CONCEPTUAL DESIGN OF ECOLOGICAL AIRCRAFT FOR COMMUTER AIR TRANSPORTATION

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Abstract

A conceptual design study was carried out on the ecological aircraft for commuter air transportation. Morphing wing concept is adopted for cruise and take-off and landing performance, changing the wing shape between laminar airfoil and high lift airfoil. Elastic materials were applied for the smooth deformation as a morphing mechanism. A morphing wing model equipped with smooth deflection of leading and trailing edge was made and tested in the low speed wind tunnel. Experimental result shows that improvement of the lift coefficient was obtained by use of the morphing wing and possibility of the ecological commuter aircraft with morphing wing.

1 Introduction

Recently small new aircrafts have been developed based on SATS (Small Aircraft Transportation System) concept [1]. However, these aircrafts still have the environmental and economical problems. Aircraft noise especially at take-off and landing phase, emissions, long runway length, operational cost, and so on. To realize the future commuter aircraft, such environmental and economical aspects should be considered more carefully.

On the other hand, many countries with small islands or small land resources for runway require new small aircrafts for the commuter air transportation. The requirements for these aircrafts is to be as follows:

1) High safety
2) Short take-off and landing capability
3) Small fuel consumption
4) Quiet operation
5) Low manufacturing cost
6) Low maintenance cost

Flight performance such as STOL, small fuel consumption and noise reduction should be achieved by the improvement of the aircraft itself, therefore some new technologies should be developed to meet these requirements. Low manufacturing cost will be achieved by the mass production like the automobile factories. Safety and low maintenance cost will be achieved through the simple system and structure, health monitoring system and reliable components with high quality management system.

In the present study, a new concept of small aircraft to meet those requirements is proposed and a conceptual design of new aircraft has been conducted. The proposed aircraft could provide a new efficient and ecological mid-range air transportation system, especially between the cities isolated by the mountains or sea. Such an aircraft is expected to take place of automobile and railway trains, if the commuter aircraft has advantage in transportation cost and convenience. This situation is not limited in business society but also in our personal society. Also low cost air taxi system with the newly proposed aircraft could change our social life drastically because our geographical world will become smaller and economic activities will be more active and our life will be more convenient.

2 Conceptual Design of Ecological Aircraft

2.1 Requirements for Ecological Aircraft

The primary requirements for the ecological aircraft are decided as follows, shown in Table 1.

Table 1. Requirements for ecological aircraft

crew	1
passengers	4
fuel consumption	10 km/litter (with fuel for diesel engine)
range	1000 km
take-off distance	240m (required runway length is 400 m)

The number of the passengers is decided to be same as other small aircrafts. The fuel consumption is decided a little better than average fuel consumption of full size car. The range of the aircraft is decided to make round trip to island which is located 500 km range from the departure airport. This geographical situation commonly exists in many countries.

2.2 Conceptual Design Procedure and Result

A conceptual design process was conducted based on the method of reference [2]. A series of iteration process to estimate the drag of aircraft, power of the engine, weight of the aircraft, aerodynamic characteristics of the main wing and size of fuselage and other components.

In this design process, a diesel engine [3] was selected in place of a gasoline engine because of the ecological and economical aspects. The amount of CO_2 in exhaust gas of diesel engines is smaller than the gasoline engines, and thermal efficiency of diesel engines is higher than the gasoline engines. For reasons mentioned above, we selected the diesel engine as a power plant. Two types of airfoil were used in the design process. An airfoil with high lift characteristics was selected to estimate the take-off distance and an airfoil with low drag characteristics was selected to estimate cruise performance.

In conventional design, some high lift devices, such as flaps or slats, are selected to achieve the high lift requirement at take-off and landing phase. These have the advantage of obtaining higher lift coefficient, but have disadvantage of complexity of mechanism and higher cost for manufacture. In this study, therefore, we applied a morphing wing concept in order to meet two requirements both at take-off/landing and at cruse conditions. The details of the morphing wing is described in section 3.

The result of the conceptual design is shown in Table 2 and Figure 1.

Comparing to the similar class aircrafts, like Cessna 172 or Cirrus SR-20, dimensions are almost same. However, relatively short flight range and the usage of a diesel engine causes smaller fuel weight. Also smaller wing load and higher engine output lead to short take-off and landing performance. Furthermore, the reason of the smaller fuel consumption is not only the wider wing span but also the installing the diesel engine. Considering to the operation at the airport in downtown, reduction of the noise is one of the most important problem to realize such an commuter aircraft. Aircraft noise consists of many factors, engine noise, propeller noise, aero-acoustic noise, and other mechanical noise. Among the aero-acoustic noise, flap and slat edge is the one of the significant noise source during the take-off and landing phase. To suppress the noise caused by high lift devices, we selected a morphing wing concept, which has no gaps or edge on the wing surface. Continuous wing surface of the morphing wing has advantage to the reduction of the noise generated by the disturbance or vortex at the wing edges. Short take-off and landing characteristics is also effective to the noise reduction in operation because of the decreasing the noisy area around the airport.

Even in small country like Japan, there is room for further development of mid-range transportation. As for long range transportation between major cities, main airliners and railways are operating frequently. On the other hand, automobiles and local trains are suitable for short transportation. But concerning the middle range, especially over the mountains and the sea, surface transportation vehicles are inconvenient because of the traveling time and cost.

The aircraft designed in this conceptual design study is focused on such middle range transportation. Comparing to the existing aircrafts, a smaller size and higher performance aircraft can be realize by means of the different approach..

Table 2. Aircraft Specifications

Dimensions		
	Wing Span	12.7 m
	Overall Length	8.1 m
	Wing area	20 m^2
	Wing Aspect ratio	8.0
	Horizontal tail area	0.448 m^2
	Vertical tail area	2.03 m^2
	Tail-arm Length	5.0 m
	Propeller diameter	2.17 m
Weight		
	Empty weight	691 kg
	Fuel weight	111 kg
	Payload weight	308 kg
	MTOW	1110 kg
Engine		
	Maximum power	170 kW
	Uninstalled weight	107 kg
	Specific fuel consumption	212 g / kWh

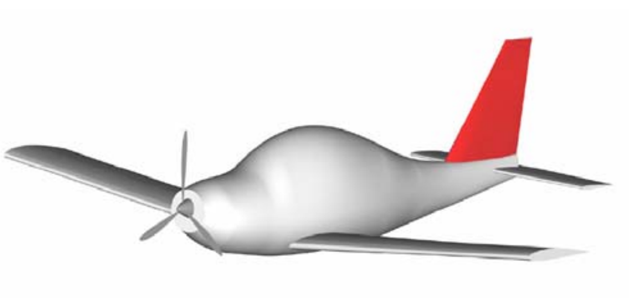


Fig. 1. Ecological Aircraft Concept sketch

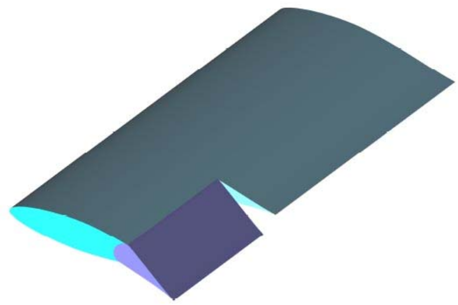
3 Morphing Wing

3.1 Morphing Wing Concept

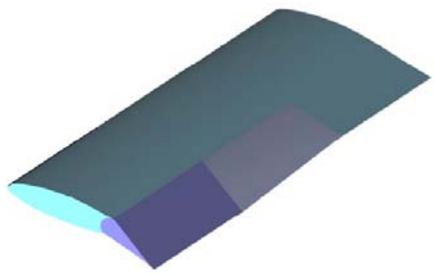
In this design study we assume a morphing wing concept. In these days, various morphing wing concepts are widely investigated, changing the wing shape; airfoil cross sectional shape, planform, dihedral, and so on. The authors also have been investigated on the morphing wing and its application [4][5]. Figure 2 shows an example of morphing wing, which changes the trailing edge camber line smoothly along the span wise direction. The feature of the morphing is smooth deformation like a bird's wing. Morphing wings adapts its shape so as to suit for the different flight conditions to improve the flight performance or flight characteristics. Applying to the control surface or high lift device, morphing wing can reduce the aero acoustic noise caused by the gaps or flap edges.

In this study for small aircrafts, we selected a simple morphing wing concept, transforming the airfoil shape by changing the camber line around the leading edge and trailing edge. As a result of this type morphing, rigid wing box can be maintained for the wing structure and morphing mechanisms can be easily mounted in the wing. Fuel tanks in the wing box can be also installed like a conventional wing structure.

Applying this morphing concept to the designed aircraft, required C_{Lmax} in conceptual design study is 2.4 at take-off and landing phase in addition to the low drag characteristics at cruise condition. Therefore we selected a laminar airfoil NACA 64_2-215 as a base airfoil.



(a) Conventional wing (Discontinuous deflection)



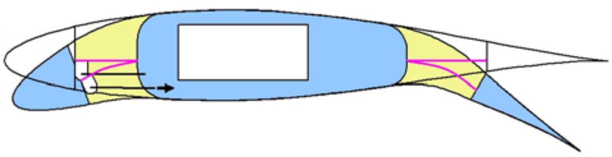
(b) Morphing wing (Smooth deflection)

Fig. 2. An example of Morphing wing

The morphing region for the leading edge is set from 0 to 20% chord location, and from 70 to 100% chord location for the trailing edge, so as to acquire the sufficient effect on the aerodynamic force. Elastic materials were used for the smooth deflection by the morphing, and smooth surface can be realized without gap or step on the airfoil surface. However, because the shape of the leading edge and trailing edge is sensitive to the airfoil characteristics, 10%C region for the leading edge and 15%C for the trailing edge were treated as a rigid component so as not to change to the unexpected shape. Figure 3(a) shows the smooth deflection of this type of morphing.

Figure 3(b) shows the schematic sketch of the morphing mechanism. To realize the smooth deflection, an elastic plates are installed at the center of the airfoil thickness, and push-pulled by the actuator. The yellow part in figure 3(b) is the deforming region which should be made by elastic materials.

(a) Base airfoil and deflected configurations



(b) Schematic sketch of morphing

Fig. 3. Smooth deflected morphing wing

3.2 Numerical Analysis of Morphing Wing

As a fundamental analysis, flow calculation around the morphing airfoil was performed. An airfoil analysis software XFOIL was used in this study, which is two dimensional potential flow analysis with boundary layer correction. it is a reliable code with many application and validations [6].

Figure 4 shows the comparison of lift coefficient in case of the various trailing edge deflection angle for 40 degree of leading edge deflection. Red line shows the original NACA 64_2-615 without deflections and 1.3 of C_{lmax}. This figure shows the larger deflecting angle of trailing edge increases the lift coefficient and C_{Lmax} and 2.5 is achieved for the most effective case of 30 degrees of trailing edge deflection. It seems reasonable the smooth deflection can be suppress the separation of the boundary layer near the trailing edge on the upper surface. Therefore higher lift coefficient is expected for the morphing airfoil than the conventional discontinuous deflection.

From this analysis, maximum lift coefficient of 2.4, required for short take-off and landing performance, can be achieved by this type of morphing wing.

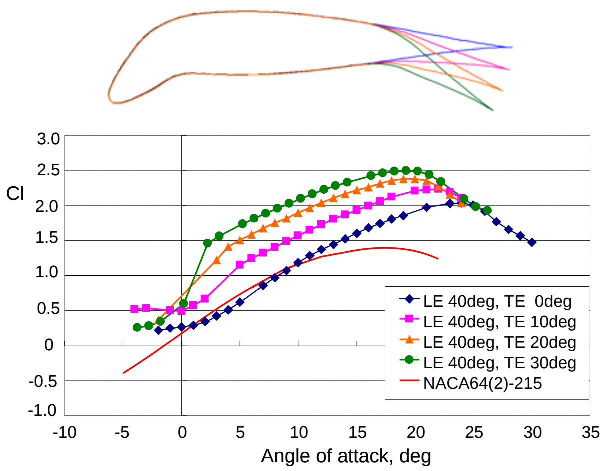


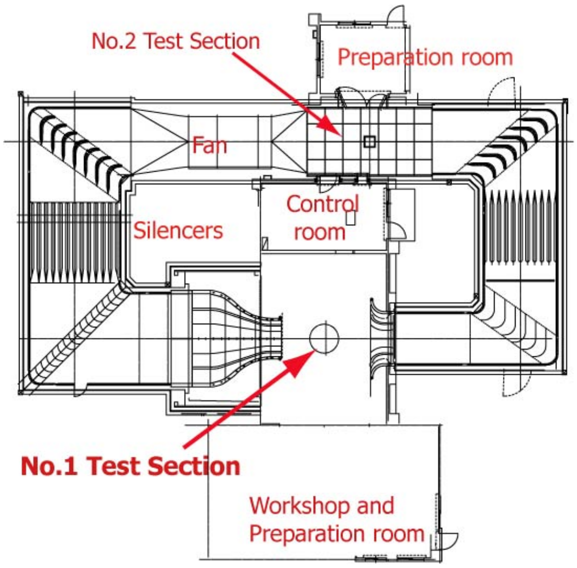
Fig. 4. Comparison of calculated lift coefficient

4 Wind Tunnel Test

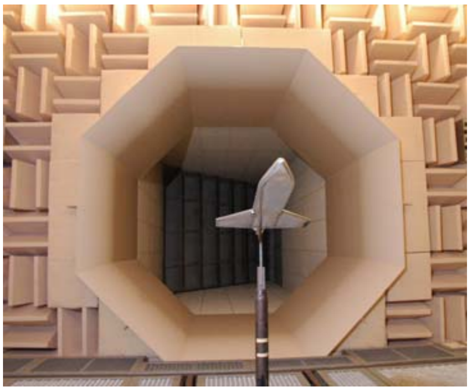
The wind tunnel test was conducted in a low speed wind tunnel. The primary objectives of the tests were to investigate the fundamental effect of the morphing wing. The test model, therefore, is a semi-span wing model, with built-in morphing mechanisms.

4.1 Wind Tunnel Facility

The experiment was conducted in the Low-Noise Low-speed Wind tunnel of Department of Aeronautics and astronautics, Kyushu university, shown in figure 5. This wind tunnel is a closed circuit and has two test sections, a closed test section and a Göttingen type test section. In this experiment, we used the Göttingen type No.1 test section shown in figure 5, whose dimension is 2 m width octagonal and 5 m length with anechoic chamber. Maximum velocity is 60 m/s and noise level is 65 dB at 40 m/s.



(a) Overview of Low Noise Wind Tunnel facility in Kyushu University



(b) Göttingen type No.1 test section

Fig. 5. Kyushu university Low Noise Wind Tunnel

4.2 Experimental Model

Figure 6 shows the experimental model set in the test section of the wind tunnel, and figure 7 and 8 show the model inside view. The semi-span wing model, whose chord length is 0.33 m and span width is 1.32 m, was used and its aspect ratio is 4.0. Base airfoil section is NACA 64_2-215 as described in previous section. Morphing mechanisms were mounted at leading edge and trailing edge parts. We used plastic plates, sponge rubber and thin plastic film as elastic elements for the smooth deflection. The surface of the model was covered by the thin plastic plate bent smoothly along the surface curvature not to disturb the boundary layer on the model surface by the gaps or steps. The model is supported on the force balance mounted on the wind tunnel lower wall with a reflecting plate for the half model test. The wing box is a 2 mm thickness aluminum rectangle tube, and the ribs are made by 15 mm thickness polyethylene plates. Rigid leading edge and trailing edge are made of expandable polystyrene covered by the plastic sheet.

Figure 9 shows the inside of the model and deflecting mechanism. Morphing deflection was performed by the small servo motors, Futaba FP-S3101, mounted inside the model. We use ten servo motors, located at five span wise sections. All the servo motors are controlled by the Renesas technology's H8 micro computer, and the deflecting commands are issued by a PC through RS-232C serial interface. Each servo motor can be operated separately, therefore span wise changing smooth deflection can be achieved. In this study, however, the measurement were conducted for the uniform deflection angles along the wing span.

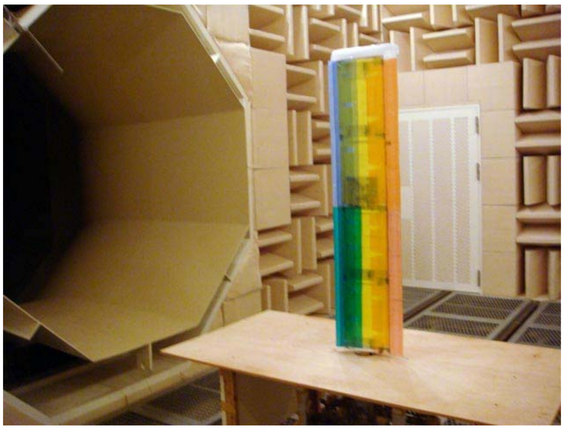


Fig. 6. Model installation in the wind tunnel

Fig. 7. Wind tunnel test model inside view

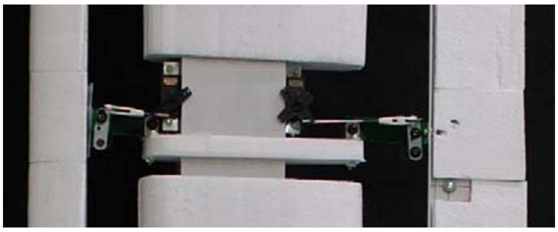


Fig. 8. Model cross section with leading edge and trailing edge deflection

Fig. 9. Model cross section with leading edge and trailing edge deflection

4.3 Measurement and Test Conditions

Lift force was measured by the wall mounted three component force balance manufactured by Nissho electrics co. ltd. Flow speed is 10 m/s and the Reynolds number based on the chord length was 2.3 x 10^5. Force data was measured at angle of attack from -5 to 20 degrees. The deflecting angles were set at 0, 10, 20, 33 degrees for the leading edge, and 0, 10, 20 degrees for the trailing edge.

4.4 Results and Discussion

Figure 10 shows the comparison of the measured lift coefficient for the trailing edge deflection angles, without leading edge deflection. LE and TE mean the deflection angles of the leading edge and trailing edge part respectively. This figure shows the larger deflection of the trailing edge angle increases the lift coefficient, but the lift increment for 20 degrees deflection is no so large than 10 degrees. This may account for the flow separation at the trailing edge on the upper surface for 20 degrees deflection case.

Figure 11 shows the comparison of the measured lift coefficient for the trailing edge deflection angles with 33 degrees of the leading edge angle. Comparing to the figure 9, the increment of lift coefficient is not seen for the larger trailing edge deflection angles. This result can be explained by the flow separation over the deflected leading edge of 33 degrees. To confirm this, effect of the leading edge deflection angle is shown figure 12, for non-deflected trailing edge. Even in case of 10 degrees of the leading edge deflection angle, the wing is stalled at the angle of attack of 10 degrees.

In this study, morphing wing geometry is defined only by deflecting the leading edge and trailing edge. Therefore the resultant airfoil geometry is not always proper for the high lift flow conditions. Further study is required to improve the lift characteristics of the morphing wing configurations with elastic deformations.

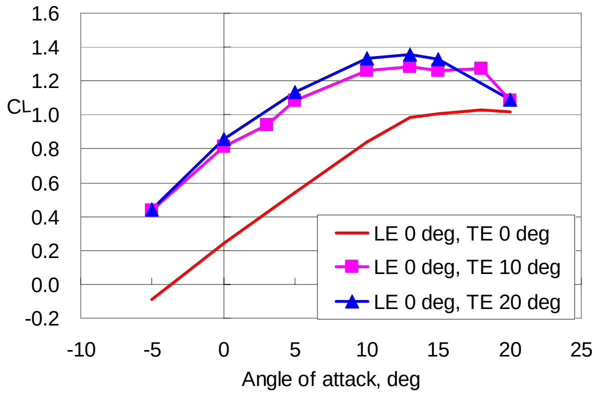


Fig. 10. Comparison of lift coefficient for trailing edge deflection without leading edge deflection

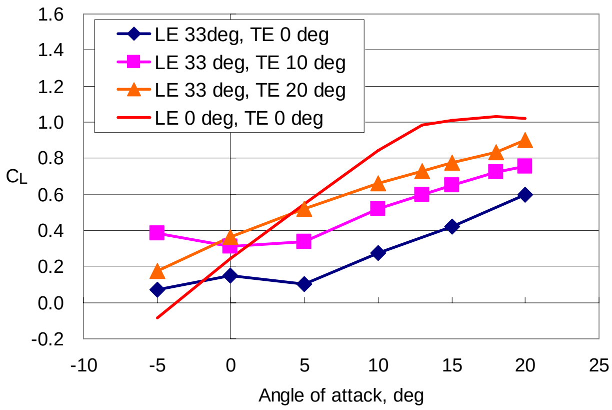


Fig. 11. Comparison of lift coefficient for trailing edge deflection with 33 degree leading edge deflection

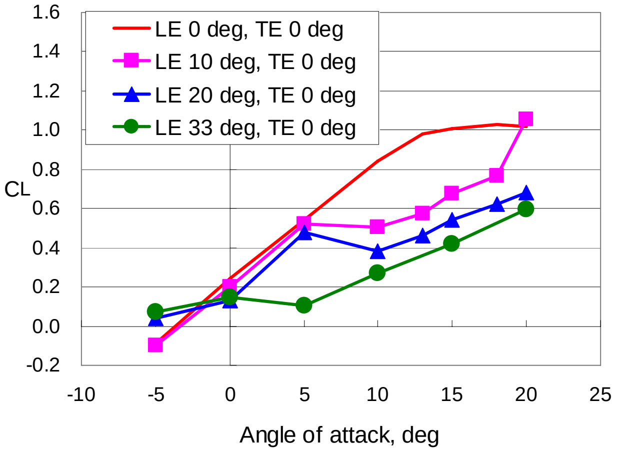


Fig. 12. Comparison of lift coefficient for leading edge deflection without trailing edge deflection

5 Conclusions

A conceptual design study was carried out on the ecological aircraft for the future commuter air transportation. Morphing wing concept was adopted for fuel-efficient aircraft with low noise and short take-off and landing performance. Wind tunnel test was also carried out on the fundamental study of the morphing wing and obtained lift characteristics. These results lead to the conclusion that there is the possibility to realize the higher performance commuter aircraft by applying the morphing wing concept with elastic deformation.

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