Design Exercise Making Use of Classic Engineering Documents

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Abstract

An ornithopter, a flying machine by use of its flapping wings, was designed and 3D-modeled starting from an idea in CODICE ATLANTICO drawn by Leonardo da Vinci in the midst of 1,500. A simple sketch in the codex was at first analyzed from the point of degrees of freedom and the geometrical consistency, the mechanism was next concretely synthesized with appropriate modifications. Industrial design was also added to the solution of the mechanism based on the concept to fit the outlook to the flapping motion of the machine and some historical research. Utilization of classic engineering materials to design exercise was discussed by thinking back the entire process of the design.

Keywords: design exercise, engineering education, creative design, classic engineering material

1 Introduction

In machine design, mechanism is one of the most essential elements, and sometimes it attracts even non-engineers by its visible motion. This is why, for example, a lot of engineering ideas on mechanism in the codices by Leonardo da Vinci [1] are published as two-dimensional engineering drawings and produced into their three-dimensional images and motion animations [2], [3]. Their stance in engineering design and three-dimensional modeling is based on faithful transcription and reconstruction of the idea sketches. There, however, is a trial to synthesize Leonardo's mechanism into a robot [4], pointing out that the ideas provide sufficient kinds of machine elements to improve a modern mechanics.

Then as a trial in design education, a design exercise starting from a Leonardo's idea sketch to an entire machine including a chassis giving appropriate outlook for the function was planned and carried out on a student. In the exercise, the student started at an analysis of a mechanism to understand its function, and then followed by a quantitative synthesis even to add supplementary elements required for the function.

In this paper, the process of the design starting from idea sketch in classic engineering material will be introduced and the utilization of the materials will be discussed on what and why the student made decisions in the design from one-on-one communication between a teacher and a student.

2 Classic Engineering Documents

There are many classic engineering documents on mechanical ideas and tutorials for both in the West and the East. For example in Codice Atlantico, not a few mechanical ideas by Leonardo da Vinci are collected, and in the East, Karakuri zui and Karakuri kinmoh kagamigusa are the most famous ones. These materials are roughly classified into two types: only a description or drawings of a raw idea and a record of actually manufactured machine. In case the former is adopted as a subject of design exercise, students should start with the verification of the consistency of the idea. In the latter type materials, illustrations and description for explanation are precise and scrupulous. In both types, the contents, however, cannot give a true shape and a true length because they had been drawn before the establishment of plural projection and standard for drawings, then nor give quantitative information including dimension; the ideas are equivalent to idea sketch in modern engineering in the beginning of the design process. We need, therefore, quantitative analysis and synthesis based on modern engineering knowledge to utilize the ideas. We also have to know that the ideas do not include consideration based on mechanics on material, fluid and thermal and dynamics since they had not established yet.

3 Creative design trial of ornithopter

3.1 Subject of the design exercise

The subject of the design trial in this report was a flying machine, the ornithopter, in Codice Atlantico shown in **Fig.1**. We have the whole copies of codices of Leonardo da Vinci as a special collection in Design Library, Kyushu University. There are four candidates on the page; the one at the center in the lower row on the page is adopted. This is because the mechanism was constructed with various kinds of machine elements such as a pulley, levers and screws, and also includes turning pairs and screw pairs. It seems to be also preferable because of having an appropriated difficulty.

In the present knowledge, we have already known that only small birds such as the hummingbird can hover and very large birds over 10kg cannot even fly [5]. We now know that it is impossible for people to fly with flapping, then the subject of the creative design is to design a machine having essential elements of flight by flapping and motion resembling to flapping of birds. It

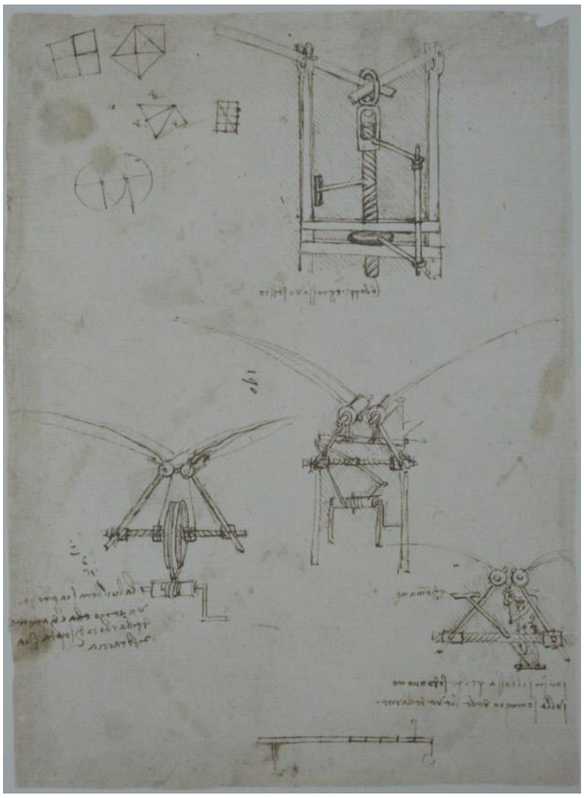


Fig. 1 Ornithopters in Leonardo's sketch [1]

is also added to the subject to give a corresponding outlook to the mechanical function.

3.2 Mechanical design

The material adopted here is the one which has not been manufactured as described in Chap.2. The teacher then directed a student to verify the idea and to find out inconsistencies to be modified before the synthesis. The student started the exercise with a close investigation of the mechanism to study an operability of the mechanism, analyses of degrees of freedom and geometrical consistency were carried out on the mechanism.

On the degrees of freedom of the mechanism, d_f, the number of machine elements and pairs in **Fig. 2** is counted and substituted into Kutzbach-Grübler's equation of degrees of freedom for two-dimensional linkage. If each pair in the figure has one degree of freedom as observed and estimated from the figures, the one of the whole mechanism is zero as evaluated by the following formula, pointing out that the mechanics cannot move at all;

$$d_f = 3(N - 1) - n (3 - 1) = 3 (3 - 1) - 3 (3 - 1) = 0$$

where N is the number of whole machine elements in the mechanism chain for one wing, and n is the number of pairs having one degree of freedom as follows: one screw pair between (5) and (6) and two revolute pairs (7) and (9). The analysis is carried out on the half of the mechanism hence the mechanism is symmetrical.

To solve the lack of degrees of freedom, we have to add an extra degree of freedom on one of the present turning pair. For example, one of the simplest solutions is to add a sliding pair between the lead screw nut (6) and the arm (8) to be a sliding-turning pair with two degrees of freedom.

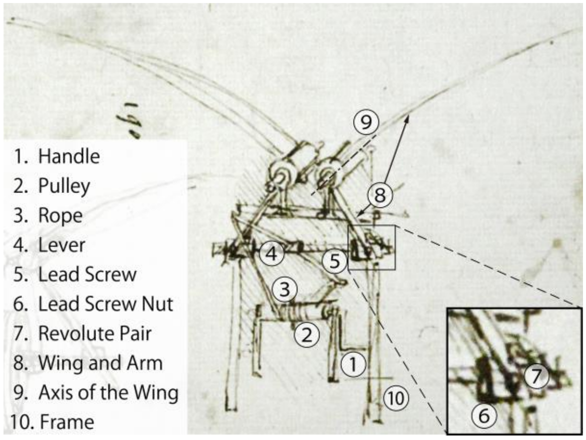


Fig. 2 Analysis and synthesis of the mechanism

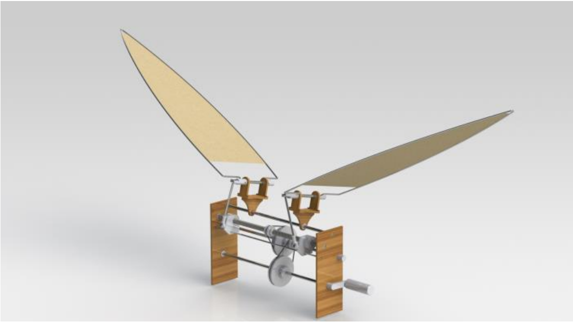
Next analyzed was the stroke of the motion. Since the lead screw (5) in **Fig.2** seems one thread, the lead screw nut (6) making a pair with the screw moves at most 1/3 of a pitch in accordance with the rotation of the lever attached to the lead screw. Measured from the figure, the magnitude of flapping angle of the wings stays insufficient less than a few degrees. The flapping mechanism driven by the lead screw which rotating angle is restricted less than 180 degrees due to the lever's interference. Then it is concluded that the driving system is inadequate and should be replaced by other some effective transmissions.

Studying the driving system on a geometrical consistency, another problem on spatial arrangement was found out. Since the lengths of the rope on wind up and down sides are the same, the position of the pulley (2) must be on the perimeter of an ellipse of which two focuses are at the ends of the lever (4). Now the distance between the pulley and the axis of rotation of the lever, lead screw (5), is fixed, the pulley is on a circular arc, indicating that the length of the lever is zero. Then the driving mechanism is geometrically inconsistent.

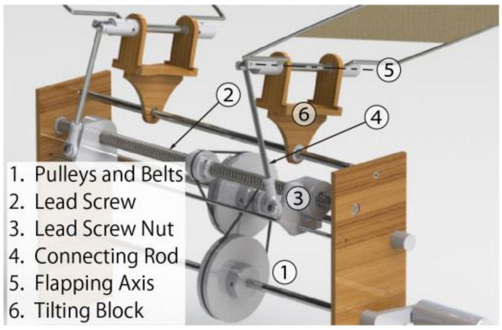
As described in Chap.2, the idea sketch will not give us true length nor true shape; designers must have a sufficient knowledge on mechanism and geometry to find out this restriction.

The rotating angle of the wing around its axis is determined the ratio of the length of the arm and the stroke of the screw pair; we can magnify the angle by shorten the length of the arm. This solution, however, is not practical because the arm length should be shortened to be almost the same to the screw pitch to give a sufficient angle.

Another solution to magnify the flapping stroke is to increase the stroke of the slider compared to the rotation of the driving shaft; the pitch of the screw should be increased. Considering that an enough stroke to make an entire flapping by less than one quarter of a revolution cannot be obtained by way of a multi thread screw or a large diameter. In this design trial for creative design, the basic principle is to keep feasible original ideas of Leonardo da Vinci. On the function, however, his idea is not acceptable in the sense of mechanical engineering. An alternative was proposed to give an enough stroke of the slider for a flapping motion by rotation of pulley not



(a) Overview



(b) Mechanical part

Fig. 3 Mechanical Design of the Ornithopter

restricted by the rotating angle of the levers and also easily magnified by multiple-stage pulley train.

Shown in **Fig. 3(a)** is the overview of the redesigned ornithopter and **Fig. 3(b)** illustrates the detail of the mechanism for flapping motion. The lead screw (2) with an appropriately increased speed through the pulleys and the belts (1) then drives the screw nut (3) back and forth. The reciprocal motion of the screw nut twists the flapping axis (5) of the wing through the connecting rod (4) joined to the screw nut with a spherical joint, then concurrently pushes up and pulls down the end of the tilting block (6) with the flapping axis, giving a feathering motion to the wing as illustrated in **Fig. 4(b)**.

This mechanism resembles to the three-dimensional model [2] referring to the same sketch, but the mechanism is improved from the original one on the verification of practical function by compensating the lack of degrees of freedom and the required magnitude of the blade motion by the synthesis of the mechanism and the alternation of the elements.

The mechanical design in **Fig. 3** included an adoption of solutions not optimal from the point of dynamics, adoptions not optimal. Taking priority of the all-round exercise including not only mechanical design but also design of appearance, the next stage of design exercise was discussed after confirming the expected motion of the mechanism.

3.3 Design of Appearance Form

In an exercise of industrial design in which a mechanical design is not included, the design process starts with an analysis of people's requirement and then its chassis envelops and hides the mechanism inside. On the other hand, in general mechanical design exercise, students are often instructed to determine the forms of its chassis and parts as simple as possible to lessen engineering complexity, for example a manufacturing cost, as the results, simple two-dimensional forms are suggested as illustrated in **Fig. 3(a)**. As an all-round exercise, design of appearance of the ornithopter was added to the basic mechanism synthesized in the previous chapter, design which positively includes a three-dimensional form.

The most important elements to be improved in design are the wings and the body of the machine when we will clearly illustrate the machine as an ornithopter. The wings and the body are the most appealing elements of the ornithopter.

Medium and large birds can fly by a lift force generated by the relative flow to their wings with generating a thrust by flapping. For the function, the remex is an essential element of the machine. Then this part is essential not only for a design of outlook but also for a mechanism and physics of flight by flapping.

At the time when the idea sketch was made, the mechanism of flight had not been clarified yet, even though Leonardo da Vinci made a hawk-eyed observation on flight mainly on a black-kite [6]. This is the reason that the each wing in the sketch consists of a single sheet and they have simple outline like a leaf.

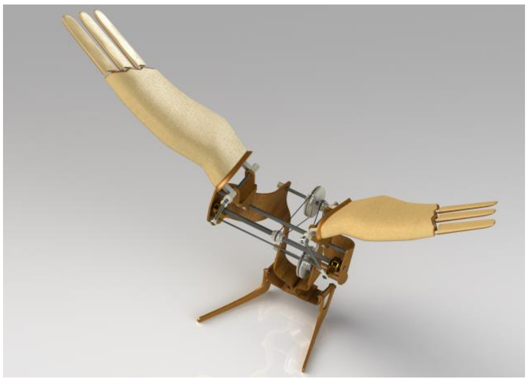
Three remiges on each wing were added at the end of the wing, capable to rotate by the flow relative to the remiges. Ordinary birds have over ten remiges on a wing; the adoption of less number of remiges is made from the point of view of appearance to easily show their existence being separated each other.

The other important element, the body, was designed next. In Leonardo's idea sketch, the two bars or rectangle plates are set parallel as a frame of the mechanism supporting the screw and the other elements above the driver. This part then will be modified like a bird's chest having a rounded and bulging shape.

To make a flapping motion of wings relatively large to the body at their bases by giving a moment of force, strong muscles as actuator are required. It is in fact that the raised round chest is easily noticed on birds. On what kind of birds are in Leonardo's works, the student made an additional research. Leonardo da Vinci observed mainly black-kite for the study of flight of birds. Otherwise he painted swans, for example in Leda and the Swan. A raised and round chest is more observable in a swan flying with continuous flapping than a black-kite by soaring. The model of the ornithopter is then determined as the swan.

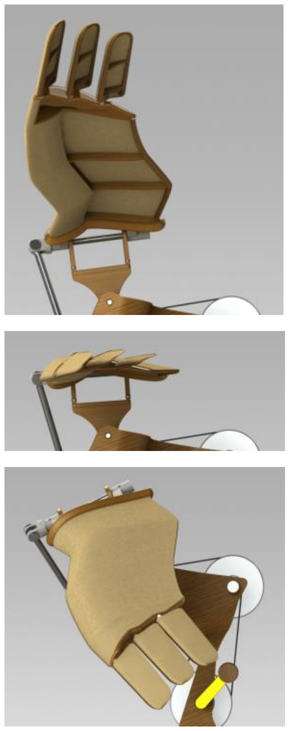
Main material of the machines in **Fig. 1** is assumed wood except some mechanical elements. The body, the frame supporting the mechanism, should be made of wood, then is designed by use of a ruled surface, a composition of cylindrical surfaces assuming a bentwood, although generating a curved surface on three-dimensional CAD is easy.

In the original idea sketch, no legs nor feet is drawn mainly because the sketch illustrates an idea of flapping mechanism of flight for a human, not a mechanical toy of a bird. The teacher suggested the student to add legs and feet to the mechanism to stand and to complete a



(a) Overview

(b) Mechanical part



(c) Flapping motion

Fig.4 Final Design of the Ornithopter

bird shape.

The legs designed by the student are short to place feet almost just beneath the body like a swan. The feet are modeled by bars not plates resembling flippers. This is due to the student's aim to keep a mechanical appearance. The length of the feet is of cause determined based on the position of the gravitational center of the body.

The overview of the final design of the ornithopter is shown in **Fig. 4(a)**. The result shows a remarkable change compared to that in **Fig. 3(a)** including the same mechanism. In accordance with the shape of the frame, the positions of the driving shaft, the screw and the pitching axis of the wings are altered from the simple vertical arrangement of the original idea sketch to the arrangement fitted to its curved contour and three-dimensional form.

4 Concluding Remarks

A comprehensive exercise on design of a small machine can be constructed by effective use of classic engineering document that describes ideas of a simple mechanism consisting of fundamental machine elements. In this paper, such trial of design of mechanism and appearance based on an ornithopter in Codice Atlantico was introduced. In the process of exercise, the motion of the mechanism was at first analyzed and necessary modifications were next added; the two-dimensional mechanism in the material was developed to a spatial linkage for a motion appropriate for the function, giving an experience composed of both analysis and synthesis. In this case, the teacher did not request a motion hysteresis between flapping-up and -down of the wings. For example by adding the above additional subject, the difficulty of the exercise can be adjusted to a more advanced level.

In adding design of appearance to the simple solution in which the flapping motion is capable by modifying the original idea sketch, the teacher frequently suggested to the student to include a three-dimensional shape fitting to the motion of flapping bird. In the process of this design practice, the student made additional research on the mechanism of flight by flapping and the difference of flight type between birds of which knowledge are reflected into both mechanical and appearance design.

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