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COMPUTATIONAL FLUID DYNAMICS AND FINITE ELEMENT ANALYSIS OF A LAWN MOWER MULCHING BLADE OPTIMIZATION

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ABSTRACT

Computational fluid dynamics (CFD) and Finite Element Analysis (FEA) were performed on a lawn mower mulching blade to optimize the blade design through increasing the lift force and decreasing aero-acoustic noise. The analysis of the current lawn mower blade included fluid dynamics around selected 2-D blade cross-sections at different positions down the length of the blade, blade structural stress and modal analysis. Then, a concept blade attempting to improve the current design was proposed and analyzed compared to the original design. The results showed a significant reduction in turbulent kinetic energy relating to aero-acoustic noise. A reduction in structural loading was also observed, due in part to a reduction in the pressure gradient near the outer cutting region. The loss of the lifting potential was compensated by using an added vertical section at the end of the blade and a chamfer on the edges at the inner radiuses.

Keywords: Lawnmower, CFD, FEA.

1.INTRODUCTION

Lawn mowers have been found to be of wide uses in the world. The modern lawnmower design demands the improvement of efficiency and noise control. A good blade produces excellent slicing action while providing high lift and noise attenuation. In this paper, Computational fluid dynamics (CFD) and structural Finite Element Analysis (FEA) were performed on John Deere mulching Blade model. This blade geometry was chosen from Pro-Engineer models. The objectives were to optimize the original blade by increasing lift and decreasing aero-acoustic noise, focusing on performance analysis and fluid mechanics around selected 2-D blade cross-sections at different positions down the length of the blade. The constraint is that the blade must remain structurally stable under operating conditions to be a valid design.

The task was to do base line analyses of the current John Deere blade, including computational fluid dynamics, structural loading, and modal analysis. Then, a concept blade was created attempting to improve on the current design. Figure 1 is a photo shot of the lawnmower's deck layout.

During use of a lawn mower, a necessary lifting effect of the grass while in the housing of the mower is required to cut the grass more thoroughly.

Lawn mower noise comes mostly from curving vortices left by the blade tips. The pressure on one surface of the blade is greater than on the other, and the result is a span wise flow of air around the tip from the high pressure to the low-pressure zone. This turbulence causes noise. The greater the loading of the prop surface, the greater the horsepower absorbed through the flow around the tip. The result is that the last portion of blade is doing nothing to contribute to the generated blade thrust.

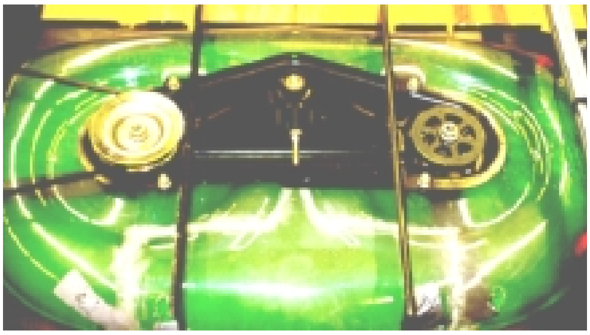

Figure1: Lawnmower deck and mulching blade

Obtaining a more efficient and effective mulching blade is a goal for all lawn mower manufacturers. To increase performance, the design must first understand the loading cycle of the blade sees during its useful life. The loading a mulching lawn mower blade experiences is complex. The blade is exposed to inertia loads, flow induced loads, static loading, rotational drag loading from the grass cutting function as well as vibration loads. All of these loads need to be understood to effectively and expeditiously obtain direction in the redesign phase. The design goal was to obtain a better understand of the internal flow characteristics of a mulching blade

We utilized computational fluid dynamics (CFD) to estimate flow induced loading that develops on the blade. Once the estimated dynamic loading was established, a further structural stress analysis was conducted using structural FEA by using the loading data obtained in the CFD results.

A concept design was proposed and its performance was compared to the original blade design; the concept design had an improved shape and included a vertical fairing, an auxiliary structure that serves to reduce drug on the outer end of the blade. This vertical structure was shaped in order to induce a pressure gradient potentially slowing down the centrifugal effects of the grass clipping and add additional cutting surface.

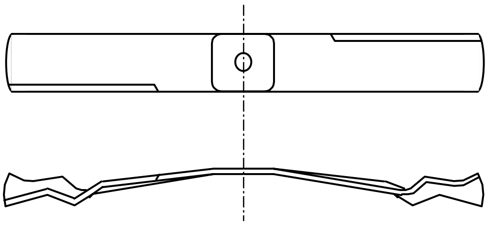

Figure 2: Sketch of mulching blade

2. CFD APPROACH

A finite volume method CFD code was used on both the original blade, as well as, the concept blade. The blade 2D cross-sections were shown below in Figure 3, four sections that have different distance from rotation center are focused. We consider the case when blade runs at 3850 rpm. Figure 4 is the 3D view of concept design.

2.1 CFD Modeling

Turbulent flows are characterized by fluctuating velocity fields. These fluctuations mix transported quantities such as momentum, energy, and species concentration, and cause the transported quantities to fluctuate as well.

The simplest “complete models'” of turbulence are two-equation models in which the solution of two separate transport equations allows the turbulent velocity and length scales to be independently determined. The standard k-ε model falls within this class of turbulence model and has become the workhorse of practical engineering flow. Robustness, economy, and reasonable accuracy for a wide range of turbulent flows explain its popularity in industrial flow and heat transfer simulations. It is a semi-empirical model, and the derivation of the model equations relies on phenomenological considerations and empiricism.

However, the simple k-ε turbulent model sometimes may over-predict the viscous effect. The new developed non-linear k-ε turbulence model has emerged for some years. In principle, this model has certain attractions as compared to standard two-equation models and the more elaborate models such as the differential stress model, which requires the solution of many more equations. The non-linear k-ε model solves only two transport equations, which is the same number solved by its standard (linear) counterpart. This model is very effective for solving rotating flow problems encountered in engineering applications.

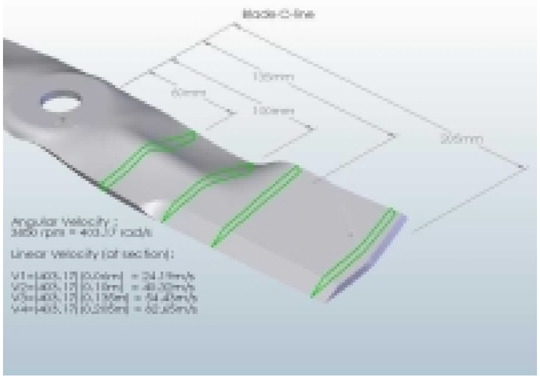

Fig 3: 2D cross-sections for CFD analysis

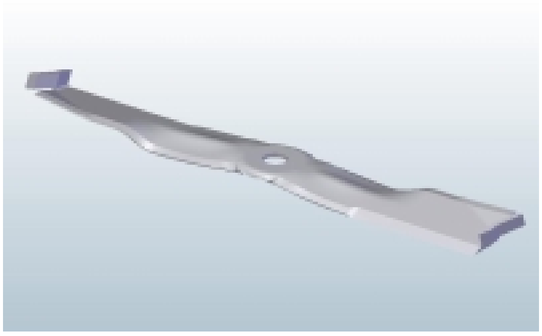

Fig 4: 3D view of concept blade

In the CFD code, initial condition assumptions were made as:

1) Ideal Gas Law assumed
2) Pressure P = 101 kPa
3) Temperature T = 288 K

For rotational speed at 3850 rpm, the max velocity of blade at 205 mm position is 82.6 m/s, because corresponding maximal Mach number =0.24 < 0.3, we assume it as an incompressible flow.

Speed inlet, pressure outlet boundary condition was applied in the CFD code. Iteration convergence was very stable in this 2D case and shown to level off. This convergence is needed for an accurate analysis.

2.2 CFD Result and Analysis

Figure 5 shows the pressure profiles on original blade and concept blade at 60 mm section. The concept blade gives a higher pressure on the bottom side so that the blade will produce a high lift force.

Figure 6 is the CFD result of turbulence kinetic energy profiles on original blade and concept blade at 135 mm section. The concept blade contributes a small turbulence kinetic energy, which would results in reduced noise.

Table 1 and Table 2 are the CFD result summary concerning the Pressure, velocity and maximal turbulence energy level.

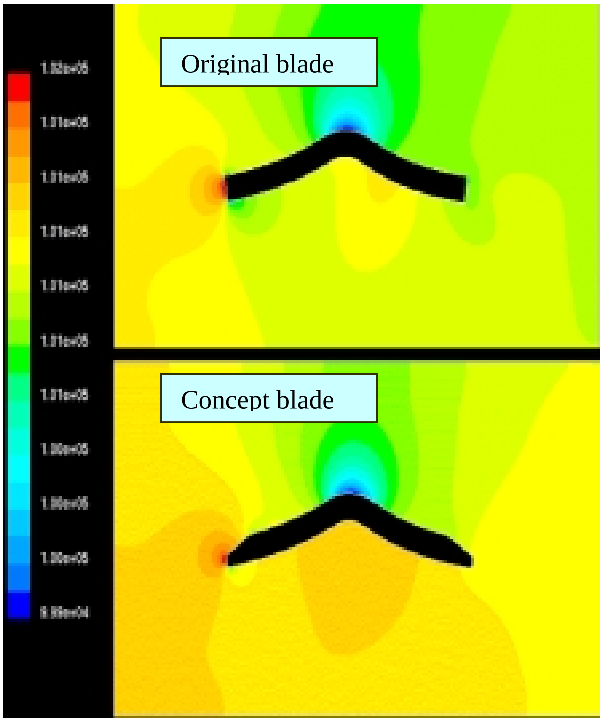

Fig 5: Pressure profiles on original blade and concept blade at 60 mm section

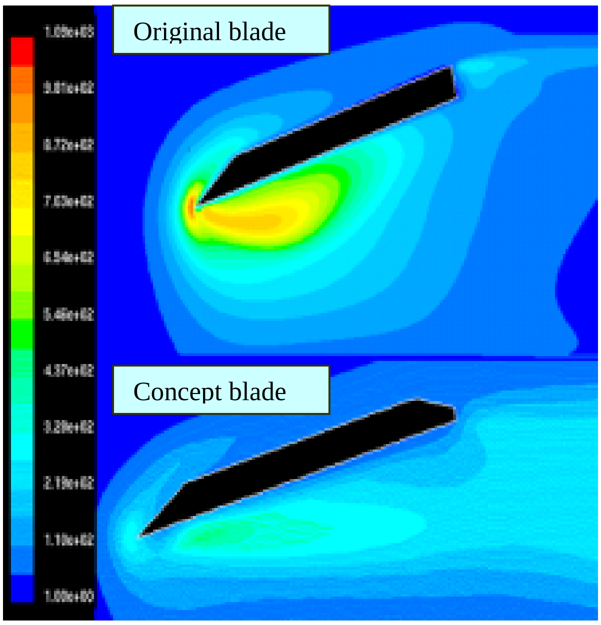

Fig 6: Turbulence Kinetic Energy profiles on original blade and concept blade at 135 mm section

The results showed a significant reduction in turbulent kinetic energy relating to aero-acoustic noise. A reduction is structural loading was also observed due, in part, to the reduction in the pressure gradient near the outer cutting region. This reduction, however, could adversely affect the lifting potential of the mowing system. The concept design included a vertical fairing blade on the outer end of the blade. This vertical blade was shaped to induce a pressure gradient potentially slowing down the centrifugal effects of the grass clipping and add additional cutting surface.

Table 1: Original Blade Design CFD Results

Radius (mm)	**60**	**100**	**135**	**205**
V_{inlet} (m/s)	24	40	54	83
P_{max} (kPa)	102	103	102	105
P_{min} (kPa)	99	99	91	71
k_{max} (m^2/s^2)	98	193	1090	3860
V_{max} (m/s)	45	69	95	175

Table 2: Concept Blade Design CFD Results

Radius (mm)	**60**	**100**	**135**	**205**	**Vertical**
V_{inlet} (m/s)	24	40	54	83	89
P_{max} (kPa)	102	101	101	102	115
P_{min} (kPa)	99	97	94	82	91
k_{max} (m^2/s^2)	57	180	478	1350	1120
V_{max} (m/s)	52	74	103	153	139

3. FINITE ELEMENT ANALYSIS

The CAD model was imported from Pro-E to Solid-Works, and then Cosmos-Works was used to analyze the loading and stress. A steel alloy was used as the material. The blades, due to planar symmetry, were analyzed using only half of the blade. The blade hubs were fixed.

3.1 Aerodynamic Load

CFD pressure results were taken as input loading into a structural FEA package (Cosmos/works) and analyze the two blades for comparison. The resultant pressure gradients acting in the vertical axis across the blade were calculated from the CFD results, subtracting the upper value from the lower See Table 3 for the detail.

Table 3: Surface pressure on the blade

	Original blade	Concept blade
Under side of Blade	99 kPa to 73 kPa	82 kPa to 99 kPa
Upper side of Blade	101 kPa to 105 kPa	101 kPa to 105 kPa
Resulting pressure difference	34 kPa(outer region) to 3 kPa (inner region)	24 kPa(outer region) to 3 kPa(inner region)

The Reynolds numbers were calculated at each cross-section and a coefficient of drag was determined using standard flat plate drag chart [3].

These gradients were applied to the blade in a distributed load configuration. In addition to the vertical loading, the blade also sees a horizontal load due to aerodynamic drag. For simplification in calculations a flat plate approximation of drag force at the corresponding 2-D cross-sections were calculated.

These drag forces, for simplification in analyzing, were applied to both blade geometries in a pure horizontal orientation. The summation of static loading on the blades during steady state operation is shown in Fig 7 and Fig 8.

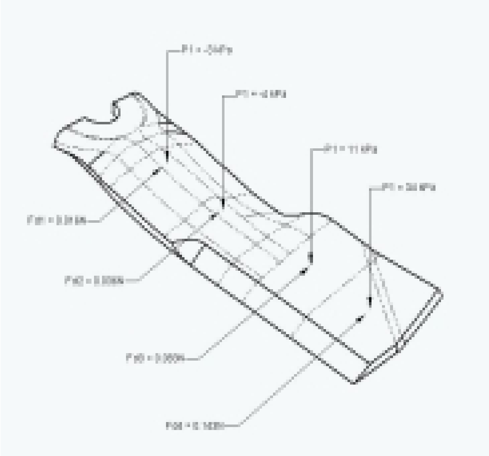

Fig 7: Pressure and drag load and on original blade

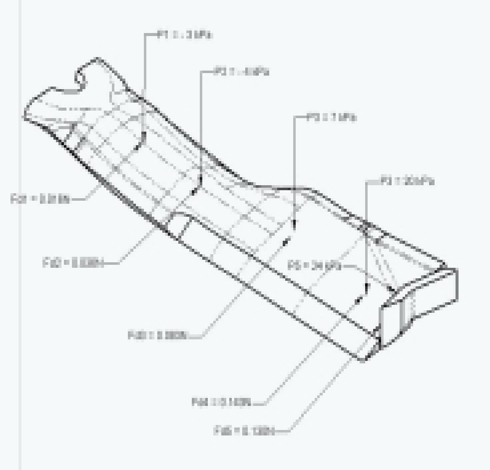

Fig 8: Pressure and drag load and on concept blade

3.2 FEA Result

The resultant deflections of the blades under these loading configurations show a maximum deflection of 0.00066m on the original blade and a 0.00042m on the concept blade.

For Von Mises stress, the original blade and concept blade have almost the same maximal value ($3*10^7$ N/m^2), and the concept blade has a less stress concentrated area. The results could be viewed in Fig 9 and Fig 10.

3.3 Modal Analysis

A Modal analysis was also performed. The operating frequency of the mower at 3850 rpm results in a 64.2 Hz frequency. The modal analysis shows the natural frequencies of the blades. This operating frequency must be avoided to assure the blade will not chatter and deform during operation due to harmonic resonance. The 1st and 2nd modes are shown below. Both modes show the natural frequency to be roughly 3x higher than the operating frequency.

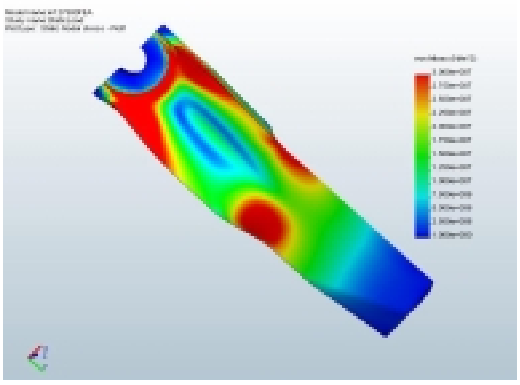

Fig 9: Underside Von Mises stress for original blade

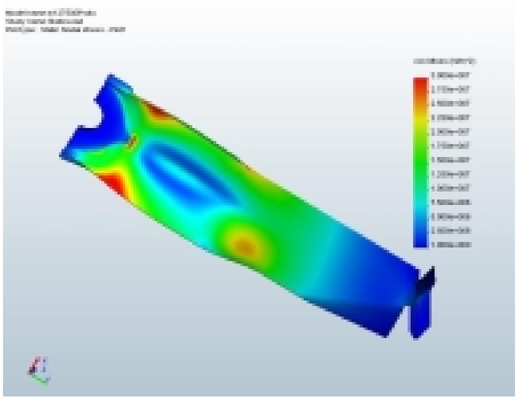

Fig 10: Underside Von Mises stress for concept blade

Table 4: Natural frequency of 1st and 2nd mode

	Original Design	Concept Design
Ist Mode	86.02 Hz	174.94 Hz
2nd Mode	186.54 Hz	175.2 Hz

4. ANALYSIS

The design objectives were to optimize the original blade design by increasing lift, decreasing aero-acoustic noise, and maintaining a structure stress and vibration level.

Aero-acoustic noise: generated by the blade is directly related to turbulent kinetic energy. The concept design shows a substantially decreased in Turbulence Kinetic Energy.

Harmonic resonance: the concept design maintained a safe harmonic distance from the operating frequency. The first and second modes are both roughly 3 times larger than the operating frequency.

Pressure Gradient: on a negative note, the concept design shows a marked reduction in the pressure gradient. The original blade had an outer pressure gradient of 34 kPa and the concept had a gradient of 20 kPa. The reduction is largest in the outer cutting regions of the blade, being velocity dependant. These reduction in lifts may also, adversely effect the ability of the mower to stand the grass up prior to cutting it.

Structural Integrity: Due to the minimizing of the pressure gradient, the most significant structural loading, in the y-axis, was also reduced. This reduction minimized the loading. The concept blade had minimum deflection under the estimated operating conditions.

5. CONCLUSION

Computational fluid dynamics (CFD) and Finite Element Analysis (FEA) were successfully applied to a lawn mower mulching blade design to achieve an optimized blade design with increased lift force and attenuated aero-acoustic noise.

The concept blade showed a significant reduction in turbulent kinetic energy relating to aero-acoustic noise. A reduction in structural loading was also observed due, in part, to the reduction in the pressure gradient near the outer cutting region. The loss of the lifting potential was compensated by using an added vertical section at the end of the blade and a chamfer on the edges at the inner radiuses.

The aerodynamic pressure from CFD computation was applied as the load for FEA input as a coupled field computation, the FEA result shows that the concept blade satisfied the structure and vibration requirement.

To verify the computational result, a further study will be directed to get the blade surface static pressure by using surface pressure transducer with thin-film sensors. This kind of thin-film sensors is being developed for measuring pressure fluctuations on a blade without perturbing the flow the surface.

6. REFERENCES

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7. NOMENCLATURE

Symbol	Meaning	Unit
P	Pressure	(Pa)
T	Temperature	(K)
k	Turbulence Kinetic Energy	(m^2/s^2)
V	Velocity	(m/s)
σ	Von Mises stress	(N/m^2)
μ_t	Turbulent viscosity	Ns/m^2
α_s	Characteristic swirl number	(None)