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Design and Development of a Low-Noise Lawnmower Blade: Application of CAD, CAE and RP Tools and Techniques

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Abstract: *This study involved the design and development of a low-noise lawnmower blade using virtual modeling tools and Rapid Prototyping (RP) principles. Computer Aided Design (CAD) and Computer Aided Engineering (CAE) tools and techniques were used to generate an optimised model of the original lawnmower blade which was prototyped using a Fused Deposition Modelling (FDM) machine. The prototype generates lower noise levels than the original blade and the virtual modeling tools are adequate enough to predict the noise levels of the proposed blade design. Furthermore, the use of RP technology in the fabrication of the blade has potential to reduce developmental cost and time.*

Keywords: *Computer Aided Design, Computer Aided Engineering, Rapid prototyping, Noise, Lawnmower Blade*

1. Introduction

The effects of noise pollution on human health are considerably greater than hearing problems (Chepesiuk, 2005). Elevated blood pressure, loss of sleep, increased heart rate, cardiovascular constriction, laboured breathing and changes in brain chemistry are all caused by noise exposure (Chepesiuk, 2005). Moreover, listening to high decibel sounds over a prolonged period can cause serious hearing loss (Hughes, 2013). Rotary lawnmowers produce an upwards of 120 dB of noise, 80 dB being the Environmental Management Authority's (EMA) upward limit for commercial areas of Trinidad and Tobago during daytime (Environmental Management Authority, 2001). Therefore, there is a need to reduce the noise generated by rotary lawnmowers.

The primary sources of electric lawnmower noise include motor noise and blade noise, the latter of which is more significant (Guentiier et al., 1977). Blade noise is generated from curving vortices formed by the blade tips when rotating. The pressure on one surface of the blade is greater than on the other which results in air flow around the tip from the high pressure area to the low pressure area, which causes noise (Reza et al., 2003). Its effects can be reduced by:

- Decreasing the rotational speed of the blade (Guentiier et al., 1977);
- Sharpening of the blade edges (Guentiier et al., 1977);
- Reducing the thickness and width of blades (Guentiier et al., 1977);
- Adjusting the curves (Moore, 1981); and
- Placing holes and winglets to break the air vortices (Moore, 1981)

Frequency domain and time domain numerical models have been used extensively to analyse rotating blade noise (Mao et al. 2014). However, these methods are tedious and require calculation of retarded times and numerical differentiations that are computationally expensive (Sinayoko et al. 2013). Their applications have been limited to fans, propellers and wind turbines (Farassat and Brentner, 1997). Tauro and Mann (1997) stated that analytical models are impractical due to the complex geometries of lawnmower blades and recommend that an experimental method be employed to analyse blade noise. Bockhoff et al. (2004) stated that experiments need to be performed taking account of the lawnmower's operating conditions for accuracy of results. However, constructing and testing physical prototypes based on trial and error approaches lead to wastage of time and resources (Manivannan, 2010).

Modifications to lawnmower blades to reduce noise are currently being undertaken. A study by Guentiier et al. (1977) showed that sharpening the leading and trailing edges of the blade reduces noise. They also found that reducing the blade speed and thinner, narrower blades reduce the noise generated. The lawnmower company Briggs and Stratton focused on designing a quieter blade by modifying the curves and placing holes to break the turbulent air using a trial and error approach (Cancino, 2014). Reza et al. (2003) used CFD and FEA techniques to optimise a lawnmower mulching blade to increase lift and reduce noise. In this study, the decrease in noise level was assumed to be the decrease in turbulent kinetic energy of the CFD model. The design engineers at lawnmower company, Viking, used ANSYS CFX fluid flow simulation software to simulate the airflow in their lawn mower deck to determine the sources of noise (ANSYS, 2010). Several variables, such as fast blade rotation, unsteady pressure and high fluctuations of the air velocity within a lawnmower deck, create a complex airflow that makes traditional development and measurement methods almost impossible (ANSYS, 2010). Therefore, there is need of a structured approach to design a low noise lawnmower blade. Thus, the study used a virtual modelling approach by Gokool et al. (2015) which combines Computer Aided Design (CAD) and Computer Aided Engineering (CAE) methods coupled with Rapid Prototyping (RP) principles to efficiently design and develop a prototype blade.

Prototyping is defined as the process of developing an approximation of the product to be produced (Ali et al., 2013). Virtual or analytical prototypes are non-tangible representations of a product, usually a mathematical or simulation model where aspects of the product can be analysed, before manufacturing a physical prototype, to test the form and function of the part (Vaughan and Crawford, 2013). Computational Fluid Dynamics (CFD), Finite Element Analysis (FEA) and various optimisation techniques are commonly used to analyse virtual prototypes. Additive Manufacturing (AM), which includes Rapid Prototyping (RP) or 3D printing, refers to technologies that build three dimensional (3D) models by the addition of material layer upon layer with use of CAD software (Ali et al., 2013). RP technologies include Stereo-Lithography, Selective Laser Sintering (SLS), Multi-Jet Modelling (MJM) and Fused Deposition Modelling (FDM) which will be used in this study. The use of AM is ever-growing in industry, since it enables the quick and cost effective conversion of design ideas with complex geometries into working models and even end-use parts (Yang et al., 2013; Meisel and Williams, 2015).

This study employed a new structured approach to the design and development of a low noise electric lawnmower blade by using CAD, CAE and RP techniques, which saved time and cost. The performance of the physical prototype blade was assessed in its operational environment in terms of noise generation, quality of cut and durability.

2. Methodology

Figure 1 shows the research methodology. The study began with reverse engineering the current blade design to produce a CAD model. Then the blade design is re-engineered using CFD simulation to model the noise generation. Central composite design (CCD) is used to determine the number of experimental runs required to effectively create a prediction model using Response Surface Methodology (RSM). Furthermore, Genetic Algorithm (GA) was utilized to find the optimal parameter condition for minimum blade noise. This was followed by a finite element analysis (FEA) of the optimised blade to determine its structural integrity. Finally, the blade was rapid prototyped and compared to the original design.

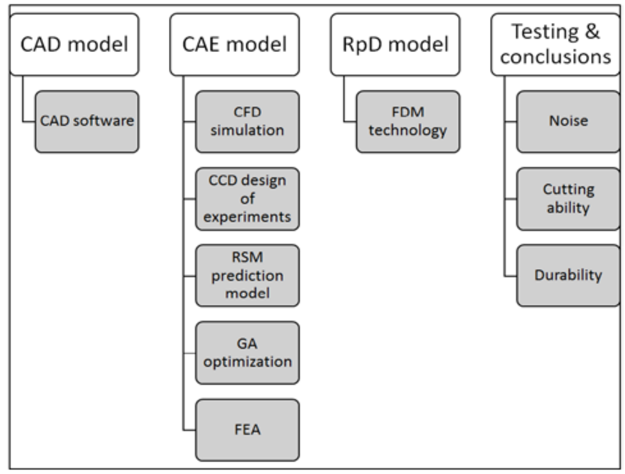


Figure 1. Research Methodology

3. Development of a Computer Aided Design Model

The dimensions of the original blade of the selected lawnmower were used to create a 3D CAD model in SolidWorks™ software. It was assumed that the curves were simple fillets, the cutting edge was straight with a thickness of 1 mm and the blade was straight if seen from the top view. The CAD model of the original blade is shown in Figure 2.

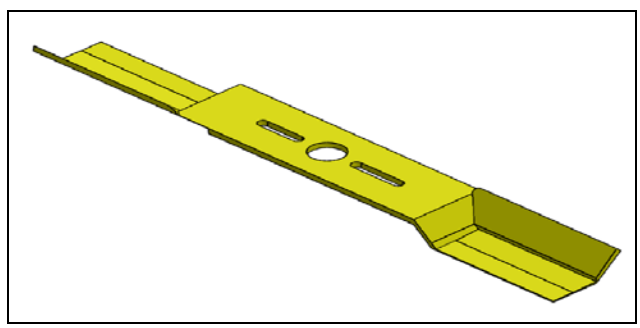


Figure 2. CAD model of the original blade

3.1 Generation of a Computer Aided Engineering Model

SolidWorks Flow Simulation™ module was used to create a CFD model of the rotating blade and it was assumed that the sound pressure was equal to the difference in dynamic air pressure between the top and bottom surfaces of the rotating blade geometry. The settings used while creating the CFD model appear in Table 1. The developed model was validated by means of CFD-based noise-angular speed and physical test runs. The results appear in Figure 3. The average deviation of the noise level was 3.58 dB. This value includes allowance for experimental errors. The material of the blade had little effect on the noise generated. Polycarbonate (PC) material was used for the virtual model and the original blade was fabricated from an unidentified plastic with metal and fiberglass reinforcements, yet there was no significant difference in noise levels. Thus, the developed virtual model was determined to be acceptable to conduct simulation runs.

Table 1. Settings of the CFD model

Option	**Setting**
Temperature	293 K
Pressure	101.3 kPa
Angular Velocity	3000 rpm
Angular Acceleration	0 rad/s^2
Air Flow	Laminar and Turbulent
Material	Polycarbonate

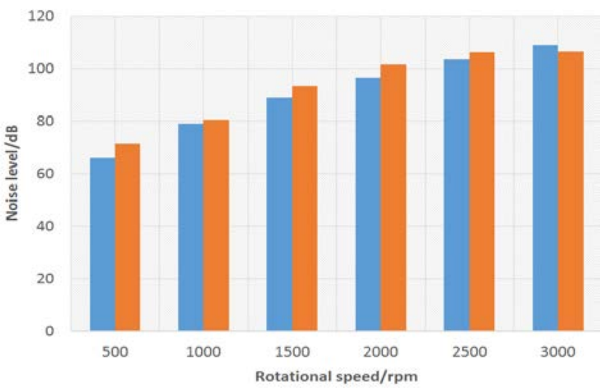


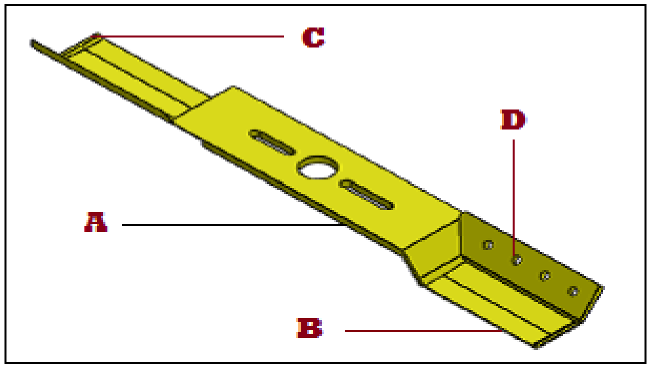
Figure 3. Comparison of the noise levels from virtual and physical tests

Central Composite Design (CCD) was used to determine the number of experimental runs required to optimise the four selected geometrical parameters. These parameters include blade thickness (A), cutting edge thickness (B), height of winglets at the blade edge (C) and diameter of added holes (D). These parameters were chosen based on previous research (Guentiier et al., 1977; and Moore, 1981). The elements of the blade—A, B, C and D—are depicted in Figure 4. To conduct experiments these parameters were set at three levels based on the geometrical constraints of the lawnmower deck and mounting. The parameters along with selected levels are in Table 2. The thirty-one experimental runs were performed using the CFD model.

The results of the experimental runs were analysed using the Response Surface Modelling (RSM) tool which is available in Minitab software (refer to Table 3.) and then the regression equation (1) was generated where the noise level was given by N_L. Equation (1) was tested and found to be in agreement with the experimental data. Figure 5 shows the deviation in experimental and calculated noise levels.

Table 2. Parameters and levels

No.	**Parameters**	**Levels**		
		-1	**0**	**+1**
1	Thickness of blade, A (mm)	5.08	6.67	8.26
2	Thickness of cutting edge of blade, B (mm)	0.8	0.9	1
3	Height of winglet, C (mm)	0	25	50
4	Diameter of air passage holes, D (mm)	0	6	12



Legend: A: Blade Thickness, B: Blade Cutting Edge Thickness, C: Height of Winglet, and D: Air Passage Hole Diameter

Figure 4. CAD model showing the four parameters under study

Table 3. Statistical Analysis of Predicted Model

Estimated Coefficients for Noise Level		
Predictor	Coefficient	P value
Constant	134.49	0.000
A	2.22	0.245
B	-1.14	0.545
C	8.31	0.000
D	-1.55	0.414
A^2	1.36	0.783
B^2	-7.11	0.162
C^2	-3.46	0.486
D^2	2.50	0.613
A^B	2.62	0.199
A^C	2.41	0.234
A^D	2.04	0.313
B^C	-2.68	0.188
B^D	-1.76	0.381
C^D	-3.24	0.116

Analysis of Variance					
Source	DF	Adj SS	Adj MS	F	P
Model	14	2392.26	170.88	2.80	0.026
Linear	4	1399.24	349.81	5.73	0.005
Square	4	391.04	97.76	1.60	0.222
Interaction	6	601.98	100.33	1.64	0.199
Error	16	976.33	61.02		
Total	30	3368.59			

$$N_L = 134.49 + 2.22\,A - 1.14\,B + 8.31\,C - 1.55\,D + 1.36\,A{*}A - 7.11\,B{*}B - 3.46\,C{*}C + 2.50\,D{*}D + 2.62\,A{*}B + 2.41\,A{*}C + 2.04\,A{*}D - 2.68\,B{*}C - 1.76\,B{*}D - 3.24\,C{*}D \quad \textbf{(1)}$$

Equation (1) was optimised by use of the GA tool, where the optimum noise level was obtained relative to the experimental parameters. The default GA tool settings of the MATLAB programme were used. The optimised results are presented in Table 4. The optimised design was tested with respect to stress, strain and deflection to ensure that the design was mechanically feasible, using the Simulation Xpress module of the SolidWorks software, before being prototyped.

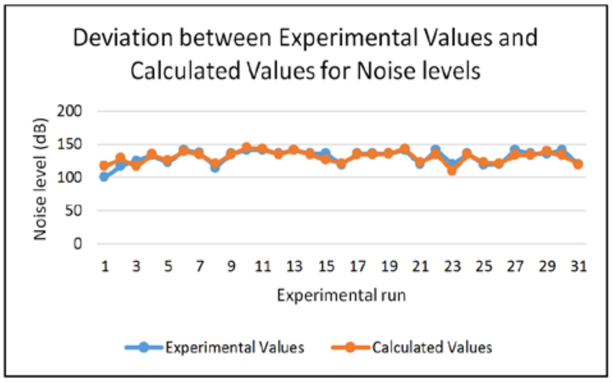


Figure 5. Deviation in Experimental and Calculated Values

Table 4. Optimised Results

Parameter	Optimum Value
Thickness of central section of blade, A (mm)	5.08
Thickness of cutting edge of blade, B (mm)	1
Height of winglet, C (mm)	1.803
Diameter of air passage holes, D (mm)	6
Noise Level (dB)	99.96

3.2 Production of a Rapid Prototype

The optimised blade model was fabricated using the Fortus FDM 400mc and PC material. The optimal blade design in STL file format was sliced and prototyped. After completion of the four-hour printing process, the RP model was allowed to cool and the support material was subsequently removed. Figure 6 shows the photograph of the 3D-printed blade. In Figure 7 the 3D-printed blade is shown alongside the original blade, displaying the design differences in terms of the added air passage holes and winglet.

Figure 6. 3D-printed blade with support material removed

Figure 7. Original and redesigned lawnmower blades

4. Discussion of Results and Inferences

4.1 Results and Analysis

Table 5 shows the noise-distance test results. It can be seen that the noise level of the lawnmower decreases as distance from it increases. Although the operator experiences 82.7 dB of noise when the original blade was used, a bystander at 3 m away from the lawnmower only experienced 78.8 dB of noise which is significantly quieter. Also, the prototype was less noisy than the original blade. The operator experienced a difference of 4.5 dB using the prototype blade which is clearly noticeable according to Bies and Hansen (2009). The prototype produced an average of 5.025 dB less noise than the original blade. However, upon cutting the 4th metre of grass, the prototype blade broke, resulting in a discontinuation of the noise-distance test. The prototype blade was not durable.

Table 5. Results of the Noise-Distance Test

Distance/m	Noise level (in dB)		Deviation (dB)
	Original blade	Prototype blade	
0	82.7	78.2	4.5
1	81.9	76.6	5.3
2	79.6	74.8	4.8
3	78.8	73.3	5.5
Average deviation			5.025

Figure 8 illustrates the comparison of grass length cut by the two blades. As seen, the original blade provides a shorter cut, removing 1.35 inches of the grass. Whereas the prototype removed 1.20 inches of the grass, the quality of cut produced by the prototype is thus comparable to that of the original blade.

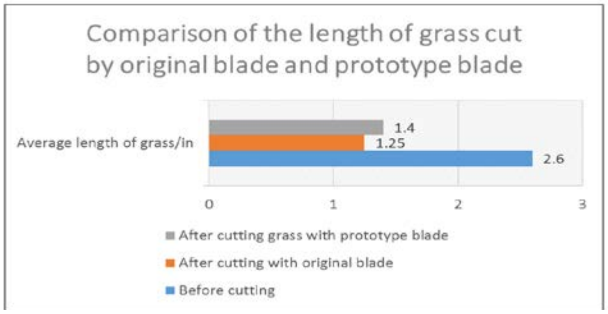


Figure 8. Comparison of quality of cut by means of grass length for the original and prototype blades

4.2 CAD and CAE Model Results

A low noise lawnmower blade was designed using CAD and CAE modelling tools and techniques. The CAD process involved the reverse engineering of the original blade to create a 3D geometrical model for use in the simulation and analysis of the CAE phase. The CAE phase involved the use of CFD and GA optimisation tools to re-engineer the blade in order to reduce the noise it generated.

The CFD model predicted the generated noise levels of the blade geometries. This saved time and cost in executing the experimental runs but simplifying a complex phenomenon such as the generation and propagation of sound lead to errors. Also, since the simulated geometries were different, the location of the sound pressure waves may have been different which could have led to inaccurate readings that were introduced in every subsequent step.

The optimisation of the parameters by use of CCD, RSM and GA was a novel approach employed to design a low noise lawnmower blade (Gokool et al., 2015). This method proved effective and can be further improved to produce less noise.

4.3 Rapid prototyping

Producing a physical prototype using the Fortus FDM 400mc enabled the faster and cheaper production of the artefact. This prototype enabled the assessment of the study objective, reduction in blade noise. Moreover, it was found that the prototype generates less noise than the original blade.

Normally material selection will affect a prototype's strength and durability (Hague et al., 2004). In the study, PC was used for the prototype, which is strong in tension and poor in impact strength compared to the other FDM thermoplastics (Fischer, 2011). Additionally, the lack of reinforcement of the blade contributed to its quick failure. It may be argued that the comparison of a reinforced blade with an unreinforced one is invalid since reinforcement introduces more factors into the investigation other than pure geometry. However, no research in the literature was encountered that showed any relationship between reinforcement and blade noise, or more so material and blade noise. This should be investigated further but until then the comparisons made in this investigation hold.

The FDM based RP technique also influenced the performance of the redesigned blade. As seen in Figure 9, the material was deposited as layers which are visibly noticeable in the produced part. These layers allow for the build-up of shear stresses which can lead to mechanical failure especially in thin sections such as the cutting edge of the blade. It is suggested therefore that if the final product is to be produced on a commercial scale, the blade should be manufactured using the process of injection moulding which provides more durable final product. If RP technique is to be used to manufacture the functional part then reinforcement and surface finish are two significant areas that need to be addressed in design and development of the blade.

The generated CAD model of the study contained a flaw where the extruded faces met. The flaw manifested as a narrow channel which might be a cause for the blade failure. This may have been prevented by using a 3D scanner to convert the physical object geometry to CAD model.

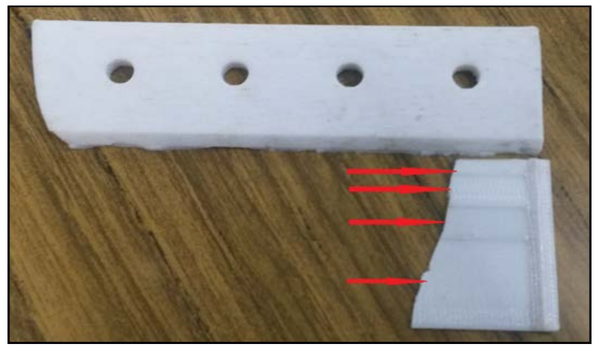


Figure 9. Broken pieces of the prototype blade showing the material layers

4.4 Environmental Impact

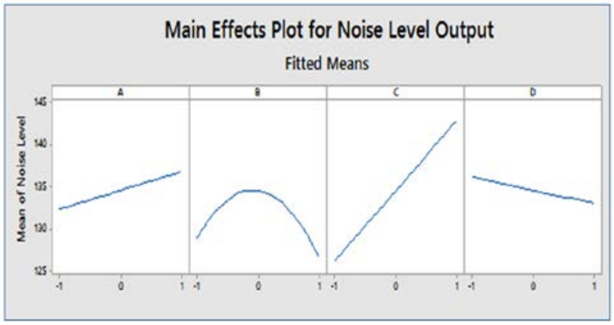
Rotary lawnmower blades have two potential environmental impacts, noise and solid waste pollution. Noise pollution affects people and animals. Although noise dissipates relatively quickly, its effects can last a lifetime such as permanent hearing impairment. The design of this low noise blade decreases the sound made by the lawnmower, which reduces the likelihood of permanent health effects. The blade design was not reinforced which simplifies its recycling at the end of life.

4.5 Relationship between Blade Noise and Parameters

The method of CCD did not only develop the fitness function for optimisation by the GA but also established relationships between the investigated parameters and blade noise which is shown in Figure 10. It can be seen that blade noise increases with an increase in blade thickness (A) and winglet height (C), and a decrease in diameter of air passage holes (D). Also, it can be inferred that the blade noise increases with an increase in cutting edge thickness (B) until a maximum is reached, after which it decreases with an increase in cutting edge thickness.

5. Conclusion

This study presented the design and development of a low noise lawnmower blade. It has shown that CAD and CAE techniques can be incorporated to create a novel



Legends: A: Blade Thickness, B: Cutting Edge Thickness, C: Winglet Height, D: Air Passage Hole Diameter)

Figure 10. Main effects plot showing the relationship between each parameter and blade noise output

redesign of a blade for minimum noise, and AM led FDM 400mc can be used to create prototypes with minimal cost and time. The prototype generated an average 5.025 dB less noise than the original blade, gave a comparable quality of cut by removing 1.20 inches of the grass stalk but its durability was greatly affected by the PC based RP process.

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