Experimental and Computational Investigation of Triple-rotating Blades in a Mower Deck*

Woochong CHON** and Ryoichi S. AMANO**

Experimental and computational studies were performed on the 1.27 m wide three-spindle lawn mower deck with side discharge arrangement. Laser Doppler Velocimetry was used to measure the air velocity at 12 different sections under the mower deck. The high-speed video camera test provided valuable visual evidence of airflow and grass discharge patterns. The strain gages were attached at several predetermined locations of the mower blades to measure the strain. In computational fluid dynamics work, computer based analytical studies were performed. During this phase of work, two different trials were attempted. First, two-dimensional blade shapes at several arbitrary radial sections were selected for flow computations around the blade model. Finally, a three-dimensional full deck model was developed and compared with the experimental results.

Key Words: Experimental and Computational Study, Computational Fluid Dynamics (CFD), Laser Doppler Velocimetry, Flow Behavior, Lawn Mower, Rotating Blades

1. Introduction

Aerodynamic investigation on a rotating blade has been one of the significant research areas for improving the designs of many rotating machines. Understanding of the mechanisms of aerodynamics of a rotating blade is one of the challenging research topics. The flowfield around a rotating blade significantly affects the blade failures, vibrations, and associated noise and other adverse factors. The observation of a rotating blade performance is important in many industrial applications such as turbines, compressors, pumps, blowers, etc. Among these devices, a lawn mower is one of very few rotating machineries that not many researchers have attempted to study. For this reason, almost no open literatures are available in the studies of lawn mower blade aerodynamics.

With today's stringent environmental policies, lawn mower manufacturers are looking to perfect the market in mulching mowers. Thus, lawn mower blade and deck designs must allow for maximum airflow and re-circulation of the grass clippings. In order to accomplish this, modifications must be made to the blade profile and cutting angles. In addition, proper mower deck layouts and geometries need to be tested to verify their airflow potential.

This study is an attempt to experimentally observe the effects of blade designs on the resultant mower deck flow profiles. The design intents of blade were to enhance the blade's structural integrity, grass suction and cutting performance, while reducing overall vibration and noise. Nonetheless, with the safety limitations inherent in lawn mower blade design, this is no small task. Some brief computational fluid dynamics (CFD) analysis was also employed to add validity to the experimental results. Additionally, high-speed video footage was taken to gain further insight into the flow conditions within the housing. Strain gages were also used to measure the strain at the surface of the mower blade. The model tested in this study is a type of three spindle, co-rotating discharging deck, which is one of the most common
riding mower decks on the market. This database can be used for aerodynamic studies in turbomachinery and other aerodynamic applications.

The flow inside a mower housing is a two-phase flow of a gas-solid particle system (air-grass clippings) similar to cyclones, separators, dust collectors, snow drifts, etc. The grass clippings circulate with air inside the mower housing after being cut. Since clipping size and motion are important factors for lawn mower performance, the flow of grass clippings was carefully investigated for the discharging mower deck. The blade tested is designed in such a way that the angle of attack varies along the radial direction. This design creates complicated flow patterns inside the deck.

Nomenclature

English symbols

- $D_d$: Diameter of deck
- $a$: Gravitational acceleration vector
- $H_l$: Height of deck
- $H_i$: Gap between deck and table
- $k$: Turbulent kinetic energy
- $L_b$: Length of blade
- $L_d$: Length of deck
- $P$: Mean pressure
- $R$: Blade radius
- $r$: Tested point radius
- $U_i$: Fluid velocity component in the $i$th direction
- $u'$: Fluctuating velocity
- $\overline{u'v'}$: Reynolds-stress
- $v$: Air velocity vector
- $V$: Air velocity
- $V_{\text{max}}$: Maximum velocity of blade
- $x$: Cartesian coordinate
- $Z$: Distance from blade to housing on axial direction
- $z$: Distance from blade on axial direction

Greek symbols

- $\nabla$: Gradient operator
- $\delta$: Unit tensor
- $\varepsilon$: Dissipation rate of turbulence kinetic energy
- $\mu$: Molecular viscosity
- $\mu_t$: Turbulent viscosity
- $\pi$: Total stress tensor
- $\rho$: Density of fluid
- $\tau$: Shear stress
- $\tau_i$: Stress tensor
- $\omega$: Angular velocity of blade (rpm)

Superscripts

- $\overline{\cdot}$: Time-average values
- $'{}$: Turbulent fluctuation

2. Experimental Set-up

The experimental facility consists of a deck model, running motor, grass feeding system, safety fence guard, pulley and V-belt system, a power supply, automatic cut-off switch system, slip ring, strain gages, a velocity measuring system (LDV), LDV traversing system, four particle generators, and a data acquisition system.

The flow pattern inside the housing was observed by using a TSI Laser Doppler Velocimetry (LDV) system. Figure 1 shows the schematic diagram of the tested mower deck. This model is clockwise triple-blades, side-discharge mower deck with a triple housing design. The dimensions are listed in Table 1. The housing is made of clear plastic for flow visualization and LDV experimentation. The deck model is installed on the steel frame test stand and powered by a 7.3 horsepower AC motor (208 volt, 3,520 rpm). The rotational speed of the blade is set to be 3,850 rpm by using a belt-pulley system. The height between the test stand and the bottom of the mower deck is adjustable from 0.025 m to 0.10 m. The artificial grass mat is attached on the wood plate (0.8 m × 1.4 m) which is installed under the mower deck to simulate the working condition of the lawn mower in a field test case. The LDV system is also installed on a movable traversing system to provide variable positioning, horizontally and vertically. Four particle

<p>| Table 1 Dimensions of tested deck and blade |</p>
<table>
<thead>
<tr>
<th>symbol</th>
<th>dimension</th>
<th>symbol</th>
<th>dimension</th>
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</thead>
<tbody>
<tr>
<td>$D_d$</td>
<td>0.69 m</td>
<td>$L_b$</td>
<td>0.43 m</td>
</tr>
<tr>
<td>$L_d$</td>
<td>1.27 m</td>
<td>$V_{\text{max}}$</td>
<td>87 m/s</td>
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<tr>
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<td>$\omega$</td>
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<tr>
<td>$Z$</td>
<td>0.10 m</td>
<td>$R$</td>
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Fig. 1 Schematic diagram of tested mower deck
generators were installed under the test table to supply seeding for the LDV test.

A grass feeding system was designed and constructed in the laboratory for experimental observations of grass cutting performance by using a high-speed video camera. The speed of the main conveyor belt system can be adjusted via an electronic variable-speed digital motor controller in the range from 0 m/s to 15 m/s. The data obtained during this experiment were collected and saved in the data acquisition system.

2.1 LDV system and seeding

A 1980 TSI model LDV system was used to measure the velocities inside the housing. The LDV system consists of several pieces of equipment, including a laser source, optic system (beam splitter, focusing lens, collecting lens, bragg cell and photo multiplier tube), signal processor, and a data processor. The LDV system used in this experiment has one component and a dual beam mode system, powered by a 30 mW maximum output He-Ne ion laser. There are three types of scattered light collection: back scatter, forward scatter, and off-axis. The forward scatter method was chosen in this study to increase intensity.

The LDV measures the velocity of particles traversing the measured volume, but not the air molecules, so seeding of the flow field must also be performed. In most air flows, naturally present particles that can generate good signals are not sufficient in number. Hence, there is a need to seed the flow with appropriately sized particles. The optimum seed particles are small enough to follow the flow and large enough to generate a sufficient amount of scattered light.

One problem with using the laser velocimetry in flows containing regions of high vorticity is that the seeding particles will not precisely follow the trajectories of fluid elements because they tend to spin out from the measuring section due to the centrifugal effects. Another problem is that the deck model has clearance between the housing and the test table. Therefore, the particles used should be harmless to humans. Measurements were performed by supplying atomized water droplets from an ultrasonic nozzle. Water droplets are continuously supplied from four nozzles installed under the test table.

2.2 Grass feeding system

The grass feeding system has been designed to utilize a free standing conveyor belt along with several sets of portable rollers. The central components of the grass feeding system are a free standing conveyor belt driven by a three horsepower electric motor, and several sets of portable rollers. The running motor with 1,750 rpm, 230 VAC and 12.5 A input is used for speed control of the conveyor belt. The system is able to cut a 1.37 m wide and 13.5 m long section of sod in approximately seven seconds. This system is an invaluable tool for the validation of a theoretical model currently being developed.

This conveyor system is powered by an electrical motor in conjunction with an electrical control box, which was provided with the conveyor unit. A Rockwell Automation SP 500 AC variable speed controller was selected based on the motor size ratings and the minimum speed required. This system can provide more power than that needed to convey the desired amount of sod at the pre-determined speed. The maximum cutting speed of actual mower is 2.22 m/s and average cutting speed is 1.33 m/s. The grass feeding speed can be controlled by the motor speed controller. If the grass feeding speed is determined then the rpm of the motor can be set by the equation:

\[
\text{rpm of motor} = 327.4 \times \text{grass feeding speed (km/h)}
\] (1)

In addition, an adjustable height mower deck mounting platform was attached to the frame of the conveyor system at 1.2 m from the end of the grass feeding system. The mower deck support assembly, which uses a three-sided angle iron frame, firmly holds the mower deck above the belt of the conveyor system. The front side of the mower deck support is opened so that the support frames would not affect the grass being fed into the blades. The running motor is also installed in the grass feeding system with vertical adjustable support frames.

2.3 Safety fence guard and automatic cut-off switch

The purpose of the safety fence was to protect the operators from flying objects, which might be drawn into the high velocity rotating blades. Another requirement was to have a power cut-off switch installed in case the fence was opened during mower operation.

For the construction of the safety fence, square steel pipes of 6 m long with 0.025 m x 0.025 m, and expanded metal sheets were used. According to the measurements of the dimensions of the conveyor belt system, the metal pipes and the metal sheets were cut and welded. Two side fences and two front fences were constructed. Hinges were mounted on the corner of the fence in order to put them together and to be easy to take the four fences apart. One of the front fences was used for an open-close door. This fence makes contact with the electric cut-off switch since it was installed on the corner of the welded side fence. The motor control box, designed with a magnetic starter and overload relay, was also connected to the
safety power switch and positioned outside of the safety fence guard. Figure 2 shows the final set up view of the safety fence with lawn mower experimental facilities.

2.4 Slip ring

The slip ring is a device used to measure the strain rate of a localized position on the mower blade. It consists of three main parts: the slip ring itself, the brushes, and the transducer.

A strain gauge is mounted on the surface of the mower blade in the location where the strain rate readings are desired. A short length of wire is connected from the gauge to the slip ring in such a way that the wire will not bind up on anything when the blade is rotating. From there, the two stationery brushes are mounted on both sides of the slip ring being careful that the metal contacts of the brushes are in contact with the slip ring and that the brushes will not interfere with the rotating blade. The wires are mounted on the brushes in a way that avoids interference between the rotating blade and a transducer readout. Figure 3 shows the final set up view of the slip ring with mower blade.

2.5 High-speed video camera

The flow patterns were observed by using a high-speed video camera. A high-speed video taping method offers valuable insight into the global flow patterns within the mower deck and is useful to compare the performance of different blades.

The NAC color High Speed Video HSV-1000 FPS camera V-054 was used. The camera has the ability to record up to 14 minutes of high speed motion at 1,000 frames per second on a standard color Super-VHS cassette. For added versatility the system is easily switched to monochrome operation for those times when a black and white image is more appropriate. The complete system consists of a video tape recorder (VCR), a video monitor mounted on an integral card, and the HSV-1000 color camera. An easy-to-use, hand held keypad controls all record and playback functions. The camera also has record and playback controls on its rear panel. The recording speed is adjustable at either 500 or 1,000 frames per second with variable shutter speeds to help capture sharper pictures. After the taping session is over, the footage can be played back at any speed or slowed to a still position through a rotary control for a frame by frame analysis.

2.6 Sound level meter

Noise levels were measured with a Bruel & Kjaer Precision Sound Level Meter Type 2203 for two different cases, one without blades, the second with blades. The sound level meter was calibrated by using the sound level calibrator Type 4230 before each measurement. This calibrates the meter at 1,000 Hz (+2.5%) and thus is independent of the weighting networks. After calibration it is possible to perform sound level measurements to an accuracy of ±0.3 dB with the Precision Sound Level Meter Type 2203. The influence of static pressure is very small, thus the calibration signal is virtually independent of barometric pressure or altitude, for ordinary use. The calibration may also be regarded as independent of temperature for most applications.

3. Experimental Procedure

Figure 4 shows the schematic diagram of the tested blade model. The blade has a deep attack angle at the tip of the blade. Twelve cross sections shown in Fig. 5 were chosen to collect data. Axial velocities were also measured at two different axial height positions from the tip of the blade. The height between the mower deck and test table is set to \( H_2/H_1 = 0.529 \). The velocity data obtained from LDV system were processed in the data acquisition system. Some preliminary test runs with the lawn mower were
conducted to determine the proper settings for the data processor, which would be kept constant throughout most of the tests. For each set of test conditions, the test section was positioned to pass through the center of the probe volume and intersect the optical axis within the plane of the intersecting laser beams. The realtime PDF was viewed while the mower was running to assure that the processor settings were appropriate. When it was determined that the mower, processor, and software were all functioning properly, and adjusted correctly, a sample of 8 000 data points was taken and stored. These data were later analyzed and displayed as a probability distribution function (PDF) histogram and a table of available statistics for each set of test conditions.

3.1 Velocity measurement

The results of the LVD tests provide a means of observing the velocity profiles for both the tangential and axial airflow directions at certain locations in the mower deck. From the velocity profiles, general observations can be made for airflow patterns. From these observations, explanations for the flow patterns can be assumed and validated with the high-speed camera tests or further LDV testing. Favorable airflow patterns can be replicated and improved with further LDV testing, while unfavorable air flow patterns can be eliminated.

The 12 sections were evenly divided throughout the mower deck, with four sections per each blade region. In each section, 15~22 points at 0.001 m increments along the blade from the tip to the center of rotation were measured. Both the tangential and axial velocities were measured at each point. For the experiments using the LDV system, several methods were employed. Since the LDV measures the particles that move along with the air flow, different particles were considered for use in the experiment. Atomized water-droplet particles projecting from four ultrasonic nozzles were mainly used as a LDV seeding during the test.

For the first testing, the deck height (the clearance between mower deck and test table) is set at 0.064 m \( (H_2/H_1=0.577) \) since this is the average height of actual mower deck usage on the field.

At a fixed mower height of 0.064 m, the LDV system will allow to change the section height of measuring points from a reference point. This reference point is located at the tip of the blade (zero reference point) and this height was increased to measure different layers of flow velocities. The section heights from the zero reference point are set as 0.025 m \( (z/Z=0.25) \), and 0.035 m \( (z/Z=0.35) \). Each mean tangential and axial velocity values given came from 8 000 different values per interval.

3.2 High-speed video camera test

Video taping was performed at several different angles of view throughout the deck. The high-speed camera recorded the motion under the mower deck at a recording speed of 500 frames per second. The video produced by the high-speed camera also was used to identify trouble locations under the mower deck that would most benefit from the redesign. Three different tests were performed with the high-speed video camera. The first video taping performed was the Confetti Test. The camera was placed at several different positions on the deck while small paper clippings were fed into the mower deck. The particle flow of the paper clippings was observed as they traveled around the path inside the deck and were discharged through the outlet of the mower deck.

In addition, 0.04 m strings were attached on the inner wall of the deck during high-speed video taping. The purpose of using Tuft Test was to observe the unpredictable flow patterns inside the deck housing. Suction, blowing, and turbulence are the main flow characteristics that need to be controlled for designing a good performance mower deck. Figure 6 shows the partial view of Tuft Test used in this experiment.

The third video taping was performed with 1.2 m \times 1.2 m sections of actual grass on plywood. Four rollers were used with the conveyor belt grass feeding system, so that all sod pieces could be cut in sequence while rolling them in at the proper height to be accepted by the conveyor belt. A few different cam-

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battery-powered precision instrument for use with resistive strain gages and will accept full, half, or quarter-bridge inputs, and all required bridge completion components for 120 Ω and 350 Ω bridges are provided. The quarter-bridge is used in current measurements. The P-3500 will accept gage factors of 0.500 to 9.900, and gage factor is settable to an accuracy of 0.001 by a ten-turn potentiometer. Digital display unit displays Gage factor. The strain gage used in this study has a gage factor of $2.10 \pm 1.0\%$.

Each point is tested three times and strain value is recorded directly from digital strain display unit. The average of these strains was then calculated, thus allowing one to obtain the strain. Figure 7 displays the positions where the strain gages were to be installed.

### 4. Experimental Uncertainty

If it is assumed that the LDV system is measuring on a real doppler burst. The error in the counter measurement of time is 0.25% at 20 MHz. The digital data system uses 10 binary bits, for approximately 0.25% accuracy. The beam angle was measured by TSI and specified to 0.1%. The total error of a doppler burst measurement is therefore approximately 0.6%, an extremely small value.

There is also some influence of velocity bias on the measurement. Velocity bias occurs because more high-velocity particles go through the measurement volume than low-velocity particles. The data sets were screened at standard deviations, and only about 0.4% of the data points were rejected out of 8000 in the experiments.

The source of error with the greatest potential for causing uncertainty is the measurement of noise instead of doppler bursts. The system and counter setup were checked so that no-particle-seeding corresponded to a zero data rate. It was also found useful to block the beam and make sure that the data rate went to zero. Generally, measurements made on noise fall considerably from doppler burst measurements. The LDV data confirm that there is little problem with bad, noise-based measurements in the current data.

The 632.8 nm laser line was used for both tangential and axial velocity components. The components were measured independently. Seed particles of ultrasonic nozzle (~20 μm diameter) were added to the fluid to provide acceptable data rates. Six thousand data points were taken at each position to determine the local mean velocity. Between 1000 and 10,000 data points were averaged, and it was discovered that results were independent for sample sizes over 4000 data points.
Another error was introduced by the uncertainty of the traversing mechanism. The traversal resolution in the three directions was ±0.2 μm with a placement precision of 0.5 mm/m.

For strain gage measurements, the transverse sensitivity of strain gage is 0.40% at 24°C and 50% relative humidity (RH). The resistance of strain gage is 120.4 ± 0.4 Ω and gage factor is 2.10 ± 1.0%. The digital strain indicator, Measurements Group Model P-3500, has ±0.05% reading ±3μ accuracy for 2.10 gage factor. Calibration of the P-3500 is accomplished using the Measurements Group Model 1550A Strain Indicator Calibrator. Since the Calibrator is specified to an accuracy of ±0.02%, the tolerances outlined in the calibration are reduced to ±0.03% to guarantee published accuracy of the P-3500[11]. The total error of a strain gage test is approximately 1.03%, and very small value.

5. Numerical Model

The numerical method used for this research is the three-dimensional finite volume difference (FVD) method with a QUICK[17] scheme for discretization of convection-diffusion terms and SIMPLEC[18] for pressure computations. The turbulence model employed for the computations is the standard k-ε with the wall-function model for the wall boundary conditions.

Two computational models have been developed and combined with the computational code to better describe the aerodynamics of lawn mowers. First, two-dimensional blade shapes at several arbitrary radial sections were selected for flow computations around the blade model. Each cross section of the blade, drawn with CAD software, was modeled for the flow computations. These blade cross sections were transported into the CFD code and computed for flow behavior analyses. Second, a three-dimensional full deck model was developed with three blades rotating simultaneously in a single computational domain. The comparison and analysis of experimental study was performed with the three-dimensional CFD modeling results. The test time and cost can be considerably reduced by employing the CFD technology since the prediction of the flow patterns can be obtained in a short period of time.

The details of the numerical modeling are given in Chon and Amano[19].

5.1 Two-dimensional model

One of the advantages of using a two-dimensional blade model is that the local flow behavior and the effect of the blade geometry perimeters on the entire flow characteristics near the blade can be observed more easily than with three-dimensional models. Moreover, two-dimensional models are less complicated and require less CPU time than three-dimensional approaches. Therefore, it was decided to start with a two-dimensional model to get some insight before moving on to three-dimensional models.

Half of the blade was analyzed since the mower blade is symmetrically the same on both sides around the rotating shaft. One side of the blade was sectioned into 18 slices of 0.001 m increments starting from 0.003 m radius. These 18 sections of the mower blade were viewed in two-dimensional. Several blade section shapes were modified to investigate the effect of blade angle and shape differences.

With the blade spinning at 3 850 rpm the tip of the blade is moving at 87 m/s. In this manner the inlet velocity conditions were evaluated based on the rotational speed at each radial section.

\[ V_{inlet} (m/s) = \frac{2 \pi \omega r}{60} \]

Before making the numerical computations, it is required to generate the correct geometry of the model and the reasonable grids. A rectangular face with a dimension of 0.205 × 0.13 m was added around the cross section view of the blade and allowed the blade to be located at the center of the rectangle. In this study, the Tri-grid type was applied for the mesh generation. Several different grid numbers were tested for velocity, static pressure, and turbulence and it was observed that the variations of these variables become less than 0.1% for Tri-grids greater than 9 000. The total grid number varies from 11 000 to 12 000 grid cells for two-dimensional computations. The final grid example is shown in Fig. 8.

The upper and lower sides of the rectangle outside of the blade, and the geometry of the blade cross section were defined as walls. Velocity inlet was used for the inlet boundary condition and static pressure inlet was used for the outlet boundary condition.

The flow is assumed incompressible due to its low Mach number condition (Ma < 0.2). This process of data input includes defining physical constants such as the density of air, set at 1.177 kg/m³, and the viscosity of air at 1.846 × 10⁻⁵ N·s/m².

The first six sections from the blade center were

![Fig. 8 Final grid of two-dimensional model at section 18](image-url)
Fig. 9 View of modified blade features for section 18 blunt on the front and rear side. This is the first portion of the mower blade that does not have a cutting. The section 18 \( r = 0.21 \, \text{m} \) was modified in changing the attack angle of the blade. The view of modified blade sections is shown in Fig. 9. The angle was modified 7° higher than original blade angle and computational results are compared.

5.2 Three-dimensional model

In this phase of study, the entire mower deck housing was adopted so that the real deck housing shape could be taken into consideration. The solution domain consisted of both upper and lower parts of the rotating blade in the deck housing. The lower side of the computational domain was extended to the ground. This is the average height of the actual mower deck. Finally, the vanes inside of housing were removed to investigate the air flow pattern only caused by blades. These vanes can be added in future computational study for comparison.

The operational mechanism of this model is that the housing and the ground boundaries are kept stationary and blades are rotating. The final rotating speed of blades was given by \( 3850 \, \text{rpm} \) (403.17 \( \text{rad/s} \)).

The three-spindle discharge type mower is an asymmetric. For this reason a three-dimensional calculation should be done for the entire model deck. The current model allows multiple rotating components in the housing. Hence, computation can be performed on the entire three-spindle deck with the simultaneous rotation of three blades.

The fluid property parameters were set the same as those in the two-dimensional model. The Tri-grid type was applied for the mesh generation. Several different grid numbers were tested for the computation and it was observed that the variations of variables become less than 0.1% for grids greater than 220,000. Therefore the total grid number was set to 266,053 grid cells. The housing, blades, and ground area were set as wall boundary conditions where blade walls can be set as a rotating wall. The open area including discharge area and the gap between mower deck and ground were set as static pressure inlet boundary conditions where the direction of flow is not defined. Figure 10 (a) shows the grids for three blades and pressure inlet boundary area.

Computations require approximately 20,000 iterations for the residuals to drop below 0.01% on a SGI Power Challenge Array at NCSA. The fully meshed three-dimensional model is shown in Fig. 10(b).

6. Results

The velocity measurements were taken at several different radial and axial sections inside the deck housing. Laser Doppler Velocimetry testing data provided the magnitude of the air velocity under the mower deck in the tangential \((x)\) and axial \((z)\) directions. This data was used to make inferences about phenomena occurring underneath the mower deck during operation. The LDV data shows that most suction occurs at the rear of the deck causing lower air velocities and at the front of the mower deck air velocity increases with the blade radius as would be expected. The maximum measured velocities are listed in Table 2. The maximum tangential velocities usually occurred at \( r/R = 0.70 ~ 1.35 \) from the center of the rotating shaft and maximum axial velocities usually occurred at \( r/R = 0.76 ~ 0.84 \) from the center of the rotating shaft. This is because the velocities near the housing wall are reduced due to the wall friction. The velocity distributions at each section are not the same due to the fact that air suction varies from location to location.

6.1 Tangential velocity

The measured results for the tangential velocity of the mower deck are shown in Fig. 11 for the front sections and in Fig. 12 for the rear sections. The total length of each test section was based on the physical
Table 2  Maximum tangential and axial velocities (m/s)  
\( (H_0/H_1=0.529) \)

<table>
<thead>
<tr>
<th>Section No.</th>
<th>( z/Z = 0.25 )</th>
<th>( z/Z = 0.35 )</th>
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<tr>
<td></td>
<td>Tangential</td>
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<td>13.6</td>
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Fig. 11  Velocity distributions at the front sections, \( (T: \) tangential, \( A: \) axial velocity) \( H_0/H_1=0.529 \)

Fig. 12  Velocity distributions at the rear sections, \( (T: \) tangential, \( A: \) axial velocity) \( H_0/H_1=0.529 \)

The maximum tangential velocity of 17.2 m/s for \( z/Z = 0.25 \) and 16.5 m/s for \( z/Z = 0.35 \) with \( H_0/H_1=0.529 \).

From these observations, explanations for the flow patterns can be validated with the high-speed camera tests. Favorable airflow patterns can be replicated and improved with further LDV testing, while unfavorable air flow patterns can be eliminated. The remainder of this section describes the velocity profiles determined by the LDV tests and includes possible reasons for both favorable and unfavorable patterns.

From the results obtained by the LDV system for the tangential velocity profile, it shows a nonlinear relationship between velocity values and the location along the blade. Overall, the velocity values increase when moving away from center of the blade as expected at the front sections of the mower deck. There are some exceptions of this behavior such as sections 1, 9, and 10 of which the velocity increases and then decreases near the perimeter of the deck. This behavior might be a result of the shape of the deck at sections 1, 9, and 10 where the air near the perimeter does not have a clear path and collides with the housing curve, which decreases its velocity. Another exception is section 5 near the discharge area, where the velocity decreases near the middle of the blade before increasing again to a maximum. This might be caused by the discharge effect where the pressure is much lower than other sections inside the housing. Sections 3 and 6 have a consistent velocity increase throughout. At the rear sections of the mower deck,
almost an opposite behavior is shown where the velocity is unpredictable and inconsistent.

Most of these sections show either decreasing or constant velocity values near the perimeter of the deck. This could be the effect of the strong suction of air at the back, which collides with the moving air inside the housing and causes it to slow down. The curved shape of the back of the housing could cause this velocity behavior, in which more collisions of air and housing walls occur. There appears to be some air collisions from opposite directions caused by the different blade rotations in some sections. An example of this air collision is seen in sections 2 and 9, and sections 4 and 11. The average magnitudes of velocities at the front sections (11.125 m/s) are higher than the rear sections (9.285 m/s). This is a favorable behavior since most of the grass cutting take place at the front sections and must be removed at the discharge area quickly to maintain high cutting performance. The overall velocity behavior inside the housing is very similar for the measurement section height of 0.025 m (z/Z = 0.25) and 0.035 m (z/Z = 0.35). This height is the distance between the crossing of the laser and the end tip of the blade.

6.2 Axial velocity

Figures 11 and 12 also represent the axial velocity distributions for front and rear sections. The results for the velocities in the axial direction quite closely follow the data trends found for the tangential direction. The maximum axial velocity at the front sections is 9.64 m/s for z/Z = 0.25 and 9.85 m/s for z/Z = 0.35 with Hb/Hf = 0.529 within this distance range. The maximum axial velocity at the rear sections is 10.8 m/s for z/Z = 0.25 and 10.15 m/s for z/Z = 0.35 with Hb/Hf = 0.529.

The average axial velocity is lower than that of tangential velocity in all 12 sections. The rear sections 8, 9, 10, 11, and 12 of the deck experience the same downward trend in velocity magnitudes as occurs in the tangential direction. This also could be the effect of the strong suction of air at the rear, which collides with the moving air inside the housing and causes it to slow down. In most sections except sections 2, 11, and 12, the velocity increases from the center of the blades to the perimeter of the mower deck. This trend is beneficial in that the higher upward velocities occur near the perimeter causing the lift of the grass before it is cut. This flow pattern improves the efficiency of the mulching effect. Any grass that does not get cut by the first sweep of the blade has the potential to get cut in the following blade paths because they are stretched upward by the lift under the deck. Sections 2 and 4 experience a dip in velocities near the blade shafts due to interfering air from the other blades.

6.3 High-speed video taping

The high-speed video is an important tool, which helps us visualize the motion of airflow inside the mower deck. Three different tests were performed with the high-speed camera. Different camera angles were taken for each time the test was run.

The high-speed camera test can tell us that the geometry of the housing needs to be modified. There is some particle scattering inside of the deck, and some particles are thrown out of the front side of the deck. The high-speed video camera clearly shows the overall flow pattern of the grass clippings. In the front of the deck some grass is blown out because the velocities are fast. These sections would most benefit by any redesign done to the mower deck or blades.

6.3.1 Confetti test When observing the results, the majority of the confetti particles where being ejected from the discharge area of the deck, while others were forced out of the front side. Few of the particles where rotating inside of the housing deck. This would suggest that the confetti pieces are not being pulled fully upward into the deck housing or possibly that the speed of the flow going towards the discharge is somewhat lower. The confetti was fed from the rear side due to the large amount of suction. The lower pull forces on the front side caused the confetti particles to be ejected from the front. The sudden change of direction of particles was due to the sudden decline of velocity of air particles inside the housing deck.

The peak in cutting section at the front center of the housing is owed to the central cutter. The cutter at the center makes the particles to bump on to the wall of the front housing, instead of helping it to go out to the left side discharge area. It is also observed that another particle crash is occurring at the front wall near the discharge area.

6.3.2 Tuft test To implement the tuft test, numerous black strings were attached on the inner wall of the housing in a radial direction. The tuft test shows that the suction is mainly occurring on the rear side and left side of the deck. And it also shows that the air was partially coming out from the left side of front deck. The platform strings indicate the air at the front side is moving from left to right and at the rear side is moving from the right to the left side of the deck. A few of strings attached on the platform is moving very unstably or aligning against the rotation of the blade. This is most likely due to the wake flow caused by the other blade rotation. All tuft tests are also recorded by the high-speed video camera.

6.3.3 Sod test Each patch of sod was carefully placed on the conveyor belt and fed under the
housing in order for grass to be cut by the rotating blades. Before cutting, shreds of white paper were placed on the sod to provide better visual flow patterns. The high-speed video camera was set up to several different view locations. The experiments with sod showed that the majority of the grass particles were being ejected from the discharge in the deck immediately after being cut. The high-speed video shows that less grass clippings make it around to the backside of the mower deck and continue to travel around the housing. And also it shows that the grass clipping are crashing at the front center wall of housing as shown in Confetti Test. The force behind the blade allows some of the grass clippings to circulate around a few times in the deck.

6.4 Noise test results

The noise test was conducted at the same time. A sound level meter was used to measure the intensity of noise coming out of the mower deck with and without the blades. Higher noise levels of its readings were anticipated in the center blade axis because of the mixing action of flows between two blades in both sides, therefore a proportional relationship was assumed between noise level and turbulence. Tests were also done with the blades removed from the system to distinguish the amount of noise being produced by just the blades alone. The noise of the mower deck without the blades was relatively high ranging from 94.2 dB to 97.2 dB. With the blades attached, the noise ranged from 106.3 dB to 109.2 dB. The loud noise can affect the airflow pattern inside the deck and lead to inaccurate results, besides causing turbulent air flow. Table 3 shows the data for noise intensity at different mower locations, and noise differences are relatively small.

There was an increase of about 11.6 dB with the blades attached.

6.5 Strain gage test results

Table 4 shows the results of strain gage tests. Based on the results, it is clear that the greatest stresses occurred on the center blade. In addition, the location of these stresses on the center blade occurred in strain gages 1, 2, 4, 6, 7, and 8 with gage 8 reading a maximum strain of 2658.53μ. The results for the left and right blades, displayed much lower values of stress, and both yielded similar results, based on the average total stress for both blades.

It is interesting to note that the strain for both the left and right blades had a maximum at gage 6, which was located at the bottom surface of each blade. At this location, the strain gage is at the trailing edge, whereas the maximum for the center blade (gage 8, bottom surface) occurred in the center of the blade. This illustrates that the strain was not perfectly symmetrical across each of the blades.

As can be seen from the results, the center blade had the highest stresses, possibly due to the rotational effects of the left and right blades. When observing the results, it was noticed that the mower blades were subjected to fluctuating strains and stresses. Therefore, the fatigue strength of the material should be of concern. If the mower blades were run for a period of time, the blades would most likely fail at a stress level lower than the static material strength.

6.6 Two-dimensional computation results

Figures 13 and 14 show the comparison of different blade angles. Overall changing to a higher angle does not produce a better flow. The higher velocities are also further back from the cutting edge as well. This section of blade has a velocity of 84 m/s, which causes considerable turbulence than the high angle mid sections of the blade.

From the inspection of velocity vector results, velocity vectors are relatively uniform in the flow field except at the bottom of the blade. There is a small vortex flow at the middle of the bottom surface.
caused by the flow separation at the sharp edge of the blade. At the trailing area of the blade, the velocity is nearly zero. It can be observed from Fig. 13(b) that the larger vortex flow occurs at the bottom of the blade. This vortex makes strong downward velocity at the bottom of the blade edge. When comparing the original and high angle velocities, the focus of the large velocities changes considerably. By giving the section another 7° up angle, it is shown large turbulence differences as well. The high angle section figure shows pronounced wake turbulence on the end tip. The maximum velocities are 167.91 m/s with original design and 190.69 m/s with higher attack angle blade design. In two-dimensional models, high pressure occurred at the upper side of each blade cross section and low pressure occurred at the bottom of each blade. From the inspection of these results, it can be seen that the highest pressure level is occurred at the front edge of the blade. Two-dimensional turbulent results shows that the region of the tail of the blade has the highest turbulent kinetic energy level since the large difference of velocity values between the upside and the trailing area of the blade cause unstable flow pattern. The modified blade also has much higher turbulent kinetic energy. With this high angle, the turbulence will react with the deck-boundary and could cause considerable noise.

6.7 Three-dimensional computation results
The total velocity vectors on three different horizontal planes are shown in Fig. 15. Figure 15(a) shows the velocity vectors above the blade plane. It shows that several small swirling flows occur around blades. This type of swirling flow was also observed in the high-speed camera test on the deck ceiling. It also clearly shows the discharge direction of air at the discharge area, and complicate flow patterns at the area between two blades. And there is a strong crash at the center wall of the front side deck. However, most of the air flows smoothly from left to right at the front side of the housing, and from right to left at the rear side of the housing.

Figure 15(b) shows the velocity vectors on the horizontal plane through the blade. The maximum total velocity is 88.8 m/s near the blade tip. The complicated flows are occurring at the regions between the two blades. Figure 15(c) shows that small swirling is also occurring at the region around blade of left side below the blade plane. This phenomenon matches with the tuft test in which small swirling spots appeared at the left side blade area. It also shows that air suction occurs most in the area on the rear and left sides of the deck. This was also confirmed in the high-speed camera test. Inlet velocities around the rear and left sides of the housing wall become higher when blades pass that region. It also shows that the air is coming into the deck when the blade is passing around the front side deck region.

The contour of the absolute static pressure on one
of the horizontal planes is shown in Fig. 16(a). The plane corresponds to the vertical location at the blade plane. The level of the pressure above the blade plane is generally higher than the region below the blade plane. The area of the center blade has a higher pressure level than the left or right blade regions in all different horizontal planes. The figure also shows that the highest pressure point appears at the front of the rotating blades and the lowest point occurs around the tip of the blades. Also it is noted that the pressure level is generally lower around the front of deck area at the plane above blade, and higher at the plane below the blade. However, the difference between the maximum and minimum values is relatively small.

The contour of turbulent kinetic energy level on the one of horizontal planes is shown in Fig. 16(b). The region of the mower center blade has higher turbulent energy levels since the flows in left and right side blade cause to crash each other around center blade area. These results are matched well with strain gage test results. In the area around the tip of the blade the level of the turbulent kinetic energy is higher than in the rest of the region for all three blades. The front of the deck area has relatively lower turbulent kinetic energy than that of the rear side of the mower deck. This result is also matched well with the noise test results. Figure also shows that turbulence energy level in the right side of the housing is lower than that in the left side of the housing since discharge area makes smooth air flow pattern. However, the difference between the maximum and minimum values for the turbulent kinetic energy level is relatively small. This observation also corresponds to the noise test and strain gage test results.

6.8 Comparison between computations and experiments

Figure 17 shows the velocity comparison between computational and experimental results at several radial positions at sections 5 and 7. In this figure, it is noted that, computational and experimental velocity patterns agree well except some of positions. The experimental values seem to be of higher magnitude than the computational values. The rationalization behind such activity rests in the computation code properties. Most of computational code produces instantaneous outputs, such as the value of tangential and axial velocities at one particular instant of time. On the other hand, the LDV measurements used for the experiment receive total velocity data relating to the vector sum of all three directional components. In effect, the experimental data tends to see a higher velocity profile in regions of highly mixed flow.
7. Conclusions

Through this study, the experimental and computational results have provided a better understanding of the velocity patterns at each section and inside the mower deck generated during the operation. Hence an optimum design of mower blade can be found in consideration of the relation between better performance and lower turbulent energy.

The computational calculations of the blade for the three-spindle type mower deck clearly show the flow pattern and other flow characteristics around the blade cross sections. These results also can be used for future blade modifications or new design developments.

The use of a LDV system and a high-speed video along with the use of CFD code has given an opportunity to verify computational flows with visual experimental results. The experimental results have provided a good picture of what the velocity patterns at each section and inside the mower deck look like.

The LDV test results show velocity magnitudes throughout the mower deck in both tangential and axial directions. The LDV data showed the air velocities in both the azimuth and axial directions allowing useful airflow diagrams to be made. LDV test data were validated by high-speed video tapings under several different test conditions. Some sections have been found to have lower than average velocities. Front inner sections (sections 2, 4 and 5) of the mower deck has the most dynamic flow results compared with other sections. This is due to the interacting action of the flows approaching from each deck compartment patterns caused by the three co-rotating blades. This phenomenon was also observed by the high-speed video testing. Section 3 of the mower deck appears to have more smooth velocity pattern. To minimize the instability of the velocity, several modifications of housing and blade design are required in the future study.

Computational model calculations agree well with the experimental results. The difference of several velocities between computational and experimental results seems to occur by the simplification of the deck design for computation. This computation method can provide a method of determining optimum values for critical design parameters before experimental validation for many other complicated rotating machinery designs.

Observations with the high-speed video taping strain gage test and noise test give the opportunity for visual verification and comparison with the LDV test. This information can be used in future designs of both mower decks and blades to achieve more desirable flow patterns.

Based on the above discussion following conclusions emerged:
1. The computational results agree fairly well with the experimentally obtained results.
2. The highest stresses were found in the center blade. This is due to the rotational effects of the moving blades on each side. The obtained data showed reasonable inconsistency with the computations. However, the greatest strain was usually found on the top surface of the blade.
3. The housing has a peak shape at the center of housing, where according to the movement of the grass clipping, is not being efficient. Modification of the housing with better curve shape design at the front housing area is recommended to make the grass particles flow smoothly.
4. The results of two-dimensional analysis show that the effects of changing the angle of the blade depend upon the velocity as well as the pressure and the turbulence around the blade. These models produced blade designs that have a higher average velocity and higher surface pressure than the current design. This could possibly be adapted to future designs that would improve the performance of the blade.

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