Development of a 3D-printed device evaluating the aerodynamic performance of rotary wings

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Abstract

Applications for remotely operated rotary wing aerial vehicles, hereafter referred to as drones, are rapidly expanding in scope and such aircraft may soon become an integral part of everyday life as well as a source of innovation. However, it is quite difficult to improve drone flight performance and reduce development costs because performance optimization depends strongly on the intended application. As a result, drones are currently developed by trial and error using various rotary wing shapes. In this study, a device for evaluating the aerodynamic performance of rotary wings is proposed. We consider it likely that our proposed device will be useful for various drone-related applications in addition to facilitating drone development because it is inexpensive to produce and can eliminate the need for large expensive laboratory equipment such as wind tunnels when performing flight characteristic evaluations. In this paper, we report on the fabrication of our 3D general fused deposition modeling (FDM) printed device along with some experimental results.

Keywords : FDM 3D printer, Rotary wing, Aerodynamic performance, Taketombo, Drone

1. Introduction

Remotely operated rotary wing aerial vehicles, hereafter referred to as drones, are currently being used for a variety of purposes such as geographical surveys, disaster prevention surveillance, and large equipment inspections, as well as logistic deliveries to isolated points. Furthermore, the use of such devices is expanding to include infrastructure inspections and other roles (Nonami 2017; Keeney 2015). However, various difficulties arise when researchers attempt to improve drone flight characteristics and restrain development costs.

One reason is the difficulty of repurposing a drone that was developed for a specific function to another role. In other words, a general-purpose design method for drones has not yet been established. Another reason is the difficulty in acquiring information needed for aerodynamic performance evaluations of rotary wings. For example, it is difficult to estimate the lift and drag acting on a rotary wing with different Reynolds numbers or/and different airfoil sections. This is because rotor quality assessments require large experimental devices and the associated measurement processes require the services of persons skilled in operating such equipment.

For these reasons, drone airframes are currently manufactured by trial and error using various rotary wing shapes (Brandt and Selig 2011; Shetty and Selig 2011), which increases development costs and becomes a factor preventing the expansion of drones into other practical uses.

In this paper, we report on the development of a device that is capable of both improving drone performance and reducing related development costs. Our proposed device makes it possible to evaluate the flight characteristics of a wide variety of rotary wings used in drones while eliminating the need for testing in large experiment equipment such as wind tunnels. For instance, easy evaluation of the aerodynamic forces on the rotary wing makes the process of searching a rotary wing configuration with a high lift to drag ratio more efficient. Furthermore, fabrication of our device is inexpensive and easy due to the use of 3D general fused deposition modeling (FDM) printing. In the sections

below, we will report on the development of our device along with some experimental results obtained.

2. Conceptual design

2.1 Inspired by a flying toy *taketombo*

Previously, rotary wing aerodynamic performance evaluations have almost always been performed using wind tunnels or similar systems. However, wind tunnel experiments are influenced by the method used to present the rotor being tested, and the reproduction of flight states, as well as the transmission and acquisition of sensor/control data required for drone operation, is difficult when an actual drone is used.

Additionally, since rotor/body interference presents its own problems, it is important to evaluate the performance of a rotor under standalone conditions. Considering these issues, the following three items were established as requirements for the design of aerodynamic ability evaluation equipment.

- (I) It must be possible to grasp the flow around the rotor blade in various flight conditions.
- (II) It must provide repeatability for specific flight conditions.
- (III) It must have fewer restrictions on flight location, and be inexpensive to produce and easy to use.

The requirements of Items (I) and (II) are those for handling various flight conditions. However, if various flight conditions are handled, the requirements in Item (III) are difficult to satisfy, for the reasons already described above.

Therefore, we began our approach to the problem by examining a flying toy *taketombo*, which are popular toy helicopters commonly made from bamboo that consist of rotor blades attached to a simple shaft that forms a vertical axis (for more details, see Ref. (Takato and Shirayama 2012)). However, it is difficult to satisfy the requirements in Item (II) using a human-launched *taketombo* model because air patterns and flight forms are difficult to reproduce when the device is launched via human hands (Yasuda 2008; Yasuda 2016).

For example, in a related study, Yasuda conducted flight experiments using *taketombo* launcher (Yasuda 2016). Reproducibility of the flight path of the *taketombo* is ensured by the launcher proposed in Ref.(Yasuda 2016), but it will be considered that a number of flight conditions could not be achieved with such a simple device. Additionally, since the launcher in Ref. (Yasuda 2016) does not meet the requirements of Item (III), and considering our requirement for a design that also satisfies Item (II), we decided to develop a new launcher that is based primarily on preceding research(Takato and Shirayama 2012). However, it is difficult to confirm whether the requirements of Item (II) were met in this study. Furthermore, the requirements for a design that satisfies the restrictions imposed by Item (III) are difficult to achieve for aerodynamic performance evaluation equipment due to the need to utilize generally available parts, ensure equipment portability and ease of installation (choosing the installation location), ensure safety, and consider environmental factors. Moreover, the flight envelope of the *taketombo* itself becomes a problem.

In order to solve these problems, *taketombo* takeoffs from human hands (hereafter referred to as hand-launched takeoffs) will be analyzed anew. An example of a typical hand-launched *taketombo* flying perpendicular to the takeoff point is shown in Fig. 1

Fig. 1 Schematic diagram of a hand-launching. (i) Grip and rotation start, (ii) Rotation acceleration, (iii) Maximum rotation speed, (iv) Launch.

Axial shaft rotation is produced by the counter movements of the user's two palms, and lift generated is by the rotation of the rotary wing. The generated lift causes the *taketombo* to take flight after the user's palms have separated from the axial shaft. In addition, the operator's arms are often used to add a catapult action to the rotation-induced lift produced by his/her hands, and hand-tilt off the vertical direction can add a horizontal vector to the *taketombo* flight. Although the basics of this flight method are simple, a variety of factors, including the axial rotation method and axial direction, must be considered when attempting high altitude and long-distance flights.

Accordingly, in order to elucidate a conceptual design for a hand-launched takeoff, we began by classifying the operation into four states, as shown below:

- (i) Grasping and rotation start: The axial shaft of *taketombo* is gripped and rotated. The axial component (shaft) remains gripped between the user's palms.
- (ii) Rotation acceleration: The rotational speed of the *taketombo* is increased as the user presses the shaft between his/her two palms and moves his/her hands in opposite directions.
- (iii) Maximum rotation speed: As shown in the figure, rotation acceleration is completed when the axial shaft begins to separate from the bottom palm of one hand and the fingertips of the opposite hand.
- (iv) Release: The axial shaft is fully released. (Sometimes release may occur at the end of (iii) above.)

Next, it was necessary to create a mechanism for mimicking a hand-launched takeoff, in addition to adding a catapult action to items (i) to (iv). Consideration must also be given to cases of forward or backward movement. The result is five required mechanisms: axial shaft grasping, axial shaft rotation, axial shaft release, axial shaft inclination, and catapult action. In this paper, imitation of catapult action and axial inclination were set aside for future study and attention was focused on the other three mechanisms.

2.2 Grasp and rotation

The imitation of hand-launched axial grasping and axial rotation was attempted first.

As shown in Fig. 1, *taketombo* axial shaft grasping is carried out by placing the shaft between the user's palms, and rotation is imparted by palm movements. Fig. 2(a) shows a simplified breakdown of this action. In this figure, the shaft (S) is set between two plates shown by (A) and (B), and then rotated by steady opposing movements of the two plates. Here, the upward movement of the right plate and downward movement of the left plate causes the shaft to rotate in a counterclockwise direction. In order to impart sufficient rotation via this mechanism, high-speed devices such as caterpillar drives or belt sanders would be needed, thus making it difficult to fulfill Item (III) requirements.

The method by which the circular objects of A, B, and C in Fig. 2(b) are pressed against the axial shaft (S) to impart rotation is hereafter referred to as the drive circle. In this method, a minimum of three drive components are needed to produce a stably rotating axial shaft.

Fig. 2 Conceptual diagram of gripping and rotating a shaft

Fig. 2(b) show the fundamental axial shaft grasping and rotating mechanism. On the other hand, when rotating the axial shaft of a *taketombo*, the ratio of the diameter of a driven shaft to the diameter of a drive circle must be taken into

consideration. In order to stably grasp the driven axial shaft and to transmit sufficient torque to the shaft for inducing the rotation speed, it is necessary to increase the diameter of the drive circle in comparison with the driven shaft.

More specifically, when grasping with three drive circles of the same diameter D , D becomes $D = 3d/(2\sqrt{3} - 3)$ if the diameter of a driven shaft is set to d . This formula about D can be obtained using the condition that three drive circles on the same plane contact each other and the driven shaft contact to the three drive circles. In the case of four drive circles, $D = d/(\sqrt{2} - 1)$. Thus, the size of the determined drive circle restrains the design. Note that drive circles exist in three dimensions, as seen in the conceptual diagram shown in Fig. 3.

In this figure, we can see how it becomes possible to grasp and rotate the axial shaft of a *taketombo* using three drive circles. However, since the stiffness of a *taketombo*'s bamboo axes is low, if excessive grasping power is used, the axial shaft will be bent, as seen in the dashed line (S') of Fig. 3(b). Accordingly, it is appropriate to set two drive circles to serve as a pair so that they can grasp and rotate the axial shaft as one set. Fig. 4 shows two drive circle sets arranged in 3-dimensional space, which efficiently allow the driven axial shaft to be grasped and rotated. The figure also shows that distortions to the low rigid axial shaft are suppressed because the two drive circle sets (labeled $\alpha 1$, $\alpha 2$ and $\beta 1$, $\beta 2$) face each other.

Fig. 3 Gripping and rotating shaft with three disks arranged in 3-dimensional space

Fig. 4 Shaft grasping by four driving circles arranged in 3-dimensional space

2.3 Conceptual construction of an open mechanism

2.3.1 Proposal A

In addition to grasping the shaft and rotating the shaft as discussed in section 2.2, an opening action is required due to the separation of the driving circles from the driven shaft, as described in operation state (iii) of section 2.1. The conceptual design for achieving mechanical takeoff of this research consists of three mechanisms, axial shaft grasping, axial shaft rotation, and axial shaft release. In the field including industrial robots, objective research into grasping and release has been conducted over the course of numerous years (Chen 1982; Lee 1988). In addition, there have also been many rotation-only mechanisms reported in this field. However, few studies combine continuous movements including gripping, rotation, and release. Of course, *taketombo* launchers, which have been little studied, have had no research on these continuous movements.

For example, in Tsuneya et al. (Tsuneya and Tsutsumi 1992), the driving motor axis and driven *taketombo* axial shaft are arranged and connected in a straight line, while in Yasuda (Yasuda 2016), in which grasping was imitated, the rotation was produced by a falling weight. In both studies, it was thought that launchers would not be designed to imitate human actions. Moreover, the stability and repeatability of action provided by the open mechanism of the driving and driven shafts resulted in problems.

For these reasons, as shown in Fig.5, a method of separating the four drive circles from the bamboo axial shaft at the shortest straight line distance was studied. In addition, based on the method shown in Fig.6, a prototype launcher was fabricated (Takato and Shirayama 2012; Takato and Shirayama 2013). In this method, each of the four drive circles is equipped with a drive motor and is supported by a large spring. When support provided to the spring is released, a drive circle is separated from a driven shaft, and the axial shaft is released.

When the experimental launcher fabricated in preceding research (Takato and Shirayama 2012; Takato and

Shirayama 2013) is used, a *taketombo* will repeatedly fly in the same manner if the same conditions are used, thereby allowing a flight form to be confirmed. However, this result is dependent on various conditions, such as adequately fixing the mechanism to a heavy platform and ensuring sufficiently high-speed rotation to generate lift. Additionally, the characteristics that govern four motor-driven drive circles results in weight increases due to the fixed launching stand requirement, which also limits portability. Furthermore, since all four motors operate independently, synchronous control is required for each motor. Taken together, these factors make it difficult to produce a launcher that is sufficiently small and inexpensive, which means Proposal A cannot fulfill the Item (III) design requirements.

Fig. 5 Schema of axial shaft release mechanism using linear movements of four disks

Fig. 6 Schema of launching mechanism in Proposal A

2.3.2 Proposal B

In this section, ideas for miniaturization and weight reduction are described. The design requirements for Items (I) and (III) necessitate quality assessment experiments, which include low altitude flights where the objectives are to travel a short distance and arrive on target.

In such cases, a sufficient number of experiments must be carried out to permit statistical analysis. Therefore, in order to satisfy Item (III), a design must ensure experimental implementation ease.

In the case of a device-launched flying object such as a *taketombo*, since the flight path and flight form are both determined at launch time, it is necessary to create different performance trajectories that allow the same object to reach the same target using the same launcher control. When weight conservation and device miniaturization are emphasized in a device based on Proposal A, the large mass of the four motors can result in reactions at the time a mounted motor disengages from the axial shaft, which may vibrate the launcher, and thus affect the launch position. As a result, it becomes theoretically difficult for a Proposal A design to meet Item (II) requirements.

With the above points in mind, this paper focuses on the open mechanism of Proposal B, as shown in Fig. 7. Fig. 7(a) shows a state in which the axial shaft is gripped by the drive circle. The drive circle made up of α - and β -axes is connected with a newly set-up γ -axis. Next, the open status is shown in Fig. 7(b). Here, the position of the γ -axis is fixed and the drive circles of the α - and β -axes rotate in a way that centers on the γ -axis.

Fig. 7 Shaft release mechanism based on rotational motion of four disks

Since the distance from the γ -axis to the drive circle created by the α - and β -axes does not change for this Proposal B model, power transfer can be attained by placing a pulley, gear, or other mechanism between the two axes. As a result, the fixed position of the γ -axis provides a power source that makes it unnecessary to drive the α - and β -axes using a motor, as is called for in Proposal A. This means that, compared with Proposal A, reactions are reduced and vibrations, which were the primary cause of launching errors, can be minimized. Moreover, the synchronous control required for four independent power sources called for in Proposal A are also unnecessary.

After selecting Proposal B to handle the axial shaft grasping, axial shaft rotation, and axial shaft release problems, we then tackled launcher miniaturization and number-of-rotations synchronization.

An overview of a typical launcher is shown in Fig. 8. One motor, shown by (M) in the lowermost part of the Fig. 8, provides a power source that drives four γ -axes via gears (or pulleys). The three drive circles of the α - and β -axes transfer torque from the purple γ -axis gears, causing it to rotate while grasping the axial shaft of the *taketombo*. The four α - and β -axes move in a circular arc around the fixed in position γ -axis while rotating, and then release the *taketombo* axial shaft.

3. Basic design and detail design

3.1 Design of power transfer mechanism and transfer part

First, we examined gears based on Proposal B discussed in subsection 2.3.2.

Power is transferred from M, shown in the lower part of Fig. 8, to the axial shaft of the *taketombo*, shown in the upper part of the same figure. Although, as explained above, the launcher structure of this paper can utilize either a pulley or gear, it was thought that gears were more advantageous in terms of miniaturization, so that usage will be examined hereafter. Nevertheless, it should be noted that the same function is achievable if the effective gear diameter is transposed to the pitch diameter of a pulley.

A breakdown of the γ -axis shown in Fig. 8 is provided in Fig. 9. The gear connected to M is labeled GE_M , while the gear in the lower part of the γ -axis (which engages with GE_M) is labeled GE_1 . The gear connected to the upper part of the γ -axis is labeled GE_2 , while the gear connected to the α -axis and lower part of the β -axis is labeled GE_3 . A tire is used to provide a friction equivalent to a pair of human palms in contact with the *taketombo* axial shaft and is labeled TI_p . As for the size of the gear or tire, the reference diameter of the GE_M motor gear is D_M and the reference circle of the GE_1 gear is D_1 . The standard semi-circle diameter of the GE_2 gear is D_2 and the reference diameter of the GE_3 gear is D_3 . The tire diameter is set to D_p and the axial diameter of the *taketombo* is set to d_b . The motor rotation speed is set at N_M . If the moderating ratio of the motor slowdown gear is set to R_M , then rotation speed N_b of a *taketombo* is shown as $N_b = N_M R_M (D_M/D_1) (D_p/d_b) (D_2/D_3)$. Moreover, when the running torque of a motor is set to T_M , Torque T_b , which drives the *taketombo*, is expressed as $T_b = T_M (N_M/N_b)$. In this case, the final transmission ratio from the motor to the *taketombo* axial shaft serves as N_M/N_b .

(a) Gripping state (b) State after release
Fig. 8 Overview of *taketombo* launching mechanism in Proposal B

Fig. 9 Launching mechanism in Proposal B, focusing on the γ -axis

Table 1 Launcher gear specifications

Part names	Parameter (ratio or diameter)	Number of teeth per gear	Value
Geared motor unit	R_M	---	1/20
GE_M	D_M	24	36[mm]
GE_1	D_1	30	45[mm]
GE_2	D_2	18	27[mm]
GE_3	D_3	18	27[mm]
TI_p	D_p	---	43[mm]
<i>Taketombo</i> shaft	d_b	---	3.5[mm]

A concrete design was produced based on this examination result. The required motor power was estimated with reference to the existing *taketombo* launcher. In our preliminary design, the output performance required to accelerate a

taketombo having a moment of inertia 8.3×10^{-5} [kgm²] to a rotation speed of 3000 [rpm] within 0.3 [s] was set as the target. The rotational energy of 3000 [rpm] (= 314 [rad/s]) was set to about 4 [J]. The minimum value necessary if the *taketombo* is to accelerate from a stopped condition to the target number within 0.3 [s] is 13 [W], so this value was set as a standard in this study and incorporated into the design.

Since a small motor capable of exceeding 10,000 [rpm] was used, the geared motor was combined with a reduction gear. The reduction unit of the geared motor can be chosen from 1/10 to 1/300. An example combined with the gear is shown in Table 1. In this example, a transmission ratio N_M/N_b is set to about 2. Additionally, if exchanged for 1/10 in the reduction gear unit (R_M), the final velocity ratio will be set to about 1. This ratio is close to a direct motor and *taketombo* axial shaft connection and allows the launcher to achieve double the running torque easily with half the rotation speed.

3.2 Example of fabrication

The generally available and inexpensive FDM 3D printer system was used for the fabrication of this device. While ABS resin was selected for most of the components, easily obtainable commercial parts were used for important functions requiring high stiffness levels, such as the hardening processing axis, ball bearing, and metal collar, and components manufactured by 3D printer were used for connections between these purchased parts.

Furthermore, the 3D print gear, in which wear is a problem, was changed from a spur gear to a helical gear, dealt with partial wear. Moreover, gear parts that were deemed susceptible to strength reduction were redesigned and increased in thickness. The erection diagram created with 3D CAD software is shown in Fig. 10 (a). However, auxiliary parts, such as the servo required for a release mechanism, have been omitted. Fig. 10 (b) shows the fully assembled launcher. The total weight of this launcher is 1.6 kg, and the external size is 12 cm x 12 cm x 30 cm.

(a) 3D CAD model

(b) Prototype device using the proposed methodology

Fig. 10 Mechanical launching device

(a) Gripping state

(b) Rotation state

(c) State after release

Fig. 11 *Taketombo* launching sequence using the prototype device

4. Experimental results

The operating state at the time of a launcher is loaded with a *taketombo* made of ABS resin is shown in Fig. 11.

Furthermore, in order to confirm launching accuracy, the arrangement plan at the time of ejection is shown in Fig. 12. In this figure, C1 and C2 indicate the installation positions of the cameras used to record the experiment.

Fig. 13 consists of sequential photographs from C1 taken at the time a *taketombo* is launched, while the sequential photographs from C2 are shown in Fig. 14. As can be seen in Fig. 13, the *taketombo* gains altitude immediately after release. In Fig. 14, it can be seen drifting slightly to the upper right as it climbs (the yellow dashed circles show the *taketombo* position). Finally, as a durability check, approximately 100 consecutive trial launches were conducted in continuous rotation over a period of 2 hours (equivalent to approximately 1000 trial launches), confirming sufficient durability of the device.

We recognize that the reproducibility of the flight path at the same condition is more important than the durability of the device. We tried a few trials and confirmed qualitatively that it may have reproducibility. However, at the present time, the reproducibility cannot be proven since we do not have a flight path measurement system. Our further study is to construct the flight path measurement system and to show the reproducibility of the flight path quantitatively.

Fig. 12 Arrangement of experiment devices

Fig.13 Measurement results from C1

Fig. 14 Measurement results from C2

5. Conclusion

In this paper, we discussed the need for equipment that can facilitate drone development, focusing on launchers that could be used to evaluate the aerodynamics of experimental rotary wings. We then reported on a newly developed device that is capable of imitating the actions of a person at the time launching a *taketombo*. In experiments aimed at imitating the action of a person launching such a device, attention was paid to three mechanisms: axial shaft grasping, axial shaft rotation, and axial shaft release. We began the conceptual design process for our device by determining the best way to imitate each mechanism, after which our focus switched to achieving each mechanism mechanically. Finally a detailed design was produced that took into consideration of the manufacture of component parts fabricated using a 3D FDM printer system.

Once the device was fabricated, *taketombo* launch experiments were conducted, the results of which suggest that our newly fabricated launcher has the ability to launch a *taketombo* correctly towards a low-altitude nearby target. Specifically, we performed 100 consecutive trial launches over a period of 2 hours (equivalent to approximately 1000 trial launches) in order to confirm the durability of the device. From these results, the potential utility of the device was confirmed and it was thought that trial production of the launcher could further facilitate aerodynamic ability evaluation of experimental rotary wings.

Our future work will focus on increasing the amount of statistical data obtained from continuous trial launches and investigating the differences in aerodynamic performance from experiments conducted using two or more rotary wings types.

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