EVALUATION OF DYNAMIC BEHAVIOR OF A DEPLOYABLE WING UAV BY DROP TEST

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Abstract

Aerial deployment technique is required for next-generation airplanes. In this technique, dynamic behavior of an airplane during deployment motion is one of the critical problems. In order to evaluate this, drop test via a balloon was performed for a small unmanned aerial vehicle (UAV) which has a foldable wing. Flight data and motion were analyzed and it became apparent that symmetric deployment motion by a servo & wire type folding method deployable airplane has no large influence on dynamic behavior.

1 Introduction

As aviation technologies advance, higher level of mechanisms for an airplane is required. A deployable wing is one of them. It attracts attention as technology for next-generation airplanes. In past, the deployable wing was mainly applied to get well storing property in the parking. Therefore the wing was deployed on the ground. But recently, a certain type of airplane required aerial deployment motion.

One of such airplanes is an airplane for Mars exploration. The Mars airplane needs large wing area to get enough lift in a low-density atmosphere on Mars. However, the Mars airplane is required to be small from a standpoint of transportation. Therefore the Mars airplane needs deployment mechanisms. In addition, aerial deployment technique is suitable for the Mars airplane because it allows to eliminate a take-off system and to take advantage of the initial altitude. Because of such reasons, several design concepts of the Mars airplane are planned to deploy in the air [1].

However, airplanes may become instability state during such deployment motion. It is mainly caused by two reasons. One is a difference of the lift on the right and left wing. And another is a reaction force of the deployment motion. Impacts of them change by speed and symmetry of the deployment motion.

Objective of this study is to show an availability of the airplane using a lightweight and reliable deployment mechanism for Mars exploration flight. This study deals with a deployable wing airplane as a first simple case of the deployable airplane. This paper presents developed deployable wing airplanes and quantitative evaluation of dynamic behavior during deployment motion at low altitude flight test. In this test, an airplane was ascended via a balloon in a stowed state. Then the airplane was dropped and started deployment motion. Finally, the airplane was reached to steady straight gliding. In these phase, flight data were logged using a flight control module.

2 Design Process of Deployable Airplane

In this section, three representative deployment mechanisms were compared and a suitable mechanism for Mars exploration flight was selected. Next, actuator was selected. Then, basic specification of an experimental airplane was set and required power for the deployment mechanism was estimated. After that, the deployment mechanism was designed and its specification was evaluated through a wind tunnel test.

2.1 Deployment Mechanism Selection

Folding method, inflatable method, and extending method are well known as a deployment mechanism [2-4]. This study deals with these three methods and selects suitable method from these.

Folding method airplane has a hinge on its wing and the wing is folded by the hinge. Figure 1 shows one of the folding airplanes. Folding method has a simple structure, therefore mass is light and reliability is high. However, the main feature of this method is that aerodynamic forces can be used to deployment motion. This fact allows that a deployment actuator becomes lightweight and a risk of aerial deployment reduces. However some additional devices might be required to prevent re-folding the wing by opposite direction aerodynamic force.

In inflatable method, a wing is deployed and keeps its shape using high pressure gas as shown in Fig. 2. Generally, inflatable method has high stowing efficiency and short deploying time. The worst thing about inflatable method is that it needs high pressure gas to withstand bending moment. It increases the risk of gas leakage. Therefore inflatable method sometime needs backup high pressure gas container to refill inner gas. This is one reason the inflatable method is usually heavy.

Figure 3 shows an extending method wing. The extending method realizes an in-flight change of a wing span using nested wings. And it is suitable for a long span wing. However, generally the extending mechanism is heavy due to the complex wing structure. In addition, this method needs a special attention on binding under the aerodynamic force.

Features of each method described above are summarized in table 1. One of the important constraints for using the Mars airplane is to be lightweight. Therefore folding method was selected in this study because it is simple and lightweight.

Fig. 1. Folding Method Airplane. (Photo by Adrian Pingstone)

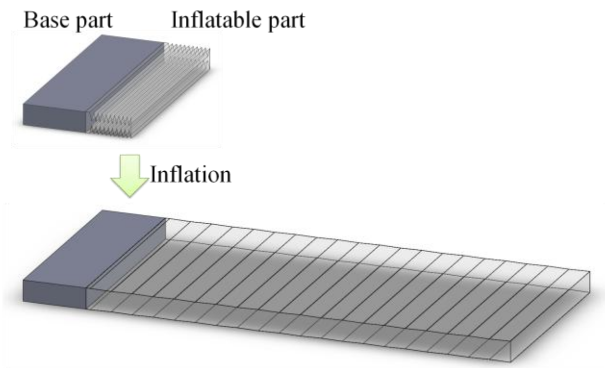


Fig. 2. Schematic Illustration of an Inflatable Method Wing.

Table 1. Features of Deployment Methods.

Deployment method	Advantage	Disadvantage
Folding	Simple structure Lightweight High reliability Deployment assist using aerodynamic force	Low stowing efficiency
Inflating	High stowing efficiency Short deploying time	High pressure Gas leakage Backup container Heavy
Extending	In-flight span change Long span	Complex structure Binding Backlash in joint area

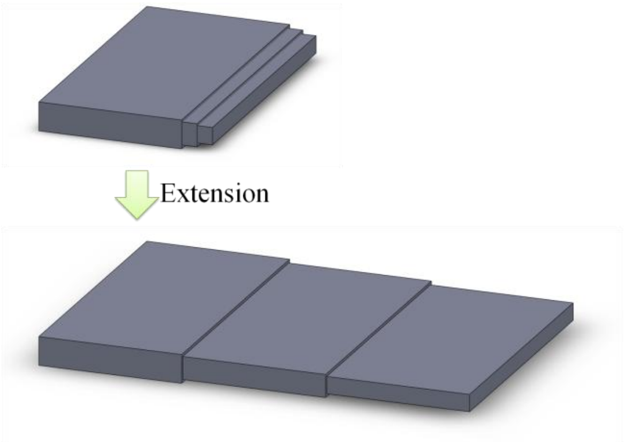


Fig. 3. Schematic Illustration of an Extending Method Wing.

2.2 Actuator Type Selection

Spring hinge type, rubber type, and servo & wire type were considered in this study. Suitable type for the Mars airplane was selected.

Figure 4 shows a spring hinge. The spring hinge has a torsion spring on a hinge axis. Many sizes and strengths of a spring hinge are commercially available. Remarks of the spring hinge are simplicity and lightness. However, a problem is that a deployment torque keeps acting during a stowed condition.

Rubber type uses rubber bands connected across a hinge as shown in Fig. 5. This method can change torque easily by changing the number of the rubber band. This is good for experiment. However, rubber type also has the problem that deployment torque keeps acting during a stowed condition. To make matters worse, a wing structure is complex and the rubber might be degraded by ultraviolet rays and low temperature on Mars.

Servo & wire type has a servomotor in a fuselage and folded wing was pulled like the rubber type using the wire through inside the wing. This type can control deployment timing and speed easily using the servomotor. But a wing structure is complex to pass the wire through the wing. And this type needs an additional control channel for this servo.

Features of each types described above are also summarized in table 2. Rubber type is not suitable for the Mars airplane in view of degradation. This study deals other two types.

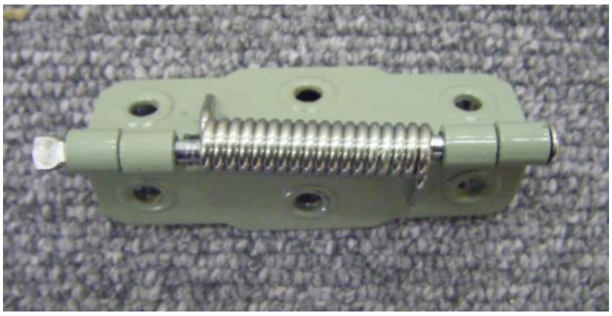


Fig. 4. Spring Hinge.

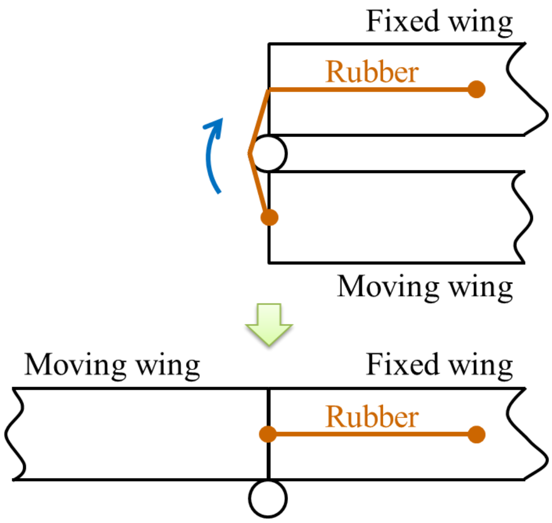


Fig. 5. Schematic Illustration of the Folding Method Wing using a Rubber.

Table 2. Features of Actuator Types.

Actuator type	Advantage	Disadvantage
Spring hinge	Simple Lightweight	Torque keeps acting during stowed configuration
Rubber	Easy torque change	Torque keeps acting during stowed configuration Complex wing structure Degradation
Servo & wire	Speed controllable	Complex wing structure Heavy Additional channel

2.3 Basic Specification of Experimental Airplane

An experimental airplane was developed based on a commercially available model airplane [4]. A mass was 0.9 kg, a span length was 1.2 m, and a chord length was 0.2 m. Moving wings were added to each wing tip. A span length of this moving wing was set to 0.4 m. A cruise velocity and wind velocity were set to 6 m/s and 2 m/s respectively. Therefore a maximum airspeed was estimated at 8 m/s.

2.4 Required Torque

Required deployment torque was estimated from the basic specification of the experimental airplane. Forces which prevent deployment are gravity, lift, and drag. The gravity was calculated assuming that the mass of the deployable wing was 50 g. The lift acts stowing direction when an angle of attack of the moving wing is negative. This force was estimated assuming that lift coefficient was 1.5 as a worst-case condition. On the other hand, the drag acts stowing direction when the angle of attack of the moving wing was near -90 degrees. This force was also estimated assuming that drag coefficient was 1.2, a drag coefficient of a flat plate facing a flow. Figure 6 shows calculated result of the required torque. Obviously the highest force was the lift. Therefore, in this study it was assumed that the required torque was the torque due to the lift.

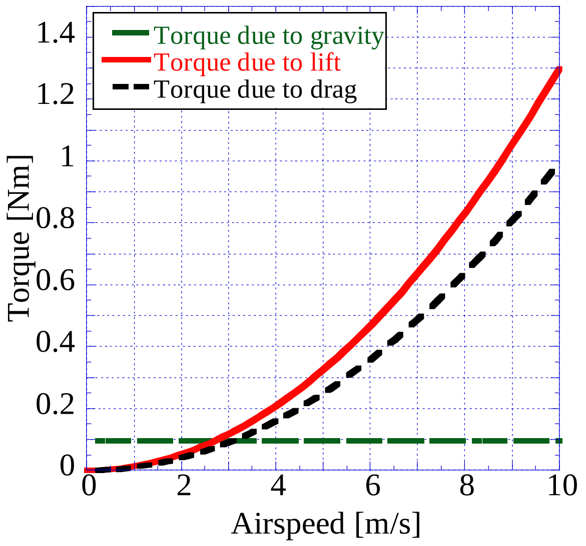


Fig. 6. Required Torque.

2.5 Spring Hinge Selection

A commercially available spring hinge which was suitable for this experimental airplane was selected. Here, a hinge angle was defined as shown in Fig. 7. Figure 8 shows a relationship between the hinge torque and the hinge angle. It follows from Fig. 8 that the hinge torque was 0.6 N·m at a deployed state (i.e. the hinge angle was 180 degrees) and 1.2 N·m at a folded state (i.e. the hinge angle was 360 degrees).

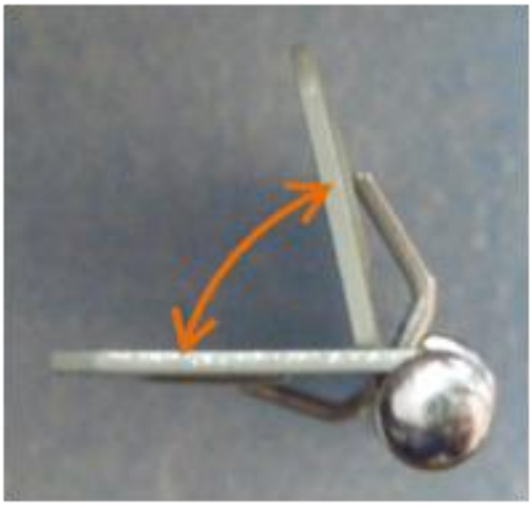


Fig. 7. Hinge Angle.

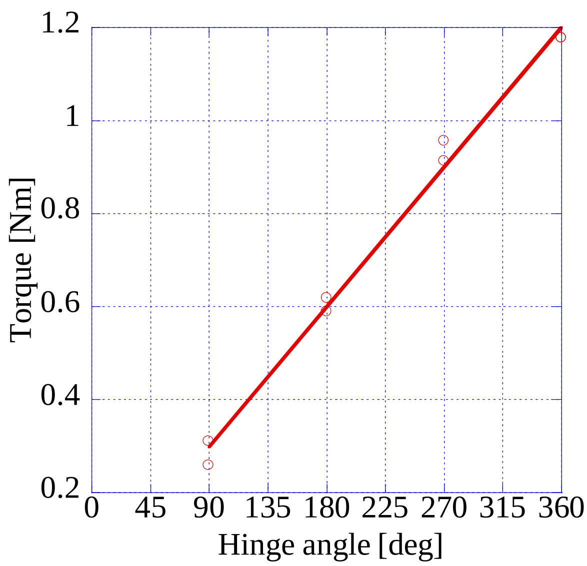


Fig. 8. Relationship between the Hinge Torque and the Hinge Angle.

This result was compared with the required torque as shown in Fig. 9. It suggests that this wing can deploy in any attitude as long as the airspeed is lower than 6.8 m/s.

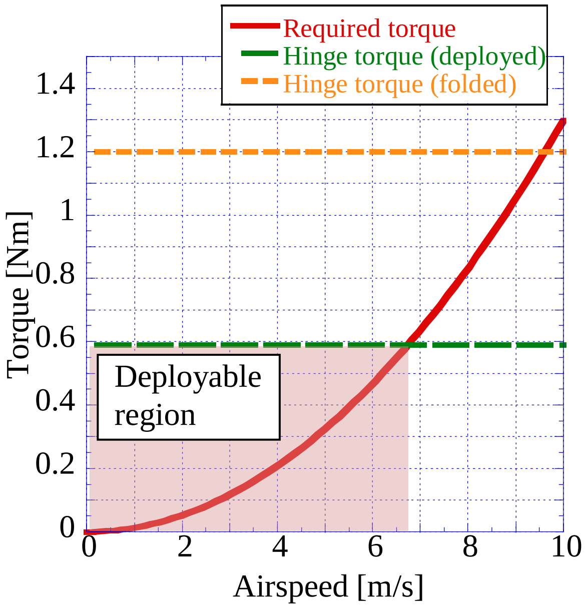


Fig. 9. Deployable Region.

2.6 Wind Tunnel Test

A wind tunnel test was conducted to validate the designed deployable region and to confirm a deployment characteristics. A maximum deployable airspeed for each angle of attack was measured. Figure 10 shows the wind tunnel in Institute of Fluid Science at Tohoku University. This wind tunnel is blow down type. Its nozzle section shape is square 790 mm on a side. A maximum velocity is about 20 m/s.


Fig. 10. Wind Tunnel.

An experimental model is shown in Fig. 11. This airfoil was Clark-Y. A white part was moving wing. Its span and chord length were 0.4 m and 0.2 m respectively. A black part was fixed wing. A spring hinge was attached across the deployment wing and fixed wing.

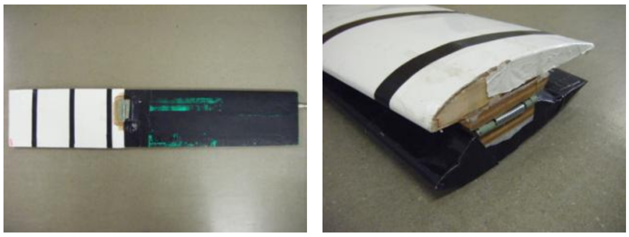

(a) Deployed State. (b) Folded Hinge Section.

Fig. 11. Experimental Model.

Figure 12 shows maximum deployable airspeeds for each angle of attack. The maximum deployable airspeed indicated maximum airspeed of this wind tunnel at the angle of attack of 0 to 15 degrees. It suggests that the wing can deploy at least this airspeed. From a distribution of maximum deployable airspeed, it became clear that a minimum value of the maximum deployable airspeeds was 6.2 m/s. This result is in excellent agreement with the estimated value. Therefore the design method described above was validated. And it was also shown that the maximum deployable airspeed varied greatly depending on the angle of attack. Therefore it was considered to be easy to deploy at actual flight until the angle of attack was positive and low value.

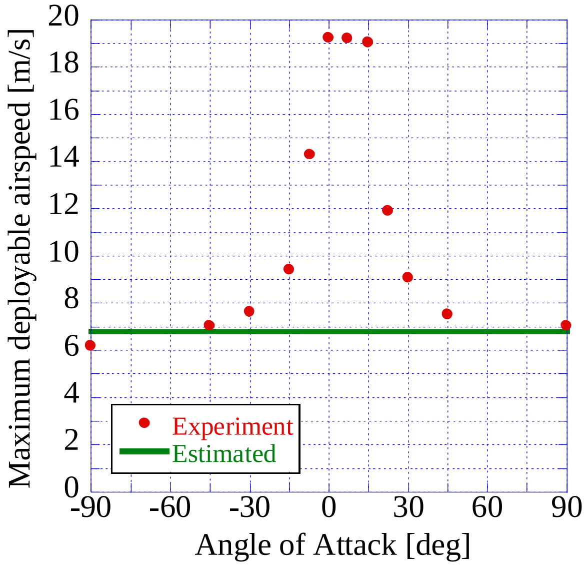


Fig. 12. Maximum Deployable Airspeed for each Angle of Attack.

2.7 Servo & Wire Type

In this study, another concept was also attempt. A main concept of this airplane is to leverage aerodynamic forces. Therefore a weak but lightweight actuator can be used. For comparison, this airplane had a servo & wire type folding wing. Specifications of airplane such as span, chord, and total mass were almost all same to the spring hinge type airplane.

Figure 13 shows a calculated torque characteristic curve of the servo & wire type folding method wing. This characteristic curve depends on a wing structure, wing thickness, strength and position of servo, etc.

Comparison of the required torque and the hinge torque is shown in Fig. 14.

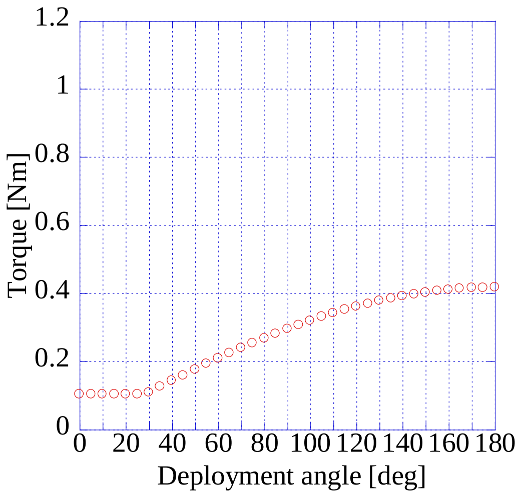


Fig. 13. Torque Characteristic Curve of the Servo & Wire Type Folding Method Wing.

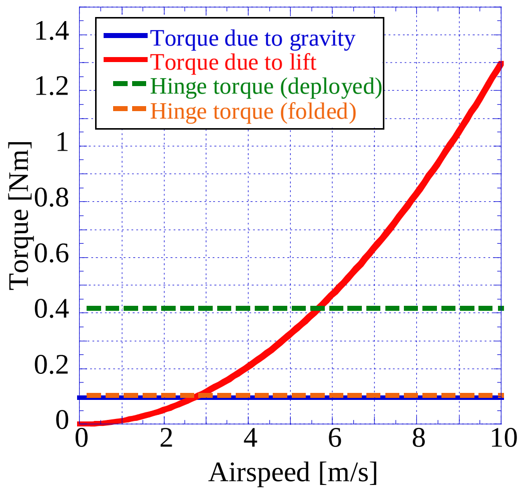


Fig. 14. Comparison of the Required Torque and the Hinge Torque.

From Fig. 14 we can see that the hinge torque in the folded state is near the torque due to the gravity. Therefore this mechanism is hard to deploy without help of the aerodynamic force.

3 Drop Test

To show the effectiveness of developed deployable wings, and to evaluate dynamic behavior during the deployment motion, a drop test was conducted.

3.1 Experimental Procedure

Dynamic behavior during deployment motion was evaluated through the drop test. Figure 15 shows its schematic illustration. In this test, an experimental airplane was ascended to the altitude of some dozen meters by a balloon in the folded state. Next, the airplane was dropped and started deployment motion. Finally, the airplane was reached to steady level flight. From about 1 second before the airplane starts dropping, flight data such as altitude, 2D position coordinate and angular rates of each axis were started logging using a flight control module. And the flight was shot by several video cameras on the ground and the balloon.

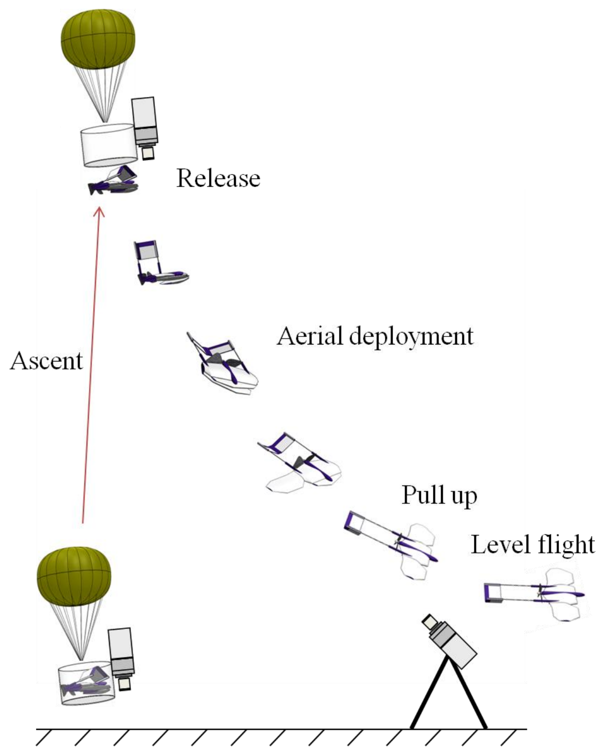
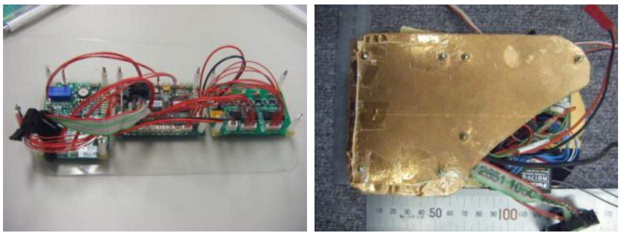


Fig. 15. Schematic Illustration of a Drop Test.

3.2 Measurement system

Flight data was obtained using a commercially-available ultra light flight control module “MAVC1” manufactured by Y's Lab INC. [6]. Figure 16 shows the MAVC1. This module could measure an altitude, azimuth angle, 2D position coordinate, and angular rates of each axis. The altitude was measured by an atmospheric pressure. The azimuth angle was measured by orthogonally placed two magnetometers. The 2D position coordinate was obtained by GPS. The angular rates of each axis were measured by a micro electro mechanical system (MEMS) rate gyro. Measurement time and sampling rate were set to 15 s and 20 Hz, respectively.



(a) Boards. (b) MAVC1 Module.

Fig. 16. MAVC1.

3.3 Equipment

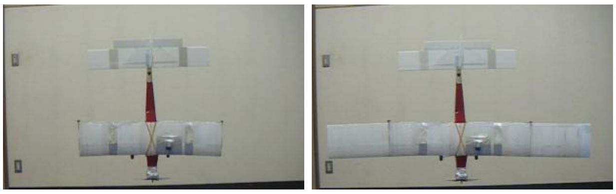
Figure 17 shows the spring hinge type folding method airplane. And this specification is shown in table 3. This specification is a little modified from described above due to the result of a stability analysis. The span became 0.1 m shorter, so the wing can deploy easier. This airplane has two spring hinges on its wing and the airplane can deploy its wing as shown in Fig. 18. Next, figure 19 shows a detail view of a hinge section. The spring hinge was connected to the fixed and moving wings through a mounting stage. This stage was subjected to the impact force of a wing finishing deploying to protect wing structure.

Figure 20 shows the servo & wire type folding method airplane. And this specification is shown in table 4. This specification is near to that of the spring hinge type. This airplane also has two hinges on its wing and the airplane can deploy its wing as shown in Fig. 21. Next, figure 22 shows a detail view of a hinge section. A brown wire was connected to the end face of the moving wing and this wire was pulled using the servo through the inside of the fixed wing.

Fig. 17. Spring Hinge Type Folding Method Airplane.

Table 3. Specification of a Spring Hinge Type Folding Method Airplane.

Mass [kg]		1.6
Length [m]		0.81
Span length [m]	Fixed wing	0.84
	Deployable wing	0.35
Chord length [m]		0.20
Airfoil of main wing		Clark-Y
Dihedral [deg]		10
Airfoil of tail		Flat plate
Horizontal tail area [m^2]		0.11
Vertical tail area [m^2]		0.051
Horizontal tail volume coefficient		0.91
Vertical tail volume coefficient		0.44



(a) Folded. (b) Deployed.

Fig. 18. Deployment of a Spring Hinge Type Wing.

Fig. 19. Detail View of a Hinge Section.

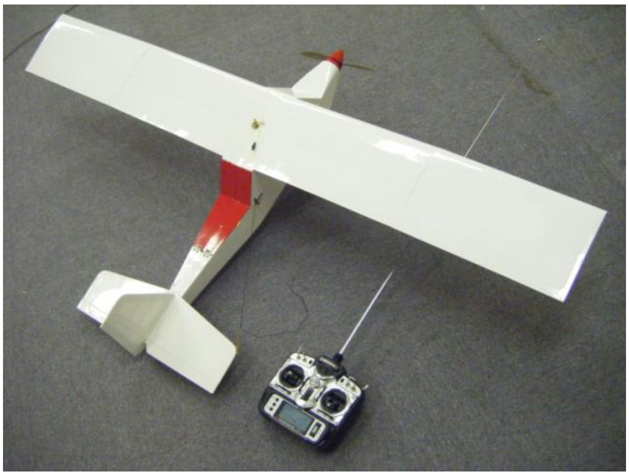
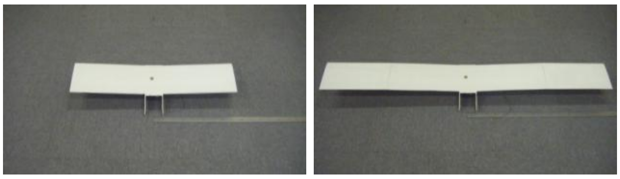


Fig. 20. Servo & Wire Type Folding Method Airplane.



(a) Folded. (b) Deployed.

Fig. 21. Deployment of a servo & Wire Type Wing.

Table 4. Specification of a Servo & Wire Type Folding Method Airplane.

Mass [kg]		1.5
Length [m]		0.9
Span length [m]	Fixed wing	0.84
	Deployable wing	0.37
Chord length [m]		0.2
Airfoil of main wing		Ishii wing
Dihedral [deg]		5
Airfoil of tail		Flat plate
Horizontal tail area [m^2]		0.057
Vertical tail area [m^2]		0.021
Horizontal tail volume coefficient		0.52
Vertical tail volume coefficient		0.19

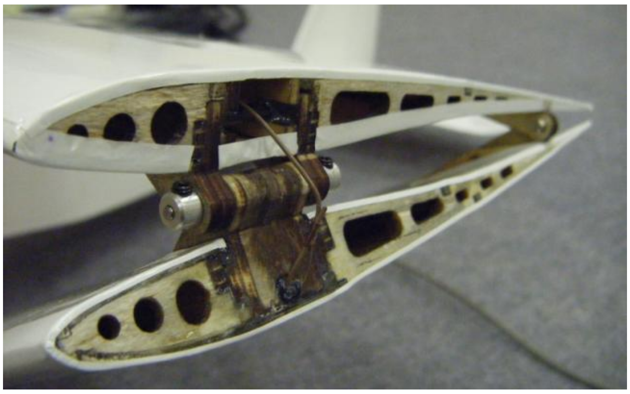


Fig. 22. Detail View of a Hinge Section.

3.4 Result and Discussion

First, a drop test for the spring hinge type airplane was conducted. However, the airplane could not deploy a right wing and crashed in a field. On this occasion, a flight control module was powered off due to impact of crash. Therefore flight data could not obtained from the flight control module. The reason why the airplane could not deploy the wing is thought that a deployment stopper mechanism was too weak. Therefore it worked in resting state but did not work with flow. So, just because the airplane crashed does not mean this type of is not suitable for aerial deployment. This experiment must conduct again.

A drop test for the servo & wire type airplane was also conducted. First, the airplane was dropped in the deployed state for comparison. The airplane could pull up smoothly. Triaxial acceleration and triaxial angular rate are shown in Fig. 23 and 24. Here, a North-East-Down coordinate system is used. A horizontal axis shows the time since the

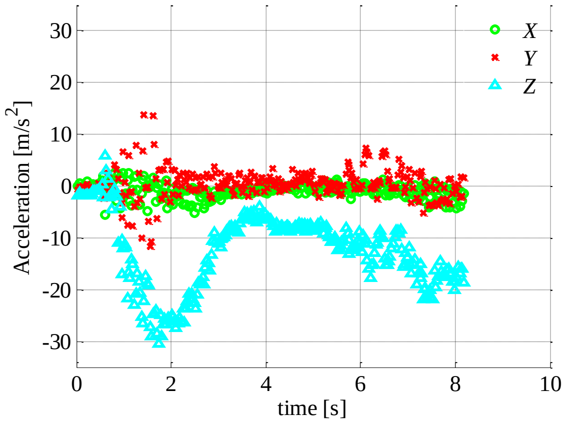


Fig. 23. Accelerations at Pull up.

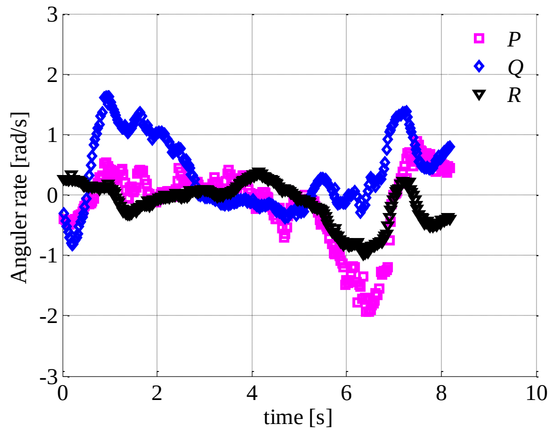


Fig. 24. Angular Rates at Pull up.

airplane starts dropping. An acceleration in Z direction and a pitch rate indicated a large change around 2 seconds. It shows a centrifugal force and pull up maneuver.

Next, the airplane was dropped in the folded state. The airplane could deploy its wing and pull up smoothly. Figure 25 shows successive picture of deployment motion. Here, time was calculated from the frame rate. From Fig. 25, it can be seen that the right wing was deployed slightly faster than the left wing. And all maneuvers finished within 3 seconds. Next, triaxial acceleration and triaxial angular rate are shown in Fig. 26 and 27. Pulses of acceleration in Y direction and roll rate were observed around 1.5 seconds. This region was compared with the data without deployment motion as shown in Fig. 28 and 29. Pulses were only observed with deployment motion. Therefore it is thought that these pulses were created from the effect of the deployment motion of the folding wing. From Fig. 25, 28, and 29, the time that pulses were observed was virtually-united in the time wings finished deploying. Therefore it is appear that the reason of these pulses is an inertial force of finishing deploying. Even such effects were observed, the airplane could succeed the aerial deployment. Accordingly, it is evident that the effect on dynamic behavior from the symmetric aerial deployment motion of the servo & wire type folding method airplane is sufficiently-small.

(a) *t*=0 [s]
Start Dropping.

(b) *t*=0.69 [s] Just before Deployment.

(c) *t*=1.21 [s]
90 Degrees Deployed.

(d) *t*=1.41 [s]
Right Wing Deployed.

(e) *t*=1.51 [s]
Left Wing Deployed.

(f) *t*=2.28 [s]
Pull up.

(g) *t*=2.83 [s] Finish Pull up.

Fig. 25. Successive Picture of Deployment Motion.

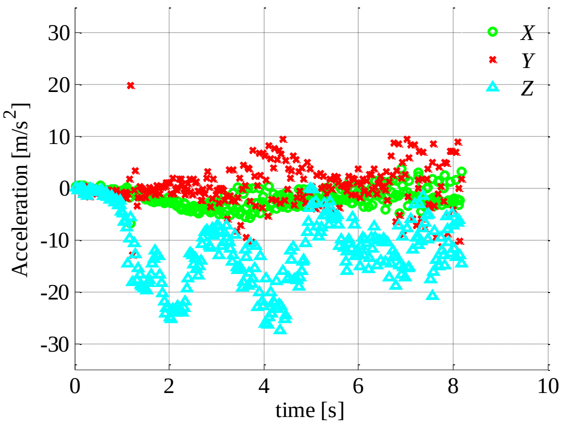


Fig. 26. Accelerations at Deployment Motion.

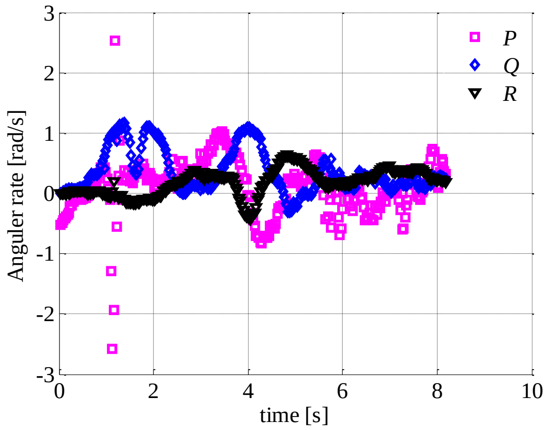


Fig. 27. Angular Rates at Deployment Motion.

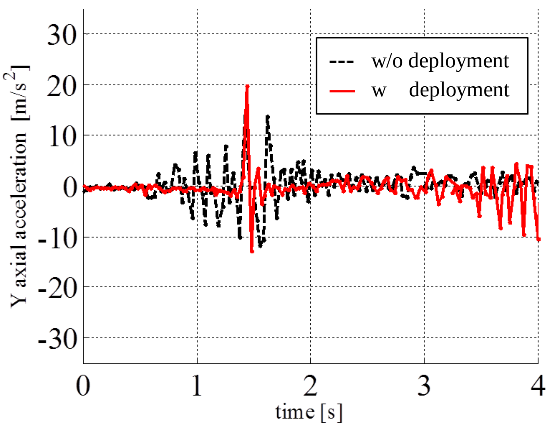


Fig. 28. Comparison of Acceleration of Y Direction.

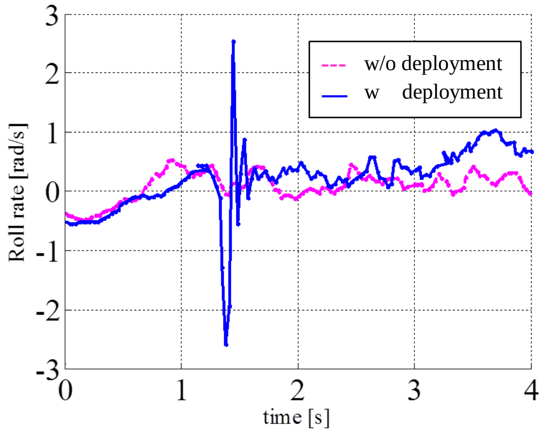


Fig. 29. Comparison of Roll Rate.

4 Conclusion

Folding type deployable wings were developed and the drop tests were conducted. A folding method was selected in this development because it was simple and lightweight. Deployment ability of this was estimated and then validated through a wind tunnel test. A result of the test was agreed with the estimation. And it was made clear that the maximum deployable airspeed differ depending on the angle of attack. The model wing could deploy easily at the angle of attack of 0 to 15 degrees. Therefore an attitude of the airplane before deployment should be low and positive angle of attack. Folding method deployable airplanes with two different actuators, the spring hinge type and servo & wire type, were tested using a balloon. The airplane was ascended by the balloon. Next, it was dropped from the air in the folded state. Then the airplane deployed its wing and its motion was logged and shot. As a result, the spring hinge type folding method airplane could not offer its flight data due to crash by the fault of the right wing deployment. The reason why was thought that a power of the deployment stopper was too weak due to the aerodynamic force. On the other hand, the servo & wire type folding method airplane could succeed a sequence of actions such as aerial deployment and pull up. This fact substantiated that the servo & wire type folding method deployment mechanism can be used for aerial deployment motion. In addition, dynamic behavior during aerial deployment motion was measured. Even though deployment motion makes a pulse on acceleration in Y direction and roll rate, these values were small and the airplane could deploy and flight stably. Therefore, effects on the dynamic behavior from the symmetric deployment motion by the servo & wire type folding method deployable airplane was small enough.

As a future work, the spring hinge type folding method airplane will be developed again and its dynamic behavior during aerial deployment motion will be observed quantitatively. In this development, the deployment stopper mechanism will be tested in an airflow using the wind tunnel. After the drop test of it, the dynamic behavior will be compared with that of the servo & wire type. Furthermore, an application scope of deployment mechanism will extend to a tail.

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