High Efficiency LED Module with 3D Bending Machine

Chung-Yi Lin[1], Jian-Shian Lin[2] , Tung-Cheng Pan[2],Yao-Chi Peng[2], Cheng-Hao Ko[1], Rong-Mou Hong[3]
[1] Graduate Institute of Automation and Control, National Taiwan University of Science and Technology
[2] Mechanical and Systems Research Laboratories, Industrial Technology Research Institute
[3]Department of Electronic Engineering Ching Yun University
E-mail: JohnnyLin@itri.org.tw

Abstract - Abstract- In this paper, a bending machine for tuning optical design of LED module is proposed. The tuning is done by changing the bending angles of each package on a given module with the help of automatic control program. Luminous intensity distribution can be controlled by adjusting the light emission path, which in turn can be implemented as changing the bending angles of individual LED packages on the module. The proposed machine is capable of bending packages to specified angles with errors less than 0.1°. Three-dimensional light distribution for bent package LED modules is also studied based on various application scenarios so that each scenario can have diversified luminous intensity distribution resulting in higher uniformity and better luminance quality. The machine has several advantages, including quick bending, high accuracy, and great customizability. These advantages make the machine meet the requirements of automatic mold forming.

Keywords: stampings, bending angles, lighting, LED,optical mold, optical design

I. INTRODUCTION

A good luminance optical design not only improves the uniformity of lighting, but also raises luminance efficiency. As a result, it is very important to have a design that provides diversified luminous intensity distributions so that requirements from different usage scenarios can be met. An LED module is used as light source in the experiments. Luminous intensity distributions of this module are adjusted by changing the bending angles of individual LED packages on the module. Fine tuning the angles eventually leads to a combination of luminous intensity distributions with maximum uniformity.

During the adjustment of LED package bending angles, any slight angle error of the light source can result in changing luminous intensity distribution and uniformity of lamination. Manual bending imposes higher errors, greater variances, slowness, and therefore unsatisfactory for fast and precise shaping. To improve bending accuracy and to shorten tuning time, an automated bending machine is proposed to overcome the drawbacks of manual bending. The machine successfully improves bending accuracy and helps

Tuning the LED module to achieve high luminance uniformity and diversified luminous intensity distributions.

The automated bending machine consists of technologies from mechanics, automated control, and optical design and integrates them all together. Integration includes servo control techniques like feed forward control[1], adaptive control[2][3], and fuzzy control based on neural networks[4][5][6], along with user interface design, communication between control system and mechanical devices, and LED lighting optical design[7].

II. DESIGN

The main concept of the multi-angle bending machine is that users can input commands through a computer-based user interface, and the commands are passed over to the control system which coordinates all the machinery to execute the commands and to provide desired outcome. Fig 1 illustrates this concept.

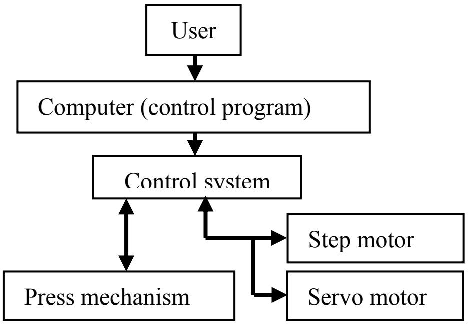


Fig 1. Design concept of bending machine

Fig 2 is the schematic of automated LED package bending machine. Users input commands through control panel, and these commands specify bending parameters and operation processes. The commands are transmitted to a control box consisting of controller hardware/software/firmware. The controller cards inside control box convert processed digital signals into analog to individually drive press mechanism (I), stampings mechanism (II), upper and lower mold base, and X-Y table (III). The mechanisms are driven according to the order specified by input commands. In the following sections, discussions of these mechanisms will be provided in the order of press mechanism, stampings mechanism, X-Y table movement, and integration of these mechanisms for package bending.

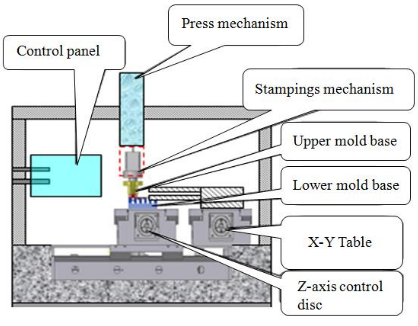


Fig 2. Schematic of automated LED package bending machine

A. Press mechanism

In the following, internal details of the bending machines are described starting from press mechanism. Fig 3 and 4 are operation flow chart and system schematic of press mechanism, respectively. The operation of press mechanism starts with converting gas pressure to oil pressure of stampings. Stampings driven by oil pressure steadily press down, and pressing speed onto LED package wire frame is adjusted through throttle valves. In a more detailed view, electromagnetic valve EV(A) compresses air into pneumatic-hydraulic converter when it is powered on. The oil-pressure piston is quickly driven down and pushes mold base into designated position. Electromagnetic valve EV(B) is powered on through delayed timer control, pushes the air-pressure piston to drive booster ram into oil cylinder. The increased oil pressure in oil cylinder generates pushing power for stampings and the target package wire frame is bent. Powering off both valves makes both the oil and gas cylinder back to their original position, and then air pressure pulls back the stampings, completing the press operation.

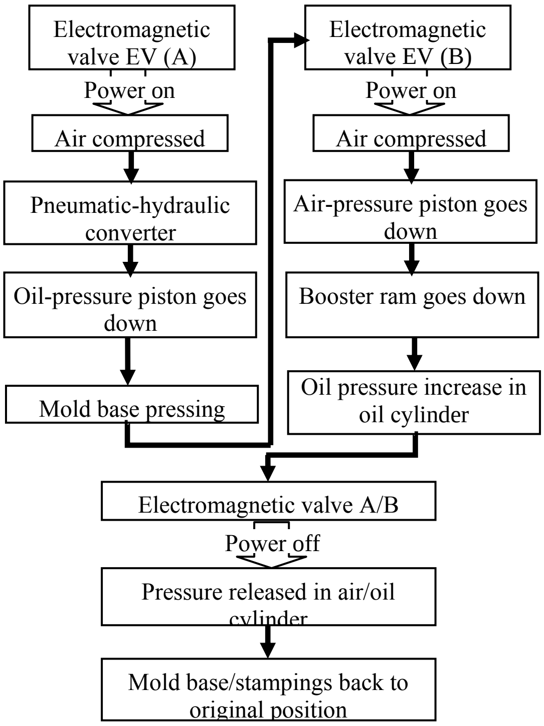


Fig 3. Press mechanism operation flow chart

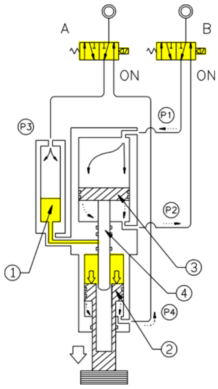


Fig 4. Schematic of press mechanism

B. Stampings mechanism

Stampings are controlled via step motors. A step motor consists of a fixed stator (permanent magnet) and a movable rotor (electromagnet). The stator and rotor form an internal gear, and the gap between them is typically filled with air bearings or ball bearings. The internal coils of step motor have two phases. Operation voltages for each phase are presented in equations shown below.

$$V_1 = R_1 \times i_1 + \frac{d\lambda_1}{dt} \tag{1}$$

$$V_2 = R_2 \times i_2 + \frac{d\lambda_2}{dt} \tag{2}$$

Equation 1 corresponds to phase 1 coil, and Equation 2 is for phase 2 coil. In both equations, V denotes voltage, i denotes current, R denotes resistance, λ denotes linked flux, and $\frac{d\lambda}{dt}$ denotes linked flux variation rate. Controlling the coil current for both phases of coil generates electromagnetic field so that rotor is pushed by magnetic force against stator, making stepping, positioning, and movement of stampings possible.

The design of press mechanism must take into account that the bending directions and angles can be different for each individual package on the module. In order to meet this requirement, mechanisms of rotating bending directions and altering bending angles are needed. In this paper, rotation of bending directions is defined as α-axis, and bending angle change is defined as β-axis. Bending angle changes along β-axis is mainly controlled by the step motor driving punch. Once the punch angle is set, rotation positioning along α-axis can be done and therefore bending directions can be controlled. Rotation in α-axis is controlled by a separate step motor, which chains another motor driving stamping and mold base simultaneously through timing belt. Fig 5 and 6 illustrate the work flow and schematics, respectively. Fig 7 demonstrates the internal design of stampings about how to control punch angles using step motors. Fig 8 is the complete design schematic of the stampings, and it shows the placement of wire frame sample as well as upper and lower mold base. Photo of the actual machine is shown in Fig 9.

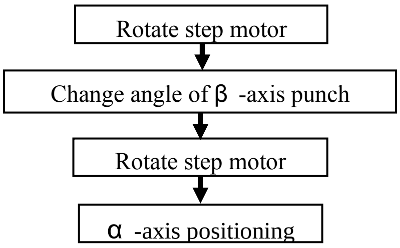


Fig 5. Positioning and rotation flow during pressing

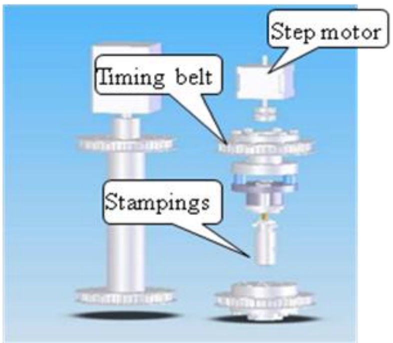


Fig 6. Positioning and rotation system schematic

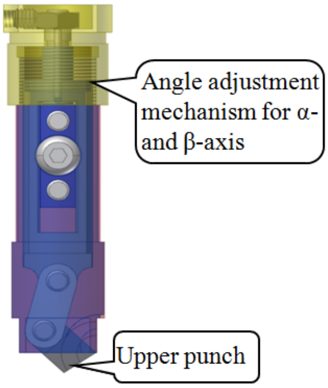


Fig 7. Stampings design schematic

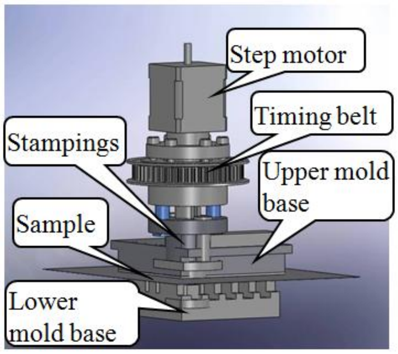


Fig 8. Stampings system schematic

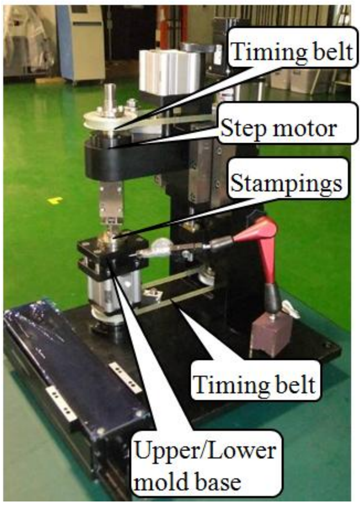


Fig 9. Photo of the actual machine

C. X-Y table

The design of sample stage X-Y table is detailed below. Two servo motors are used in X-Y table for positioning control. Lower mold base is installed on the stage, and a sample is placed onto mold base. X-Y table is responsible for positioning selected package into designated location. In bending process, selection of package on wire frame requires X-, Y-, and Z-axis movement. X-Y table transports and shifts the wire frame on X-Y plane, and the upper and lower mold bases are pressed or released via air cylinders. The schematic design and photo of X-Y table are shown in Fig 10 and 11, respectively. As seen in photo, X- and Y-axis each have their own servo motor controlling the movement.

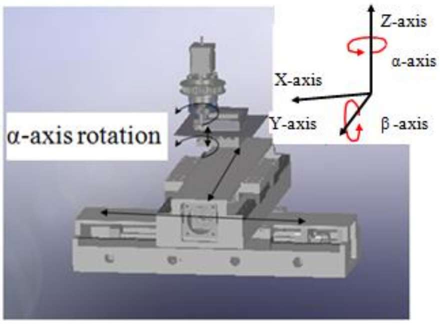


Fig 10. X-Y table schematic

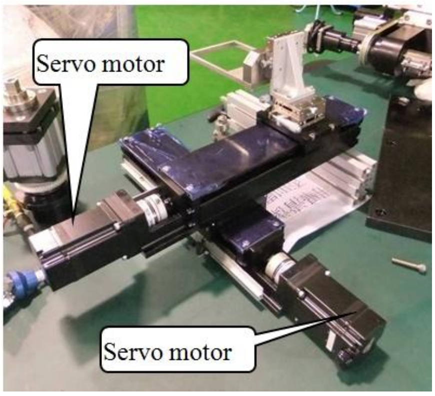


Fig 11. Photo of X-Y table

Major components of multi-angle bending machine include X- and Y-axis servo motor control, compression forming system, automated control, central programmable control, machine frames and enclosures. Module to be processed is positioned first, then parameters for all axes are set and the system starts the shaping process. Shaping is done in a fully automated and customized fashion. The operation process is shown in Fig 12. Fig 13 is the photo of the machine.

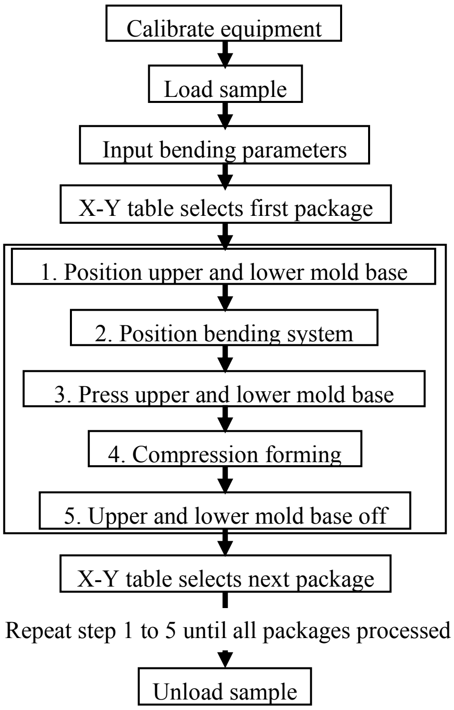


Fig 12. Bending machine operation process

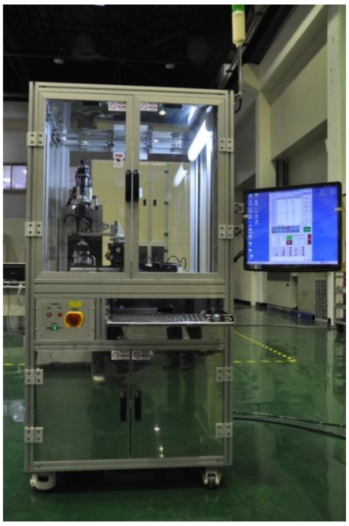


Fig 13. Photo of multi-angle bending machine

III. EXPERIMENTS

Experiments are conducted to test whether the actual bending angles produced by the machine meet user specifications. The sample chosen for experiment is LED light cup wire frame, since the motivation of developing this machine is to perform angle shaping on LED light cup wire frame so that customized optical designs of the module can be realized. The testing sample has a dimension of 100mm by 100mm and consists of 25 packages, where each package has different bending angles, as shown in Fig 14. Fig 15 is the LED wire frame module processed by bending machine. Optical control is carried out by changing the angles of θ and φ. Fig 16 shows the photo of LED package taken from sideways demonstrating angle φ.

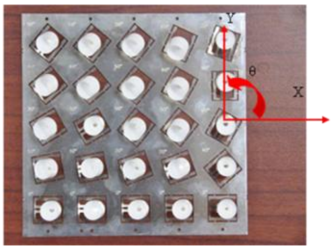


Fig 14. LED wire frame module

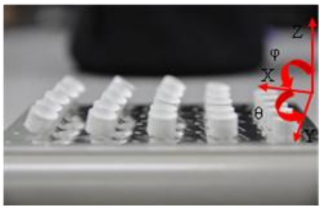


Fig 15. LED wire frame module with bent packages

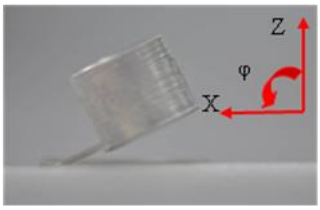


Fig 16. Bending of a single LED package

Since the LED wire frame module consists of 25 differently angled individual packages, each package needs to be measured separately. The measurement is done by an optical microscope calibrated with level instruments. Bent light cup is fixed on sample platform of optical microscope, and the Z-direction sideways photo is taken via CCD sensor, positioning with the assistance of cross cursor. The photo is analyzed with angle measurement equipment to obtain measured angles and to calculate corresponding error. The process is repeated ten times for both left and right bending angles for mean values. Right bending angles range from 5° to 30° with a stepping of 5° as shown in Fig 17. Left bending angles range from -5° to -30° with a stepping of -5° as shown in Fig 19. Results of the measurements are less than ±0.1 degree.

Trend charts for errors are shown in Fig 18 and 20, where the horizontal axis is the bending angle of light cup and the vertical axis denotes mean error of the given bending angle. As shown in the charts, average error of bending angles is roughly 0.04 and the trend curves show a zigzag pattern. The zigzag pattern is likely resulted from mechanical errors of the bending machine. Nevertheless, the error values, which are always lower than 0.1°, indicate the high accuracy of this automated multi-angle bending machine and its readiness for applications in lighting fixtures that demand high uniformity.

The completion time of bending an LED light cup wire frame module is 90 seconds. Divided by 25 individual packages, each light cup takes 3.6 seconds to bend, meeting the requirements of fast bending and shaping.

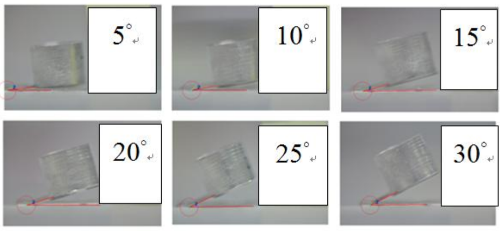


Fig 17. Right bending angles

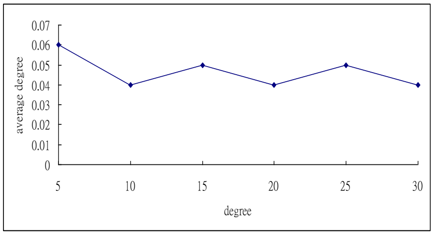


Fig 18. Error trend chart of right bending angles

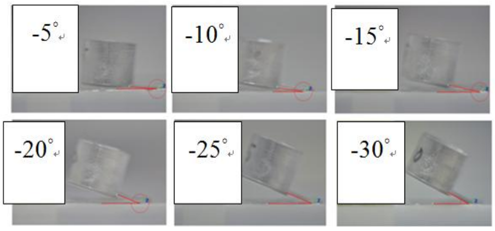


Fig 19. Left bending angles

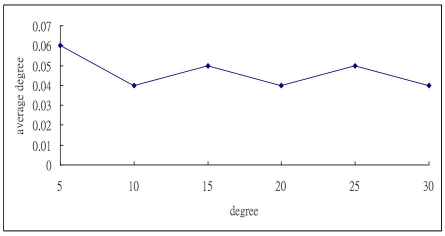


Fig 20. Error trend chart of left bending angles

IV. OPTICAL EXPERIMENTS AND ANALYSIS OF MEASURED RESULTS

The bending angles produced by the bending machine have very high accuracy. As a result, the machine is leveraged for making modules with high luminance efficiency and diversified light distribution curve. The optical properties of these modules are further analyzed and discussed. The LED modules used in the experiments are a pair of 5-by-5 LED light cup modules for symmetric light distributions. Light distributions are measured via light intensity instrument as shown in Fig 21. Light source to be measured is installed on a rotatable platform. Spinning the platform, CCD sensors of the instrument can measure light intensity of the light source from all angles. The computer software accompanying this equipment converts raw data into light intensity curve.

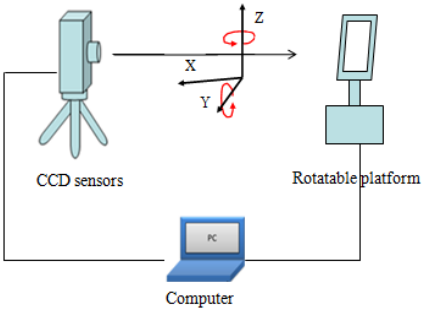


Fig 21. Light intensity measuring instrument

Light intensity curves for unbent LED modules are shown in Fig 22. The horizontal axis denotes light source angle, and the vertical axis denotes light intensity (unit: cd/k lm). Red and blue curves respectively denotes tangent of 0° to 180° and 90° to 270° in three-dimensional spatial light intensity distributions. Both curves peak at 0° because the light cups are not bent and all lightings are centered, resulting weaker surrounding light intensity. Rotation angles of unbent LED modules are shown in Fig 23. Z-axis rotation angle θ denotes built-in rotation angles of the LED modules, and Y-axis rotation angle φ denotes bent angle produced by bending machine.

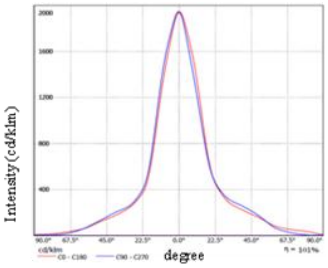
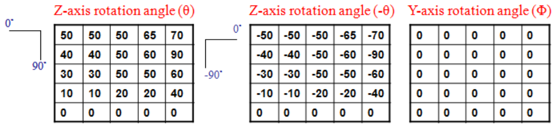


Fig 22. Light intensity curves of unbent LED module



Z-axis rotation angle (θ)

50	50	50	65	70
40	40	50	60	90
30	30	50	50	60
10	10	20	20	40
0	0	0	0	0

Z-axis rotation angle (-θ)

-50	-50	-50	-65	-70
-40	-40	-50	-60	-90
-30	-30	-50	-50	-60
-10	-10	-20	-20	-40
0	0	0	0	0

Y-axis rotation angle (Φ)

0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0

Fig 23. Angles of unbent LED module

The relationship between luminance and light intensity is illustrated in Fig 24. E denotes the luminance of the observation plane, and D denotes the perpendicular distance between light source and observation plane. θ denotes light source angle from the observation point. Since the goal is to have uniform luminance across the plane, luminance at observation point perpendicular to light source shall be the same as the point with angle θ, inducing Equation 3. For a given light source angle θ, the light intensity required is solved as Equation 4, which indicates direct proportional relationship between angle and light intensity. However, the angle must be smaller than 60° for all directions to avoid glaring.

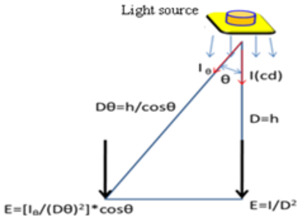


Fig 24. Relationship between luminance and light intensity

$$\frac{I}{D^2} = \left[\frac{I_\theta}{(D\theta)^2}\right] \times \cos\theta \qquad (3)$$

$$I_\theta = \frac{I}{\cos^3\theta} \qquad (4)$$

Based on the constraint, the resulting high luminance efficiency light distribution is shown in Fig 25. The horizontal axis denotes light source angle, and the vertical axis denotes light intensity (unit: cd/k lm). Red and blue curves respectively denotes tangent of 0° to 180° and 90° to 270° in three-dimensional spatial light intensity distributions. The blue curve has two peaks around 50°, which are designed to improve the uniformity of luminance distribution. The red curve has only one peak in 30°, and the reason for this design is to provide directional lighting when light source is placed on the edge of observation plane, therefore only one-sided luminance distribution is needed. In Fig 26, Z-axis rotation angle θ denotes built-in rotation angles of the LED modules, and Y-axis rotation angle φ denotes bent angle produced by bending machine, showing the mapping between luminance distribution curve and bending angles.

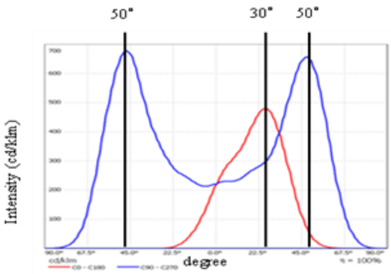
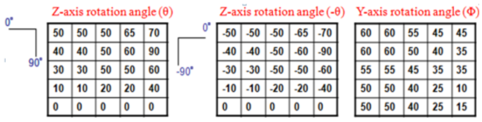


Fig 25. Light intensity curves of bent LED module



Z-axis rotation angle (θ)

50	50	50	65	70
40	40	50	60	90
30	30	50	50	60
10	10	20	20	40
0	0	0	0	0

Z-axis rotation angle (-θ)

-50	-50	-50	-65	-70
-40	-40	-50	-60	-90
-30	-30	-50	-50	-60
-10	-10	-20	-20	-40
0	0	0	0	0

Y-axis rotation angle (Φ)

60	60	55	45	45
60	60	50	40	35
55	55	45	35	35
50	50	40	25	10
50	50	40	25	15

Fig 26. Angles of bent LED module

The light intensity measurement results from unbent and bent LED modules are imported into DIALux simulation software. The scenario chosen for simulation is aerial road lighting and the LED modules are used as street lamps for a 16-meter wide two-lane road. The lamps are cross spread on both sides of the road and any two lamps on the same side have a distance of 24 meters. Simulation results for unbent and bent LED modules are shown in Fig 27. For unbent modules, light concentrates in the area right below the light source, shown as circular patterns with red center area denoting high light intensity. Areas between two light sources are purple, which means low luminance. Using unbent LED modules as light sources provides insufficient and uneven lighting. On the other hand, areas between two bent LED modules are mostly yellow green, indicating a more even luminance and solving the problem of unbent LED modules. In summary, LED modules processed via the automatic bending machine provide not only higher efficiency and better uniformity for luminance, but also decent results for diversified light distributions.

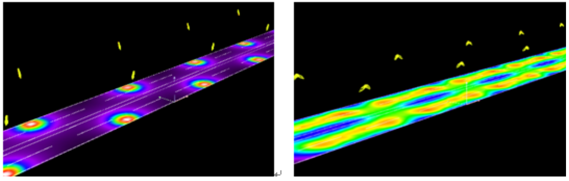


Fig 27. Luminance uniformity of unbent (left) and bent (right) LED modules

V.CONCLUSION

The automated bending machine integrates various technologies from optics, mechanics, and electronics. It has a good user interface that provides decent usability. As of control, the automated bending machine is programmable and provides high accuracy. The bending process is fast, which is advantageous for shaping. LED modules can also benefit from automated bending machine because different light distribution can be easily produced and tested.

Based on iterated experiments and verifications, errors of bending angle provided from automated bending machine are always less than 0.1°, indicating high accuracy of this equipment.

Speed is a critical factor for automated machines. Experiments show that automated bending machine can process a 25-cup LED module within 90 seconds, i.e. 3.6 seconds per LED light cup bending. This is very fast compared to manual labor.

The automated bending machine is capable of realizing customized optical designs for LED modules, which provide high luminance efficiency and diversified three-dimensional light distributions. The proposed optical design fully leverages every single LED light source, increases lighting quality, and offers better luminance efficiency.

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