900T-300 manufactured by Advanced Mechanical Technology Inc. (Watertown, MA). The electrical power was measured for the Makita and Craftsman saws using model NI-9225 and NI-9227 modules manufacturer National Instruments (Austin, TX). The electrical power was not measured for the Research saw; since the lab did not have instrumentation to measure the three phase electricity used by the Research saw.

Each test setup consisted of a particular combination of tool, blade, and blade stiffener. The data were collected with a hierarchical clustering given by the position, test setup, and run number. There are a total of 1293 samples of the sound power level with 1120 in the loaded condition and 173 in the unloaded condition. The order of testing was not randomized. The test setups were very different between the loaded and unloaded conditions, so separate regressions were conducted for the loaded and unloaded conditions.

The sound power level, L_w was adjusted for the feed rate, to account for the cumulative noise exposure. It is desired to minimize the cumulative noise exposure for a defined task and not just the sound power level. When the sound power level is adjusted for the feed rate the variable L_{wfr} is used

$$L_{wfr} = L_w - 10 \log_{10} \left(\frac{\text{Feed Rate}}{\text{Reference Feed Rate}} \right), \quad (1)$$

where the feed rate is measured in inches/s and the reference feed rate is 1 inch per second.

In the loaded condition, dependent variables include: Tool ID, Blade Number, Blade Stiffener Present, Damping Treatment, Feed Force, Downward Force, Feed Rate, and Electrical Power (not measured for Research saw). Because there are only 12 saw blades and three of those blades are duplicates several of the dependent variables are highly correlated with one another. To preclude multicollinearity, relatively few dependent variables were included in the model.

The saw blade properties were not included in the model since many of the properties are highly correlated with one another. Additional saw blades must be tested to reduce the correlations if accurate estimates of the effects of blade properties are desired. Blade properties in the dataset are the blade manufacturer, blade model, number of teeth in blade, tooth material, number of outer expansion slots, number of vibration stabilizing slots, thin and thick kerf, type of blade coating, new or used blade, blade thickness, kerf thickness, hook angle (degrees), ATB angle (degrees), maximum speed (RPM), nominal blade diameter, and nominal bore size.

6 REGRESSION METHODOLOGY

In linear regression, it is assumed that all samples are independent and have a common amount of variability. However, when data is sampled in a clustered manner the assumptions of independent samples and equal variability among samples are not satisfied. To model the sample dependence

and changes in sample variability, a linear mixed model can be used. Mixed models include coefficients for both fixed and random effects. The fixed effects are the same as the coefficients in ordinary linear regression. The random effects add random intercepts based on the clustering hierarchy to account for dependence of the samples and changes in variability given the clustering hierarchy. In this paper, multiple samples of the A-weighted sound power level from the same test setup are more similar than samples of the A-weighted sound power level from other test setups. By using a linear mixed model, model validity is improved and inferences made on the population are more generalizable (Jiang 2007).

In this paper, a linear mixed model using the R-statistical programming environment MASS package with the program glmmPQL was used to calculate the coefficients for the fixed and random effects (R Core Team 2014; Venables 2002; Breslow 1993). This model improves the generalizability of the results by taking into consideration the dependence and changes in variability of the samples based on the clustering of the data sampling. Linear regression was applied using the continuous and categorical variables for each of the slices. The results of the mixed model were compare to the fixed effects only model using the glm function from the stats package in the R-statistical programming environment.

7 RESULTS

There are several model limitations which effected the model selection. The downward force was too correlated with the intercept. The interaction between the Tool ID and blade number could not be included in the model due to a singularity. Only the main effects for the Tool ID and blade number were included in the model. Due to experimental design, only the effect of a blade stiffener can be estimated. No estimate of the effect of the viscoelastic treatment on the blade stiffener can be made. The final model includes the Tool ID, Blade Number, $10\log_{10}(\text{Feed Force})$, $10\log_{10}(\text{Feed Rate})$, and $(10\log_{10}(\text{Feed Rate}))^2$. The model equation is

$$L_{w,ijk} = \beta_0 + \mathbf{Tool ID}_j \beta_{1,2} + \mathbf{Blade}_j \beta_{3,\dots,13} + \text{Stiffener}_j \beta_{14} + 10\log_{10}(\text{Feed Force}) \beta_{15} + 10\log_{10}(\text{Feed Rate}) \beta_{16} + (10\log_{10}(\text{Feed Rate}))^2 \beta_{17} + \mathbf{ZU}_{ijk}, \quad (2)$$

where the indices i , j , and k are the hierarchy of the clustering of the data sampling. Index i is the position, index j is the test setup, and index k is the test run number. The names of the categorical levels are shown in Tables 5 and 7 in the left column. The bold faced terms **Tool ID** and **Blade** are categorical variables with three levels and 12 levels respectively. The bold faced terms **Z** and **U** represent the hierarchy of the clustering and the random intercepts of the clustering respectively. The \mathbf{ZU}_{ijk} terms are only used in the mixed model and do not appear in the fixed effects model.

Tables 5 through 8 show the results of the regression models. Model selection was based on ignoring saw-blade interactions, requiring at least one blade to be significant at the 0.01 level of significance, and removing other main effect variables that had a significance less than 0.05 unless there was a higher order significant term based on the main effect.

In Table 5, the response is the A-weighted sound power level, L_w without the feed rate adjustment. The Research saw and Craftsman saw have sound power levels approximately 4.6 and 3.8 dBA lower than the Makita saw respectively. Blades 6 and 7 are the Diablo 40 teeth thin kerf blades which have a sound power level 3.5 dBA lower than the CMT 40 tooth blade. On average the blade stiffener reduces the sound power level by 3.7 dBA. Increasing the $10\log_{10}(\text{Feed Force})$ by 1 unit increases the sound power level by approximately 0.635 dBA. A feed force of 3.2 lbs increases the sound power level by approximately 4.0 dBA. A feed force of 11.6 lbs increases the sound power level by approximately 7.0 dBA. The parabolic feed rate terms are

concave down everywhere. The parabolic feed rate model was selected since it had the best fit to the data. On average, low (feed rate < 0.6 in/s) and high (feed rate > 2.7 in/s) feed rates will reduce the sound power level by more than 1 dBA.

Table 5: On the left is the glmmPQL mixed effects model. On the right is the glm fixed effects model. This is the model using the response L_w (dBA). The P-value probability significance codes in Tables 5 through 8 are 0 *** 0.001 ** 0.01 * 0.05 . 0.1 1.

| Fixed Effect | glmmPQL L_w | | | | | glm L_w | | | | |
|--|---------------|-----------|---------|---------|----------|-----------|-----------|---------|-----------|----------|
| | Estimate | Std.Error | T-value | P-value | Pr(> t) | Estimate | Std.Error | T-value | P-value | Pr(> t) |
| (Intercept) | 103.7 | 1.29 | 80.23 | 0.000 | *** | 103.3 | 0.719 | 143.6 | < 2.0E-16 | *** |
| Craftsman Saw - Makita Saw | -3.81 | 0.375 | -10.16 | 0.000 | *** | -3.72 | 0.191 | -19.5 | < 2.0E-16 | *** |
| Research Saw - Makita Saw | -4.64 | 0.421 | -11.01 | 0.000 | *** | -4.68 | 0.225 | -20.8 | < 2.0E-16 | *** |
| Blade 2 - Blade 1 | -1.13 | 0.844 | -1.33 | 0.187 | | -1.21 | 0.433 | -2.80 | 5.19E-03 | ** |
| Blade 3 - Blade 1 | -2.12 | 0.755 | -2.81 | 0.007 | *** | -1.65 | 0.402 | -4.10 | 4.48E-05 | *** |
| Blade 4 - Blade 1 | 2.20 | 0.718 | 3.07 | 0.003 | *** | 2.12 | 0.370 | 5.73 | 1.40E-08 | *** |
| Blade 5 - Blade 1 | -1.80 | 0.632 | -2.84 | 0.006 | *** | -2.04 | 0.331 | -6.17 | 1.08E-09 | *** |
| Blade 6 - Blade 1 | -3.51 | 0.831 | -4.22 | 0.000 | *** | -3.56 | 0.421 | -8.44 | < 2.0E-16 | *** |
| Blade 7 - Blade 1 | -3.83 | 0.848 | -4.52 | 0.000 | *** | -3.97 | 0.434 | -9.14 | < 2.0E-16 | *** |
| Blade 8 - Blade 1 | -0.774 | 0.929 | -0.83 | 0.408 | | -0.811 | 0.488 | -1.66 | 0.097 | . |
| Blade 9 - Blade 1 | -0.223 | 0.714 | -0.31 | 0.755 | | -0.168 | 0.364 | -0.462 | 0.644 | |
| Blade 10 - Blade 1 | -0.307 | 0.783 | -0.39 | 0.696 | | -0.648 | 0.400 | -1.619 | 0.106 | |
| Blade 11 - Blade 1 | -0.181 | 0.702 | -0.26 | 0.797 | | -0.316 | 0.357 | -0.884 | 0.377 | |
| Blade 12 - Blade 1 | 4.03 | 0.710 | 5.67 | 0.000 | *** | 3.75 | 0.362 | 10.4 | < 2.0E-16 | *** |
| Stiffener Present == TRUE | -3.70 | 0.360 | -10.29 | 0.000 | *** | -3.56 | 0.182 | -19.6 | < 2.0E-16 | *** |
| 10log ₁₀ (Feed Force) | 0.635 | 0.127 | 5.00 | 0.000 | *** | 0.680 | 0.072 | 9.50 | < 2.0E-16 | *** |
| 10log ₁₀ (Feed Rate) | 0.283 | 0.121 | 2.35 | 0.019 | * | 0.494 | 0.081 | 6.07 | 2.01E-09 | *** |
| (10log ₁₀ (Feed Rate)) ² | -0.119 | 0.046 | -2.59 | 0.010 | ** | -0.086 | 0.038 | -2.26 | 0.024 | * |

If the sound power level response is adjusted using the feed rate, then the model equation becomes

$$L_{wfr,ijk} = \beta_0 + \mathbf{ToolID}_j \beta_{1,2} + \mathbf{Blade}_j \beta_{3,\dots,13} + \mathbf{Stiffener}_j \beta_{14} + 10\log_{10}(\mathbf{Feed Force}) \beta_{15} + 10\log_{10}(\mathbf{Feed Rate}) \beta_{16} + (10\log_{10}(\mathbf{Feed Rate}))^2 \beta_{17} + \mathbf{ZU}_{ijk}, \quad (3)$$

where $L_{wfr,ijk}$ is the feed rate adjusted sound power with the hierarchy of clustering of data samples.

In Table 6, by adjusting the sound power level with the feed rate on the left side of equation (3), then the estimate of 10log₁₀(Feed Rate) is reduced by 1. All of the other estimates are unchanged.

To better understand the effect of modelling the feed rate, an improperly specified model which does not account for the fixed effects of feed rate or feed force was analyzed. Table 7 shows the results of the improperly specified model. Within Table 7, the glmmPQL and glm regression methodologies still agree with one another; however, there are significant differences between Table 5 and Table 7. The model intercept changed from 103.7 to 107.9 dBA. The coefficients of the blades relative to one another changed. In Table 7, blades 6 and 7 are only 0.5 dBA lower than blades 2 and 3 instead of approximately 2 dBA when the feed rate was considered in Table 5. A change of 2 dBA relative to the two types of circular saw blades is practically significant and on average statistically significant at the 10% level of significance. The effect of the blade stiffener changed from -3.7 dBA to -3.5 dBA from Tables 5 to 7 respectively which is insignificant.

Table 6: The model with response L_{wfr} has the sound power level adjusted for the feed rate, the estimate associated with the feed rate is reduced by 1 and all of the other estimates are unchanged. On the left is the glmmPQL mixed effects model. On the right is the glm fixed effects model.

| Fixed Effect | glmmPQL L_{wfr} | | | | | glm L_{wfr} | | | | |
|---------------------------------|-------------------|-----------|---------|---------|----------|---------------|-----------|---------|----------|----------|
| | Estimate | Std.Error | T-value | P-value | Pr(> t) | Estimate | Std.Error | T-value | P-value | Pr(> t) |
| $10\log_{10}(\text{Feed Rate})$ | -0.717 | 0.121 | -5.95 | 0.000 | *** | -0.506 | 0.081 | -6.204 | 8.89E-10 | *** |

Table 7: On the left is the glmmPQL mixed effects model. On the right is the glm fixed effects model. This is the model for L_w with no feed rate included in the model as a fixed effect.

| Fixed Effect | glmmPQL L_w | | | | | glm L_w | | | | |
|----------------------------|---------------|------------|---------|---------|----------|-----------|------------|---------|-----------|----------|
| | Estimate | Std. Error | T-value | P-value | Pr(> t) | Estimate | Std. Error | T-value | P-value | Pr(> t) |
| (Intercept) | 107.9 | 0.523 | 206.3 | 0.000 | *** | 107.9 | 0.238 | 453.5 | < 2.0E-16 | *** |
| Craftsman Saw - Makita Saw | -3.66 | 0.393 | -9.324 | 0.000 | *** | -3.66 | 0.179 | -20.50 | < 2.0E-16 | *** |
| Research Saw - Makita Saw | -5.05 | 0.381 | -13.266 | 0.000 | *** | -5.05 | 0.173 | -29.16 | < 2.0E-16 | *** |
| Blade 2 - Blade 1 | -1.25 | 0.727 | -1.722 | 0.088 | . | -1.25 | 0.331 | -3.8 | 1.61E-04 | *** |
| Blade 3 - Blade 1 | -1.24 | 0.727 | -1.701 | 0.092 | . | -1.24 | 0.331 | -3.7 | 1.94E-04 | *** |
| Blade 4 - Blade 1 | 2.58 | 0.642 | 4.024 | 0.000 | *** | 2.58 | 0.292 | 8.8 | < 2.0E-16 | *** |
| Blade 5 - Blade 1 | -0.579 | 0.603 | -0.960 | 0.339 | . | -0.579 | 0.274 | -2.1 | 0.035 | * |
| Blade 6 - Blade 1 | -1.73 | 0.727 | -2.38 | 0.020 | * | -1.73 | 0.331 | -5.2 | 2.09E-07 | *** |
| Blade 7 - Blade 1 | -1.97 | 0.727 | -2.71 | 0.008 | ** | -1.97 | 0.331 | -6.0 | 3.28E-09 | *** |
| Blade 8 - Blade 1 | -0.457 | 0.727 | -0.629 | 0.531 | . | -0.458 | 0.331 | -1.4 | 0.167 | . |
| Blade 9 - Blade 1 | 0.505 | 0.727 | 0.695 | 0.489 | . | 0.505 | 0.331 | 1.5 | 0.127 | . |
| Blade 10 - Blade 1 | 0.667 | 0.727 | 0.917 | 0.361 | . | 0.667 | 0.331 | 2.0 | 0.044 | * |
| Blade 11 - Blade 1 | 1.69 | 0.727 | 2.319 | 0.023 | * | 1.69 | 0.331 | 5.1 | 4.06E-07 | *** |
| Blade 12 - Blade 1 | 5.27 | 0.727 | 7.251 | 0.000 | *** | 5.27 | 0.331 | 15.9 | < 2.0E-16 | *** |
| Stiffener Present == TRUE | -3.45 | 0.347 | -9.937 | 0.000 | *** | -3.45 | 0.158 | -21.8 | < 2.0E-16 | *** |

In Table 8, the glmmPQL and glm models agree very well for the unloaded condition. In Table 8, the sound power level in the unloaded condition the blades did not significantly change the sound power level, so the effects of the blades were ignored and a simpler model was used. In the unloaded condition the NIOSH quiet circular saw has a sound power level 25 dBA lower than the Makita and the Craftsman has a sound power level 7.5 dBA lower than the Makita. These are significantly lower sound power levels; however, the sound power levels in the loaded condition are generally more important than for the unloaded condition when estimating worker exposure, because power tools are only temporarily used in the unloaded condition.

Table 8: On the left is the glmmPQL mixed effects model. On the right is the glm fixed effects model. This is the model for unloaded sound power level in dBA.

| Unloaded Fixed Effect | glmmPQL L_w | | | | | glm L_w | | | | |
|----------------------------|---------------|------------|---------|---------|----------|-----------|------------|---------|-----------|----------|
| | Estimate | Std. Error | T-value | P-value | Pr(> t) | Estimate | Std. Error | T-value | P-value | Pr(> t) |
| (Intercept) | 106.7 | 0.328 | 325.2 | 0.000 | *** | 106.7 | 0.189 | 565.5 | < 2.0E-16 | *** |
| Craftsman Saw - Makita Saw | -7.55 | 0.453 | -16.7 | 0.000 | *** | -7.56 | 0.259 | -29.2 | < 2.0E-16 | *** |
| Research Saw - Makita Saw | -25.1 | 0.430 | -58.4 | 0.000 | *** | -25.1 | 0.246 | -102.1 | < 2.0E-16 | *** |
| Stiffener Present == TRUE | -1.02 | 0.384 | -2.66 | 0.010 | * | -1.01 | 0.220 | -4.61 | 8.1E-06 | *** |

Table 9 shows a summary of the relative sound power levels of the saw blades in the loaded condition using saw blade CMT 251.040.07 as the reference. The last column of Table 9 shows the nominal costs of the saw blades based on a survey of price information on the internet. This shows the Freud Diablo D0740X blade is of lower cumulative noise level and relatively low cost

for this population; however, the sample size of blades is small. In the unloaded conditions the blades were not significantly different than no blade.

Table 9: Circular saw blade relative levels in the loaded condition. Lower relative levels are better.

| Blade Number | Manufacturer | Model Number | Number of Teeth | Relative Level (dB) | New/Used | Nominal Cost US Dollars \$ |
|--------------|--------------|----------------------------|-----------------|---------------------|-----------|----------------------------|
| 1 | CMT | 251.040.07 | 40 | 0.0 | New | 15.90 |
| 2 | CMT | 250.024.07 | 24 | -1.1 | New | 10.50 |
| 3 | CMT | 250.024.07 | 24 | -2.1 | New | 10.50 |
| 4 | Forrest | Woodworker II, WW07Q307100 | 30 | 2.2 | New | 80.10 |
| 5 | Forrest | Woodworker I, WW07Q607100 | 60 | -1.8 | New | 99.90 |
| 6 | Freud | Diablo D0740X | 40 | -3.5 | New | 17.13 |
| 7 | Freud | Diablo D0740X | 40 | -3.8 | New | 17.13 |
| 8 | Freud | Diablo D0724X | 24 | -0.8 | New | 10.13 |
| 9 | Freud | Diablo D0724X | 24 | -0.2 | New | 10.13 |
| 10 | Oldham | B725-P | 140 | -0.3 | Used-Worn | 3.20 |
| 11 | Oldham | B725-HG | 60 | -0.2 | Used-Worn | 12.04 |
| 12 | Oldham | B725-4216 | 16 | 4.0 | Used-Worn | 7.31 |

8 DISCUSSION, CONCLUSIONS, AND FUTURE WORK

The Research saw had the highest weight and slowest rotational blade speed which may have affected its sound power relative to the other two circular saws. Future work may use a DC motor with a lower weight and higher speed to eliminate any effect of saw weight and speed on measured sound power. The wood used in this study was oak hardwood which is a limiting case of a hardwood for measuring noise levels. The sound power level measurements may be repeated with the material type and study methodology; specified in IEC 62841-2-5 to determine, if the results are similar, and for a more effective comparison with manufacturer data.

Multiple saws were compared in this study, because one individual saw may interact differently with particular blades. Having three saws and using a mixed model strengthens the generalizability of the study over one saw with a simple comparison model. A more in-depth study of the relationship between sound power, feed-rate, and feed-force May use just one saw and vary the feed-rate and feed-force.

One focus of this study was to determine the best available options for low-noise saw blades. The study identified one low-noise saw blade that is available and affordable; however, the sample size of saw blades was small. A future study with a larger sample of blades claiming to have low-noise levels would better determine the availability and affordability of low-noise saw blades.

When comparing saw blades the goal is to select the saw blade which has the lowest cumulative noise exposure for a defined task. This goal can be achieved by using a model which adjusts the sound power level for the feed rate and accounts for other parameters affecting sound power.

The lowest predicted sound power level for any saw setup in the loaded condition is 93 dBA which is above the NIOSH recommended exposure limit of 85 dBA, so it would still be necessary to use hearing protection. Additional research in reducing the noise emissions of the workpiece is needed.

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10 REFERENCES

- Breslow, N. E., & Clayton, D. G. (1993). Approximate inference in generalized linear mixed models. *Journal of the American Statistical Association*, 88(421), 9-25.
- Crocker, M. J. (2007). Handbook of noise and vibration control. John Wiley & Sons. p 841-846, 975-986, 994
- Garvey, D. J. (2015). Hearing Conservation in Construction: New Perspectives on an Old Problem. *Professional Safety*, 60(9), 30.
- Groß, L., & Heisel, U. (2009). Noise at circular and dimension saw work stations. *Noise Control Engineering Journal*, 57(6), 578-584.
- Hayden, C. S., & Zechmann, E. L. (2009). Relevant test methods for establishing sound power levels of powered hand tools. *Noise Control Engineering Journal*, 57(3), 279-290.
- Hufnagel, A. (2010). The effects of structural damping on the radiated noise of circular saw blades during operation. *The Journal of the Acoustical Society of America*, 127(3), 1741-1741.
- IEC 62841-2-5 (2014). Electric motor-operated hand-held tools, transportable tools and lawn and garden machinery - Safety - Part 2-5: Particular requirements for hand-held circular saws
- ISO 3744 (2010). Acoustics - Determination of occupational noise exposure and estimation of noise induced hearing impairment, International Organization for Standardization, Geneva, Switzerland
- ISO 7960 (1995). Airborne noise emitted by machine tools - Operating conditions for woodworking machines, International Organization for Standardization, Geneva, Switzerland
- Jiang, J. (2007). *Linear and generalized linear mixed models and their applications*. Springer Science & Business Media. Accessed on: 2015/04/23: Available at: <http://link.springer.com.ezaccess.libraries.psu.edu/book/10.1007%2F978-0-387-47946-0>
- Leu, M. C., & Mote, C. D. (1984). Origin of idling noise in circular saws and its suppression. *Wood Science and Technology*, 18(1), 33-49.
- Maue, J., & Hertwig, R. (2004). Noise Reduction of Circular Saws by Means of Low-Noise Saw Blades. *Mechanika/Akademia Górniczo-Hutnicza im. St. Staszica*, 23(2), 237-241.
- Neitzel, R. L., Stover, B., & Seixas, N. S. (2011). Longitudinal assessment of noise exposure in a cohort of construction workers. *Annals of occupational hygiene*, 55(8), 906-916.
- Reiter, W. F., & Keltie, R. F. (1976). On the nature of idling noise of circular saw blades. *Journal of Sound and Vibration*, 44(4), 531-543.
- R Core Team (2014). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Accessed on: 2015/04/26 Available at: <http://www.R-project.org/>
- Suter, A. H. (2002). Construction noise: exposure, effects, and the potential for remediation; a review and analysis. *AIHA Journal*, 63(6), 768-789.
- Venables, W. N. & Ripley, B. D. (2002) *Modern Applied Statistics with S*. Fourth Edition. Springer, New York. ISBN 0-387-95457-0, Accessed on: 2016/03/18 Available at: <http://www.stats.ox.ac.uk/pub/MASS4>
- Wang, T., Yao, T., & Duan, G. L. (2012, November). Optimization Design on Vibration and Noise Reduction of Damping Sandwich Circular Saw. In *Applied Mechanics and Materials* (Vol. 215, pp. 433-437).