Theoretical Design and Analysis of a Flying Broomstick

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Abstract: A flying broomstick not only exists in fiction, but is also possible according to scientific analysis and design. This article explains almost every aspect of the physics and engineering principles of a flying broomstick, including dynamic mechanism, steering mechanism, manufacturing, and many more, in preparation of production of a real flying broomstick.

Key words: Flying Broomstick Theoretical Design Robotics Engineering

Outline:

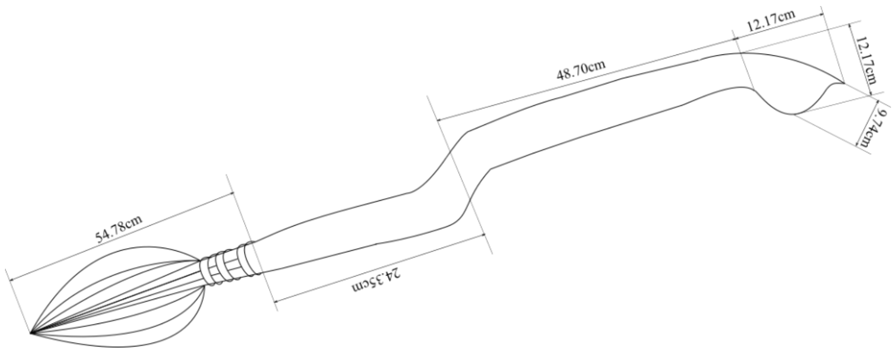


Fig. 1 Diagram of Appearance Design (would be introduced in 7th part in detail)

1 Introduction

Stories of witches flying above us on broomsticks in the night have existed for centuries, and become even more popular due to the *Harry Potter* series of books and movies. However, a real flying broomstick does not yet exist. I was curious about the reason, whether it is theoretically or technologically possible, or simply because nobody ever to make real this legendary magical implement.

My interest in modern magic, both the science and art, led me to analyse the mechanical and aerodynamic aspects, as well as manufacturing and selling of flying broomsticks. My investigation allowed me to conclude that a flying broomstick is possible in the muggle (nonmagical) world. My personal goal is to empower myself educationally, and financially to make a flying broomstick real. I would be tremendously grateful if my dream of flying on a broomstick can come true one day, in cooperation with people who share my dream of making magic real. Fig. 1-1 illustrates the starting nomenclature of the broomstick.

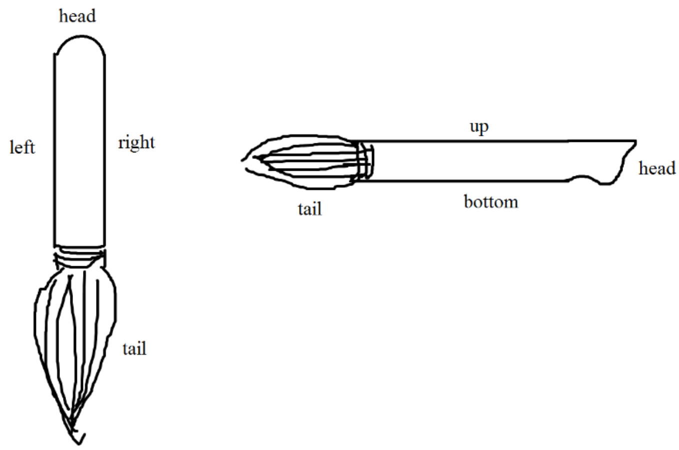


Fig. 1-1 Top and side view of the flying broomstick

2 Dynamic Mechanism

The main issues of anything that can fly are lift and control. There are many flying machines and air vehicles; balloons, rockets, airplanes, and drones, invented in recent centuries. The size range is large, with the Airbus, being longer than seventy meters; while others are as small as insects, only a few centimetres. But there is a main difference between a flying broomstick and these flying machines, which is the restriction of appearance and thus the principle of flying. Since the stereotype of a flying broomstick is already formed that it needs to be in the shape of a normal broomstick without any wings, a new method of flying is needed.

The inspiration of my first conception comes from a jet plane. Though it might be a little bit unstable for a thin stick to keep balanced without a pair of wings – which would instead become a large mechanical owl instead of a flying broomstick – the method of injecting air is able to help the broomstick take off and fly into the sky.

Fig. 2-1 A diagram of the flying principle

As shown in the Figure 2-1, I designed four slots near the bottom sides of the flying broomstick, in which two of them are closer to the head and the other two are closer to the tail, so air can be ejected from these slots and create a force. When all four of them are open, the speed of the outgoing air is used to dynamically balance the flying broomstick.

Just like normal cars have four wheels, the broomstick has four slots and each point to a direction that is not completely vertical, to allow turning and accelerating. The speed of ejecting air and the control mechanism would be explained in the next part of the essay. To estimate the requirement for the broomstick to float in a certain height, let us assume that all the air is vertically ejected for the moment.

Since the purpose of this vehicle is to make people move conveniently, it needs to be light and easy to carry. For me, an appropriate mass that I could carry around for some time is approximately 5 kg. I will also assume the weight of passenger to be 60kg.

According to the model of rocket and the law of conservation of momentum, the mass of the rocket m, the mass of the ejected air dm, the speed of the rocket v and the comparative speed of the ejected air u satisfy

$$m\,dv = u\,dm + mg\,dt. \qquad \text{Eq. 2.1}$$

The result after integration is

$$\frac{1}{u}(v_f - v_i) = \ln\frac{m_f}{m_i} + \frac{g}{u}t, \qquad \text{Eq. 2.2}$$

where subscripts f and i represent the final and initial state respectively, and g is the gravitational acceleration, about 9.8 m/s^2.

Since we are calculating the condition when the broomstick is floating statically in the sky without moving up and down, both v_f and v_i are zero, so the result can be simplified as

$$m_f = m_i e^{-\frac{g}{u}t}. \qquad \text{Eq. 2.3}$$

The maximum speed of the ejected air in a modern turbine engine is about 600 m/s. If we let $u = 600\ \mathrm{m/s}$, then after ten minutes' working, the final mass would be less than 0.01% of the initial mass, which is hardly possible. That is why I added another hole in the head of the broomstick as shown in

Fig. 2-1, which is used for incoming air. In this way, the total mass m of the broomstick and the inside air could nearly remain a constant, and the modified equation is:

$$m\,dv + v\,dm_1 = u\,dm_2, \qquad \text{Eq. 2.4}$$

where v means the speed of the broomstick, dv means the change in the speed which could be set as zero under the precondition of our discussion, dm_1 means the mass of the intaking air from the hole in the head per certain time, and dm_2 means the mass of the ejected air per certain time.

When $dv = 0$, we can get:

$$v\,dm_1 = u\,dm_2. \qquad \text{Eq. 2.5}$$

So the speed of the broomstick and the speed of the ejected air have such relationship with dm_1 and dm_2, and thus they could all be controlled conveniently by changing how much proportion the slots and holes are opened.

The above analysis is based only on rigid-body mechanics, and now let us take a look in fluid mechanics. According to Bernoulli's Equation, when two points are in the same fluid flow, there is no friction or compression, and then the fluid in these two points satisfy

$$p + \frac{1}{2}v^2 + \rho g h = \text{Constant}, \qquad \text{Eq. 2.6}$$

where p is the pressure of each point, ρ is the density, v is the velocity, h is the height.

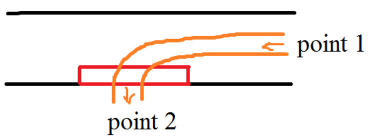


Fig. 2-2 Diagram of a stream of airflow

If we take point 1 and point 2 in Fig. 2-2 and apply the Bernoulli's Equation, where point 1 is a peaceful point inside the broomstick and the air is close to static and atmospheric pressure, and point 2 is just outside one of the four slots, the height difference of these two points can be ignored, so the Eq. 2.6 becomes

$$\Delta p = \frac{1}{2}\rho v^2, \qquad \text{Eq. 2.7}$$

where Δp is the pressure difference between two points, ρ is air density and v is the velocity of ejected air from the slots.

Combine Eq. 2.7 and force balance equation, we have

$$n\Delta p S = mg, \qquad \text{Eq. 2.8}$$

where Δp has the same meaning as in Eq. 2.7, n is the number of slots that are taken into consideration, and S is the area of the open slots.

After simplification, we get the equation of the velocity as such:

$$v = \sqrt{\frac{2mg}{n\rho S}} = \sqrt{\frac{2*65*10}{4*1.29*0.05*0.1}} = 220\,\mathrm{m/s}. \qquad \text{Eq. 2.9}$$

The total mass is assumed to be 65 kg just like before. When all four slots are open to the size of 5cm*10cm, and then the calculated velocity of the ejected air is about 7m/s. It is a considerably reasonable value, showing the design and idea is practical.

Now, here comes the energy problem. The power of controlling the slots and holes could be generated from electricity in rechargeable Li battery, which is probably the easiest answer to the energy problem, but I want to do it in a better way. If possible, I want to make my beloved broomstick a green and clean flying vehicle. I know there are tons of experts looking into the energy problem, trying to raise the efficiency of different energy storage, thus my perception may merely be called as some childish fancies and ideas, but I would still not give up for them.

To begin with, magnetic field seems to be a fine resource of energy. Just imagine, if I can make use of a strong magnetic field as big as a sport field, and then the broomstick made of permanent magnet could float like a maglev but a lot higher, and fly around freely by controlling the intensity of the magnet. But the main problem, which is also the main reason why this idea is unrealistic, is that the normal geomagnetic field is too weak to be made use of and would decrease as the altitude increases, and the artificial magnetic field that is strong enough to raise all those flying vehicles would harm the health of people who are so close to them. A common sense of safe magnetic field strength would be about 5T, as used in medical MRI. Let along the difficulty and cost of producing such big and strong magnetic field.

The second idea comes from a short video I saw in the thermodynamics class. When a wheel-like memory metal is half immersed in water, it could make use of the temperature difference and roll fast. It reminds me of the central idea of energy problem, which is finding a way to make use of a widespread energy form that we could not utilize before or to raise the efficiency of transforming it, instead of finding new energy resource. It is possible to generate a motor and drive a flying broomstick if memory metal is adopted in serving energy, though the specific form of the engine has not yet come to my mind.

According to Law of Conservation of Energy, the sum of kinetic energy and potential energy should be equal to the output energy from energy resources times efficiency, so we have:

$$\frac{1}{2}mv^2 + mgh = \eta m_w c\Delta t, \qquad \text{Eq. 2.10}$$

where m is the total mass of the rider and the broomstick, v is the flying speed, h is the flying height, η is the transform efficiency of the energy, m_w is the mass of water, c is the specific heat capacity of water, and Δt is the temperature difference that can be made use of. Let us assume that the rider weighs 60kg, the broomstick weighs 5kg, the speed is 20m/s, the height is 50m, the efficiency is 5%, the temperature of water is 80℃ at the beginning and 10℃ in the end, thus we can calculate and get the mass of water:

$$m_w = \frac{1/2\, mv^2 + mgh}{\eta c \Delta t} = \frac{1/2 * 65 * 20^2 + 65 * 10 * 50}{5\% * 4200 * 70} = 3\text{kg}. \qquad \text{Eq. 2.11}$$

Since the total mass of the broomstick is about 5kg, the calculation result 3kg suggests the idea to be a little bit impractical. But if we could find a way to increase the energy transform efficiency and combine the method with others, it may be able to work.

The third idea is about radio energy. We are in the sea of radios and the energy of radio is wasted everywhere around us. There are already a few examples of making use of the radio energy to create zero-energy-consumption watches and to charge mobile phones. The only problem so far is still the energy transform efficiency. Therefore, by developing technologies in wireless communication and radio-frequency identification, it would probably come true that our flying broomstick could make use of some of the wasted radio energy in the mid-air to serve a little bit electricity, though considering the power density of the background electrical and magnetically radiation, this form of energy could only serve as an implement of others.

Moreover, the final idea comes from a piece of news saying that scientists has find an approach to safely make use of nuclear battery and to launch a car. The concept of nuclear battery has come out for more than two decades, but the usage of it is still limited due to wide fear of the consequence of nuclear radiation leakage. It is perhaps the most mature and likely method among all my fancies. If the battery could launch a car, it would not be a problem to launch a broomstick. Therefore, when people are able to accept that nuclear batteries are safe to use, this clean energy source could be widely applied to flying broomsticks and many other vehicles and stuffs.

3 Steering Mechanism

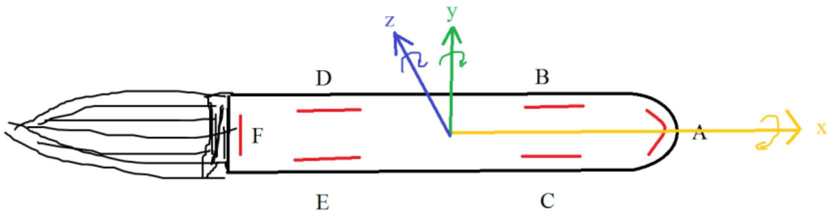


Fig. 3-1 Top view of six gates for motion control

Actually, the basic motion principle of a flying broomstick is pretty simple and similar to that of a quadrotor. The four slots B, C, D and E as shown in Fig. 3-1 just like four rotors of a quadrotor, and the extra two holes A and F is mainly used for pushing the broomstick forwards. The Cartesian coordinate system has been identified in the figure, in which x-axis and y-axis is in the paper plane, and z-axis is perpendicular to the plane of the paper.

Normally, the broomstick only needs to move forward and shift in yaw angle, but since it is flying in a 3D coordinate, I would explain how to control the broomstick in every direction. In order to stay nearly stable or fly with a constant speed in the mid sky, all four slots from B to E would open to the same extent and create an upwards force to compensate for the gravity, and in order to make sure the mass of air inside is almost the constant, the two holes A and F would open accordingly and inhale air.

To move forwards, the turbine or fan inside hole F would reverse and hole A would open wider, so air being inhaled by hole A and being ejected from hole F could create a forward force together, while slots B to E would make sure the broomstick stay in the approximately the same altitude. As for having a backwards acceleration, in other words to decelerate, it is simple to do the contradictory thing compared to flying forwards: just reverse the turbine inside two holes so that hole A would eject air and hole F would inhale air.

In order to fly upwards, slots B to E could open wider in the same time to the same extent, while hole A and F both intake air, thus vertical acceleration is generated. And when it comes to fly downwards, just close four slots a little bit until the height is ideal, open again to the extent that could maintain the height.

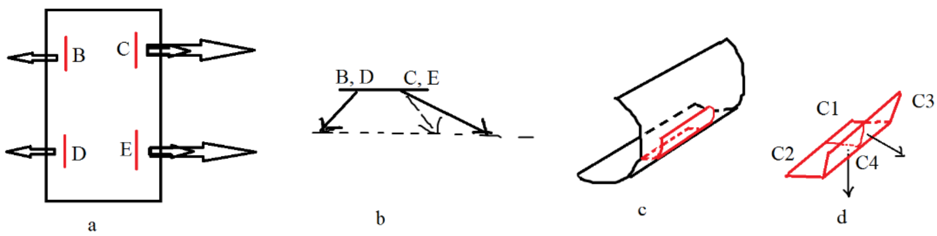


Fig. 3-2 Diagram of shift leftwards in yaw direction

In order to shift leftwards in yaw direction, open slots C and E wider (Fig. 3-2a) and also change the direction of the ejected air (Fig. 3-2b) to cause a leftwards force while keep vertical force the same. This could be accomplished by close different position of the slots. Fig. 3-2c shows the detail of a slot, for example, slot C, and Fig. 3-2d shows the model and simplified diagram of the slot C. We can roughly divide slot C into four areas, C1 to C4. When slot C is open to its maximum, all four areas are not covered. When we need to make the slot narrower, we can cover C2 and C4 with some impermeable material, thus only half of the air could be ejected from the slot and the direction is not changed. When we need to change the direction of the ejected air, we could switch the opening area from C1, C2 to C3, C4. Therefore, by combining these motions, the slot could control both the quantity and the direction of the ejected air, and hence achieve the goal of turning leftwards or rightwards in and only in yaw direction.

In order to shift in pitch angle, which could be considered as a combination of moving forwards and upwards, we could simply control the slots B and C open wider, and then the head would be higher than the tail like an angry horse and the rider should be careful not being tossed off the broomstick. To shift in another direction, slots D and E could open wider together, the rider would be in a posture accelerating towards the ground.

In order to shift in roll angle, slots of the same side, like B and D, or C and E, would open wider without changing the direction of the ejected air. Then the torque would make the broomstick roll around axis x, which is perhaps the most dangerous operation for the rider. Unless people need to hide from some rapid attacks – for example a fast *Bludger* (a type of ball appear in *Harry Potter* series which is designed to knock people off the broomstick) coming towards the face, otherwise it is safer to shift only in yaw angle instead of pitch or roll angle.

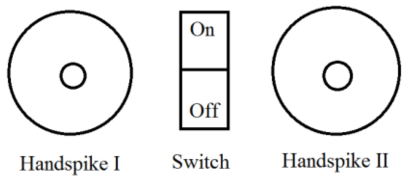


Fig. 3-3 Diagram of user panel

All those controlling could be accomplished by an on-board chip that connect a user panel and other dynamic elements on the broomstick. The user panel (Fig. 3-3) could contain a switch that functions as the main control of on and off, and two round joysticks that each could rotate one hundred and eighty degrees, thus the rider could command all kinds of motions. For instance, the joystick I could mainly control the height, when the centre ball is pushed forwards or backwards, the broomstick would rise or fall down. When it is pressed and pushed, it controls the pitch and roll angle – this kind of design is meant to avoid the rider from mistakenly rotating in a dangerous angle, since the action of press reveals their purposes of acting dangerously. The joystick II could control the motion in the horizontal plane, where forwards and backwards of the centre ball controls acceleration and deceleration, leftwards and rightwards controls the shift in yaw angle. These two joysticks could exchange if the rider is a left-handed.

The integrated circuits on the chip would translate the command on the user panel into real control on motors and six gates, thus the process of controlling is accomplished.

4 Landing Mechanism

Since the basic motion principles and control problem have all been explained, we could combine those movements to complete actions that are more complicated, like taking off and landing, and of course, each movement could have more than one solution.

Taking off could be considered as a combination of flying upwards and forwards. Before starting any of the programs on the broomstick, the rider could first mount the broomstick and hold it at the height of about one metre. Then activate the broomstick by switching the switch from off to on. When none of the joysticks are moved, the broomstick would autonomously understand this command as floating statically. And then depending on the habit of the rider, people could either fly upwards first and forwards later, or pitch around axis y and fly forwards in a direction somewhere near vertical and horizontal.

The process of landing is somewhat similar to the taking off, which requires a reduction of height of velocity. This could be done by offering a small backwards acceleration to the broomstick and slowly shut off all six gates. An unskilled rider may need a wide area to slow down and land, while experts could accurately land in a narrow space after practice.

A potential danger of landing is that, when the rider is close to the land but the speed is not slow enough for safe landing, he or she may hurt or even break legs when trying to fall on to the land. There are two solutions to the problem: adding an arm-brace and an instrument panel that shows height and speed.

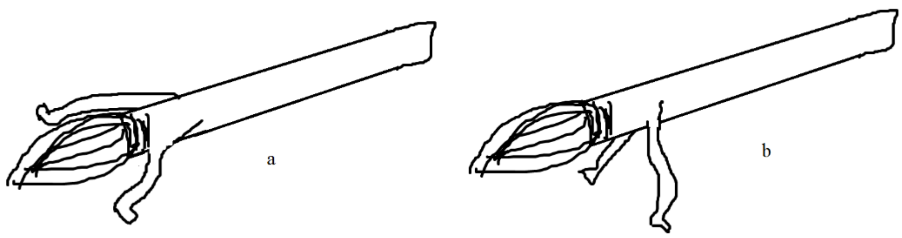


Fig. 4-1 Diagram of an arm-brace when (a) draw back and (b) stretch out

A pair of braces (as shown in Fig. 4-1) are alike to training wheels on bicycles for children, which is also aimed for unskilled riders but the function is not to keep balance. When the rider is high in the sky, the braces could draw back and be locked around the tail, so the flying process would not be disturbed, but if the rider wishes, he or she could also extend the braces and put his or her feet on it to make the sitting posture more comfortable. When the rider is preparing to land, the extended braces would be the first part of the broomstick that touches the ground. Therefore, even if the unskilled rider does not reduce the velocity within a safe region, as long as the broomstick is not upside-down, the braces would bear the force and momentum of crash, the rider would be greatly less likely to hurt himself or herself.

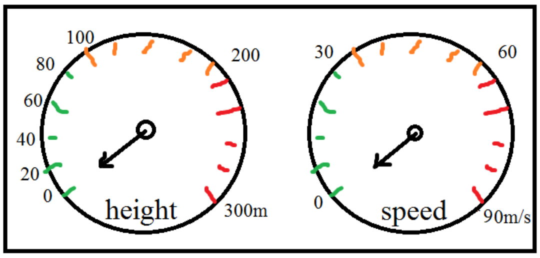


Fig. 4-2 Diagram of an instrument panel

The second solution got its idea from panels on modern airplanes. In the current design, there are two instruments on the panel (Fig. 4-2), showing the height and the speed of flying, respectively. Each panel is divided into three regions: green region means the height or the speed is safe, orange region is a warning, and red region means dangerous height or speed. The value marked in the diagram is a vague denotation, which should be changed according to the real limit of the broomstick.

Fig. 4-3 Diagram of the air hole A and the wind fan near the head of the broomstick

The principle of measuring the height is based on the temperature and pressure of the upper air, and could be supplemented by sonar or smart camera that could help recognize obstacles and avoid crashing. And the principle of measuring the velocity would be a similar structure to normal wind fans that test the velocity of the wind in meteorology. Pay attention that the air hole A (Fig. 4-3) near the head of the broomstick would affect the airflow in some way, so the wind fan should have some distances above and ahead of the air hole. That is the reason why the head of the broomstick is designed to have a protuberance in the very front (Fig. 4-3).

Overall, this instrument panel should be useful for the rider to understand his or her height and speed and thus be able to maintain in a safe height and speed during both the process of flying and landing.

5 Technical Problems

When air is rapidly ejected from slots and air holes, there is a high probability that some noise would be produced. Though the exact frequency and loudness of the noise could barely be estimated since they depend a lot on the real structure and production, some backup solutions of the potential problem have already been estimated during the process of designing, to ensure that noise problem would be an under-control element at the time of experiencing, debugging, improving and updating. But of course, actual solutions should be optimized during practice.

Noise mainly due to two sources: the rotating turbines produce fast airflow inside the broomstick, and the ejected air that may crash and rub the broomstick on the way of coming out. To solve the problem from inside to outside, we could learn from modern muffler. Structures with multiple tiny pores are able to absorb unwanted sound wave and release as heat energy, so we should trade-off between power loss and noise.

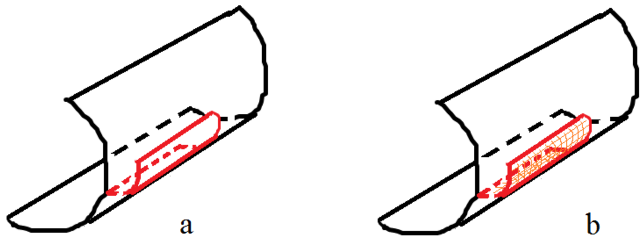


Fig. 5-1 Diagram of air gates (a) without and (b) with multihole structure

As seen in Fig. 5-1, when the total area of air gates stay the same but the structure is changed from a big hole to multiple tiny small holes, the amount of air being ejected during certain period of time is nearly the same and the frequency spectrum of the noise would move to higher frequency. By this way, the noise that could be heard by human ear would reduce greatly, but creatures that could hear higher frequencies, like dogs, may be disturbed. To reduce the noise level in all frequencies, we could coat several layers of sound absorption material inside the broomstick and on the surface of air gates. However, many small holes with the same total area as fewer large holes increases big edge drag, which would still require a new solution.

Another potential technical problem is vibration problem. Unlike cars that vibrate due to uneven road, broomsticks vibrate because of self-resonance and instable airflow. Self-resonance mainly caused by inside components with a similar or same resonance frequency. This could be avoided during the process of manufacturing and individual testing, so the main problem is to deal with vibration caused by meteorology, which would be mentioned and emphasized again in the next part.

The lighter the broomstick is, the more severe the vibration could be in the face of the same instable airflow, so we could make the broomstick heavier if it would frequently confront gale and storm. And to feel less vibration, the rider could fix a cushion onto the broomstick if he or she wishes. And just like cushions on bicycles and cars, cushions on broomsticks could also contain spring-like vibration absorber.

By far, all the methods are purely mechanical and theoretically simple, and actually we could also apply some high technologies and smart facilities. To measure the vibration more accurately, vibration sensor could be added inside the broomstick, and predict the potential danger of flying under the current circumstance. If the on-board chip calculates a high level of danger, the main panel could show some red lights or digital danger level, warning the rider to stop and maybe maintain the broomstick or wait for the meteorology to improve.

After broomsticks are being widely accepted and used, vibration sensors and other sensors could send back information about the relationship between the status of the broomstick and the accidents. Then by using machine learning and other smart technologies, the chip could predict better and give warnings early enough for the rider to be prepared.

Finally, the last crucial technical problem that I could think of is thermal management. Thermal wastes would be produced by running turbines and chips, therefore cooling fluid is needed, which could be either liquid or gas. If we use some chemical cooling liquid as cooling fluid, then as we discussed in the second part about energy issue, the temperature difference energy could be utilized as a second electricity supporter. And if we separate part of the incoming air and use them as cooling liquid, no external cooling liquid needs to be added every other day, but the cooling effect may be a little bit worse. Therefore, different methods or their combination could be employed under different situations.

6 Special Meteorological Conditions

Though according to a questionnaire (as seen in the appendix of the article, Question 17), around half of responders are not willing to fly in terrible meteorological conditions, we still need to be fully prepared in case facing these situations in necessity.

One of the solutions that could prepare for nearly all the special and terrible meteorological conditions is to equip broomsticks with parachutes. A possible concern is that, when the flying height is only about one hundred meters, the effect of the parachute is limited, since the height is not high enough for air resistance to function for a long time and to decrease the falling velocity to a safe region. But after all, it is better to have one than not, even only to provide riders with some sense of security.

The parachute could be equipped in the centroid of the broomstick and the rider, or two parachutes are equipped near both the head and the tail of the broomstick, thus when they are launched, the rider would still remain in balance, instead of being tumbled off the broomstick at emergency.

To deal with the problem of low visible distance in night, heavy mist or snow, it would be useful to equip prelights and rear lights on the broomstick. The rule of signal lights could simulate that of cars, and thus it would be easy for drivers to learn.

Not every broomstick need all these equipment, though, since one of the principle of flying swiftly is to reduce the total weight and cut down unnecessary equipment. Therefore, stuffs like signal lights could be dismountable or even fitted onto helmets without having to carry everywhere.

Some other meteorological conditions could be much more severe and harmful for broomstick riders, such as gale, storm and hail. Because in our design, the main power and flying principle replies a lot on airflow, hence, when there are strong wind or outside force that could affect airflow, it is really dangerous still thinking about travelling by broomsticks. A sincere advice would be please trying to avoid flying in these weathers, just like general advices for travelling on cars in terrible weather.

When broomsticks become a common vehicle, there should be supporting policies and legislations, which is part of flight management issue. Those policies should stipulate the minimum distance between two broomsticks, the maximum speed during rush hours, and many other traffic rules. If it is necessary sometime in the future, the government may need to build some specialized flight routes, which fresh riders could fly above, to ensure the safety of cars and pedestrians. Nevertheless, of course these issues would not be a concern before broomsticks are successfully produced.

7 Appearance Design, Manufacturing and Cost

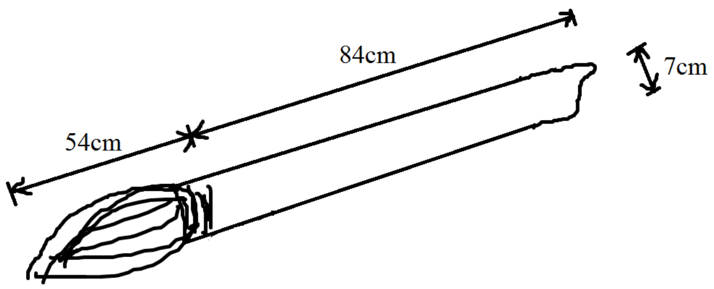


Fig. 7-1 Diagram of Appearance Design

As shown in the very beginning and in Fig. 7-1, the appearance of a flying broomstick highly resembles that of a normal broomstick, which has a long stick and a twig-like tail. This is the simplest and the most basic shape, without any outer equipment like cushion, lights or arm-brace.

The length of the broomstick is set after considering the convenience of holding, storing and the comfortability of riding. Assume the average height of an adult is about 160cm (which is about 5ft 3in), then the length should be no longer than human height, otherwise it would be inconvenient to hold and carry around. Referring to the length of a normal broomstick and the result of questionnaire (as seen in appendix, Question 11), it would be acceptable to most customers if the broomstick is shorter than 140cm. And also considering aesthetics and other aspects, for example the inner space should be big enough to contain all the equipment, in my first-version-design, the broomstick is 138cm, with a main body of 84cm and a tail of 54cm. Therefore, these two parts satisfy the law of golden section, and looks beautiful and harmonious.

As for the material for the outside shell, I think carbon fibre would be my first choice. For the first thing, it is able to bear high temperature, frequent friction and corrosion, and thus it would not easily break or require maintenance. For the second thing, it is a lightweight material with high strength, which is perfectly ideal for broomsticks. In addition, it is soft and easy to form any shape during processing, making it possible to work out all the elaborate details on the broomstick.

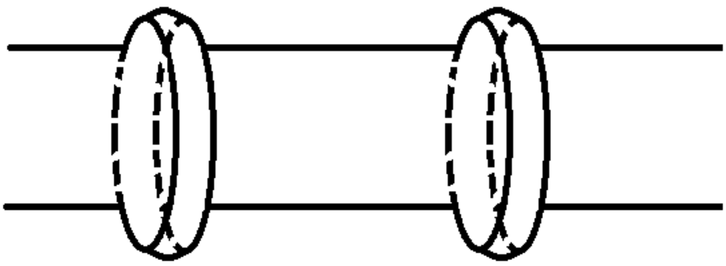


Fig. 7-2 Diagram of knots on the surface

However, if the surface were too smooth, it would be hard to grasp tightly and maybe the rider would even slip off the broomstick. To avoid this kind of potential danger, the surface should be coarser, which could be done by painting some coating on the surface after production. These coating could also function as a colouring, which would be most popular if looks similar to woody pattern, according to Question 13 in the questionnaire.

Another design is to add some knots or protuberances on the surface along the length, as seen in Fig. 7-2, then the rider is able to grasp tightly on these positions. The idea comes from the structure of natural wood and the body of dragonflies. Since insects such as dragonflies already achieve what we aim to do, which is to fly and to switch directions swiftly, we could learn from their physical structures, though a dragonfly has no one riding on it. The main reason of switching direction swiftly is wings that flap at high frequency, and their bodies with similar structure of protuberance every few distance. Another benefit of these knots is that the capacity within these positions could contain more equipment.

The manufacture of the broomstick would be in some way difficult, since the inner components could be complex and refined but the total volume is small, since the diameter of the cross-section would be no more than ten centimetres, otherwise it would be inaesthetic. And it would be the best if the outside shell is a whole complete part instead of separate parts, considering the strength and safety problem. Thus, I summarize the main principle of manufacture into one sentence: from inside to outside, from head to tail.

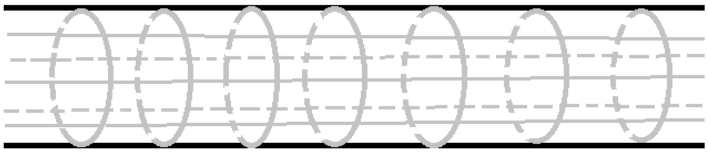


Fig. 7-3 Diagram of grid holder during manufacture

As seen in Fig.7-3, we could first construct a grid holder, which is made by a material with low melting point or an organic material that is easy to discompose under certain condition. Then all the components could be connected to the holder bit by bit and when everything inside is properly assembled. After that, it comes the step to cover the outer carbon fibre shell onto the grid holder, from head to tail, but wait for a moment before the assemble of the tail. Then making use of carbon fibre's resistance to high temperature and corrosion, heat the whole broomstick to a certain degree or wash with certain chemicals depending on the material of the holder to get rid of it. And the last procedure is to concatenate the tail to the body. If the broomstick passes tests afterwards, it would be ready for sell.

The selling price depends on the configuration of the broomstick, which would surely defer from those with light, cushion, parachute and those without. For a reference, an appropriate average price would be somewhere between 3,000 and 8,000 dollars, according to Question 6 and 7 in the questionnaire in the appendix. Therefore, the quality of material and the cost during manufacture would be limited by the budget.

8 Comfortability and Requirement of the Rider

As I have mentioned before in the fifth part of the article, when talking about the vibration problem, a cushion with spring and vibration absorber would be helpful to reduce the rider's sense of vibration, and would also be comfortable to sit on compared to sitting on a bare thin stick. Nevertheless, it may not be aesthetic to watch, since in no magical stories that wizards or witches would put a cushion on broomsticks, therefore, it would looks better if the cushion could be transparent or hidden beneath clothing.

To make the travel more comfortable, we could also supply the rider with gloves and helmet to resist winds and frigidity in low sky. If it is necessary, we could also set a safety belt on the broomstick, to prevent the rider from being tumbled off.

Another problem that requires more attention is that all the pockets on clothes of the rider must have zippers and be closed off, otherwise things in the pocket may spill out, which could be a peril to people or vehicles below the flying route, and be a loss to the rider. Consider some riders may do not have cloth with zippers, we could offer baggage to store things in the pocket and hang underneath the pocket, and we could also produce and sell cloth with zippers after the industry of broomstick begin to develop.

Similar to taking driving courses and getting driver licenses before drivers are allowed to drive on the road, broomstick riders would also be required to take training courses and tests for flying licenses in the future. The test would contain age limitation, physical examination and flying technique. This part is also something should not be a concern before broomsticks are actually produced, but as soon as it becomes a fact, these issues would all pop out quickly as they did when cars first appear and require early thoughts.

9 Customer Opinions

I published a questionnaire containing 26 questions online and after four and a half years, I collected data from 591 Chinese interviewees and get to understand potential customer opinions towards broomsticks. A few questions ask about a sport called Quidditch in *Harry Potter* series, which is not the main concern of this article, so I would not analyse data from these questions. The questions and exact data about proportion for each answer have been listed in the appendix.

Since the inspiration and motivation mainly comes from the *Harry Potter* series, I first asked about people's familiarity with *Harry Potter* (Question 1 to 3) and flying broomsticks (Question 5). More than half of the interviewees know about these stories, belong to a member of fans and have imagined being a witch or wizard, and most people would like to own a flying broomstick as a transportation if possible. Therefore, the potential number of people who would purchase a broomstick is considerable. There is no need for us to worry about whether flying broomstick would have its market, since the survey supplies that the answer is positive.

As we have discussed in the seventh part about cost problems (Question 6 and 7), nearly half of people would purchase a broomstick without hesitation if the price were lower than ￥20,000, which is around $3,000, and the highest acceptable price would be ￥50,000, which is around $7,500. Therefore we should consider the budget and do our best to limit the price within the region of ￥20,000 and ￥50,000, which equal to about $3,000 and $7,500. The reason why potential customer's psychological price is within this range may be affected by the current price of cars. Therefore, the price of the flying broomstick could refer to that of cars only by multiplying a factor.

Question 8 and 9 ask about psychological speed customers would like to have. Question 8 prepares for the condition that the broomstick not being able to float in static but only to fly in a minimum speed. The minimum speed should be less than 10km/h (about 6.2mph) according to about half of the interviewees. A possible error about this problem is that people may not understand the question correctly, but anyway, as long as we are able to stop the broomstick in the mid-sky, this circumstance would not be a concern.

Question 9 asks about the lowest maximum speed that people could accept. Of course, the higher the limit is, the more people are satisfied, but we should also consider aspects like cost and industrial technique. When the maximum speed is 80km/h (about 50mph), more than half of people would be satisfied, so it could be an expectation during producing.

Question 10 to 13 concern about physical and appearance design. About general style, people who prefer light and small broomsticks, and people who prefer heavy and strong ones are almost the same. I guess that women would prefer the first style while men may prefer the second, statistically the number of women and men equals, resulting in an equal data result.

The most popular length would be shorter than 1.4m (about 4ft 7in), and the most popular diameter for section would be 4～6cm (about 1.6～2.4in). The actual length and diameter for section could be different for different series or versions of broomsticks, to satisfy all kinds of favours.

As for the color of outer shell, the most popular one would be wooden color and pattern, which is easy to understand, since in most literature, movies and legends, flying broomsticks and normal broomsticks are indistinctive in appearance, and normal broomsticks are usually made by wood. The second favourable color is metallic orange, followed by red, azure and yellow. The result offers a reference for producing and selling.

The most meaningful question should be Question 14 in my eyes, which concerns about energy issue. A great amount of people – nearly half of the total – do not like either gasoline or electricity, so they urge for a new energy, implying that many people nowadays care about energy problems and broomsticks with new energy resources could be popular. If they must choose between the two, more people would vote for electricity than gasoline, which accords with the design in the second part of this article.

Question 15 suggests that the main reason why people may be hesitant to purchase or use a broomstick due to their doubt on its safety. Therefore, as long as we are able to ensure the safety of broomsticks and persuade people to accept that fact, the potential of broomsticks is unlimited.

Question 16 to 19 concern the safety measures. As I have expected, most people agree that it is necessary to have specialized training courses and flying licenses tests. More people would avoid flying in terrible weathers than those who would. Though more people think it is necessary to build specialized flying routes than those who disagree, more than half of them feel it is not likely to achieve. Therefore, it would be an issue worth debating after real broomsticks are produced.

The later four questions are about Quidditch sport, which is out of our discussion, and the final three are general information of interviewees. The biggest proportion of interviewees are young adults, people with high education background and company or government employees, suggesting the constitution of the potential customers.

Overall, the survey convinces me that the flying broomstick have a wide market that is completely vacant at present, and potential customers would be willing and affordable to purchase them.

10 Conclusion and Future Designs

For future design, there could be some additional functions, for example, we could apply technology to help broomsticks “recognize” their owners and prevent from being stolen. Some simple methods could be adding a password system or fingerprint recognition system in the chip; some more advanced methods could be voice recognition or facial recognition by applying machine learning.

Since we will be adding more and more functions to the centre chip, it would gradually develop to a mini computer, and then we should think about potential danger of being hacked. The web security is an issue concerned by all IoT (short for Internet of Things) things, so it is the same with flying broomsticks. The exact algorism of protection program depends on the structure of chips and algorism of web connection, so this part would be omitted in this article.

Inspired by various app in our mobile phones recently, we could also create an app for flying broomsticks. The mobile phone is used as the main controller for the broomstick, to reduce equipment and also mass of the broomstick, and to ensure the safety of people’s own broomstick. When the owner connects his or her mobile phone and the broomstick, the broomstick would recognize it as the owner and be unlocked.

For a later future, we could exploit self-flying area, hoping that broomsticks are able to navigate and fly by itself, by communicating with other broomsticks nearby and recognizing the environment through sensors.

Just like different types of cars, we could also divide broomsticks into two main types: those for daily usage and those for competition usage. Each would focus on different aspects and functions, for example, daily usage does not need high speed but must be tremendously safe, while broomsticks for competition should be swift enough and therefore may be able to reduce some safety equipment.

As a conclusion, according to my theoretical design and analysis, the flying broomstick is feasible and I really look forward to the day that it actually comes true.

11 Acknowledgement

I shall first say "Thank you" to J.K. Rowling, who created the whole amazing wizarding world of *Harry Potter*, and gave me inspiration and motivation of completing this theoretical design and analysis of flying broomsticks. She also drew more than twenty generations of flying broomstick drafts, widening my thoughts on concept designs.

I shall also appreciate Professor Jeff Wragg from College of Charleston, who taught me Scientific Writing in Fudan, and Professor Dennis M. Briggs from UCLA, who was my professor of Introduction to Electrical Engineering during my exchange quarter there. The two professors have looked over this essay and gave me many encouraging feedbacks. Their encouragement is a great psychological support to me on my way to making these designs come into reality.

My childhood friend Yufan Pan has been as excited by the idea of flying broomsticks as I do, and there was a time when we walked in the campus and were fancied about the conception together. I really missed that time and should thank her for the shared passion in the very beginning.

Another friend of mine, Wenkai Huang, has helped me a lot when implementing Quidditch game in Virtual Reality. We are still in the stage of writing program, debugging and learning about principles of online multi-user VR games, but modelling the Quidditch field and single-user flying experience is already super exciting and inspiring. I cannot wait to see the accomplishment of the VR Quidditch game.

Finally, I shall thank my parents, who gave me full support when I shared the idea of analysing, designing, and producing flying broomsticks. Without their support, I would not be able to have my wizarding dream for such a long time ever since childhood.

12 Appendix A

The questionnaire is published online on a Chinese questionnaire website (1diaocha.com) on August 20th, 2011 and the result is recorded on February 12th, 2016. The total investing time is about four and a half years, and the total number of interviewees is 591. People could choose to skip some questions if they do not want to answer. The translated questions and the proportion of answers are listed below.

Q1: Have you ever seen or read any *Harry Potter* book or movie?

(1) Never heard of it.	10.94%
(2) Have heard of it but never seen or read any.	33.50%
(3) Have seen or read some of them.	35.69%

(4) Have finished all of them. 19.87%

Q2: Are you a super *Harry Potter* fan?

(1) No, I'm not. 41.99%

(2) Yes, but not a super one. 44.01%

(3) Yes, absolutely a super fan. 14.00%

Q3: Have you ever imagined being a witch or wizard?

(1) Never. 34.68%

(2) Yes, sometimes. 38.72%

(3) Yes, often. 18.18%

(4) Yes, always. 8.42%

Q4: Are you interested in a sport called Quidditch in the series?

(1) Never heard of it. 28.28%

(2) Have heard of it but no interest. 35.35%

(3) Have heard of it but only a few interest. 26.09%

(4) Have heard of it and very interested in it. 10.27%

Q5: Do you want to own a flying broomstick as a transportation?

(1) No. 34.23%

(2) Barely yes. 37.44%

(3) Of course. 28.33%

Q6: What is the highest price that you would purchase a broomstick without hesitation?

(1) Less than ￥10,000 (about $1,500). 44.39%

(2) ￥10,000～￥20,000 (about $1,500～$3,000). 18.43%

(3) ￥20,000～￥50,000 (about $3,000～$7,500). 14.24%

(4) ￥50,000～￥100,000 (about $7,500～$15,000). 11.39%

(5) ￥100,000～￥200,000 (about $15,000～$31,000). 4.86%

(6) ￥200,000～￥500,000 (about $31,000～$80,000). 2.85%

(7) More than ￥500,000 (about $80,000). 3.85%

Q7: What is the highest price that you would barely purchase a broomstick?

(1) ￥10,000～￥20,000 (about $1,500～$3,000). 43.29%

(2) ￥20,000～￥50,000 (about $3,000～$7,500). 21.31%

(3) ￥50,000～￥100,000 (about $7,500～$15,000). 16.44%

(4) ￥100,000～￥200,000 (about $15,000～$31,000). 10.07%

(5) ￥200,000～￥500,000 (about $31,000～$80,000). 5.87%
(6) More than ￥500,000 (about $80,000). 3.02%

Q8: What is the minimum speed of your broomstick should at least be?
(1) Below 5km/h (about 3.1mph). 36.13%
(2) 5～10km/h (about 3.1～6.2mph). 24.03%
(3) 10～20km/h (about 6.2～12mph). 18.15%
(4) 20～50km/h (about 12～31mph). 10.25%
(5) 50～80km/h (about 31～50mph). 11.43%

Q9: What is the maximum speed of your broomstick should at least be?
(1) 10～20km/h (about 6.2～12mph). 25.08%
(2) 20～50km/h (about 12～31mph). 18.06%
(3) 50～80km/h (about 31～50mph). 14.38%
(4) 80～100km/h (about 50～62mph). 13.21%
(5) 100～150km/h (about 62～93mph). 10.54%
(6) 150～200km/h (about 93～124mph). 4.52%
(7) 200～240km/h (about 124～149mph). 4.68%
(8) More than 240km/h (about 149mph). 9.53%

Q10: What style of flying broomstick would you like to have?
(1) Weight light, looks small and cute. 50.34%
(2) Weight heavy, looks strong and safe. 49.66%

Q11: What is an appropriate length for you?
(1) Shorter than 1m (about 3ft 3in). 21.94%
(2) 1～1.2m (about 3ft 3in～3ft 11in). 22.11%
(3) 1.2～1.4m (about 3ft 11in～4ft 7in). 20.60%
(4) 1.4～1.6m (about 4ft 7in～5ft 3in). 14.41%
(5) 1.6～1.8m (about 5ft 3in～5ft 11in). 8.38%
(6) 1.8～2m (about 5ft 11in～6ft 7in). 5.86%
(7) Longer than 2m (about 6ft 7in). 6.70%

Q12: What is the most comfortable diameter for section in your estimation?
(1) Less than 2cm (about 0.79in). 19.80%
(2) 2～4cm (about 0.79～1.6in). 18.96%
(3) 4～6cm (about 1.6～2.4in). 20.47%
(4) 6～8cm (about 2.4～3.1in). 15.77%

(5) 8～10cm (about 3.1～3.9in). 8.89%
(6) Larger than 10cm (about 3.9in). 16.11%

Q13: What color would you like for your broomstick?
(1) Wooden color and pattern. 28.79%
(2) Metallic bright red. 11.65%
(3) Metallic normal orange. 14.64%
(4) Metallic light yellow. 9.65%
(5) Metallic bright green. 7.82%
(6) Metallic gentle azure. 10.15%
(7) Metallic romantic lavender. 6.82%
(8) Metallic pure black. 2.83%
(9) Metallic light taupe. 3.16%
(10) Metallic bright silver. 1.83%
(11) Metallic pure white. 2.66%

Q14: What kind of energy would you like your broomstick to use?
(1) Gasoline or diesel like cars. 21.55%
(2) Electricity like trolleybuses. 25.42%
(3) Neither, better have a new one. 42.76%
(4) Does not matter. 10.27%

Q15: Do you think it is safe for broomsticks to fly above roads?
(1) No, it is so dangerous that it should be prohibited. 27.10%
(2) It depends on the performance of broomsticks and other situations. 40.74%
(3) It is alright, at least safer than cars. 23.06%
(4) Yes, I think it is very safe. 9.09%

Q16: Do you think it is necessary to have specialized training courses and tests for license before flying?
(1) No, it is not necessary. 29.17%
(2) Yes, it is necessary. 42.50%
(3) Yes, it is highly necessary. 28.33%

Q17: Are you willing to fly on a broomstick in special or terrible meteorology like gale and storm?
(1) Yes, I am willing to do so. 30.86%
(2) No, I don't want to do so. 48.06%
(3) Does not matter. 21.08%

Q18: Do you think it is possible to have specialized flying routes besides roads, so people could fly above those routes and ensure the safety of cars and pedestrians?

(1) Absolutely impossible. 26.72%
(2) Not likely. 30.42%
(3) It is possible. 23.53%
(4) It is highly possible. 9.08%
(5) I don’t know. 10.25%

Q19: Do you think the specialized flying routes mentioned in the previous question is necessary?

(1) No, it is not necessary. 30.13%
(2) Yes, it is necessary. 35.86%
(3) Yes, it is highly necessary. 19.87%
(4) I don’t care. 14.14%

Q20: Are you willing to spend some money and purchase an entire Quidditch court?

(1) No, I wouldn’t. 25.77%
(2) I need to consider for some time. 49.01%
(3) Yes, I think it is meaningful. 25.23%

Q21: What is the reason why you may hesitate in the previous question?

(1) It must be expensive and I could not afford it. 43.42%
(2) I’m not interested in it. 38.38%
(3) It is meaningless and those who would is silly. 18.20%

Q22: Would you participate or recommend your children and your friends to participate in Quidditch?

(1) No, I don’t believe there would be real Quidditch so it must be a lie. 29.68%
(2) No, because it could be really dangerous. 33.09%
(3) Yes, it is good to have some sports. 27.34%
(4) Yes, it would be brilliant and exciting. 9.89%

Q23: Are you willing to corporate with companies of flying broomstick and Quidditch?

(1) No, I don’t want to do so. 26.04%
(2) I need some time for consideration. 47.75%
(3) Yes, I’d like to. 16.22%

Q24: Could you please tell me your age?

(1) Younger than 10y. 13.98%
(2) 10～20y. 15.41%
(3) 20～30y. 40.68%

(4) 30～40y. 18.46%
(5) 40～50y. 6.63%
(6) Older than 50y. 4.84%

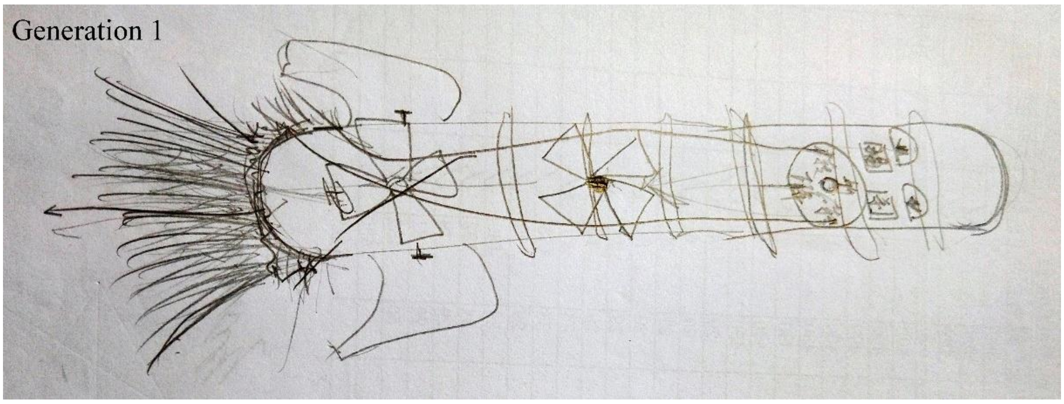
Q25: What is the highest education attainment that you got?
(1) Below junior high school. 12.21%
(2) Graduated from junior high school. 14.36%
(3) Graduated from senior high school. 21.01%
(4) Graduated from universities or colleges. 45.60%
(5) Higher than all the above. 6.82%

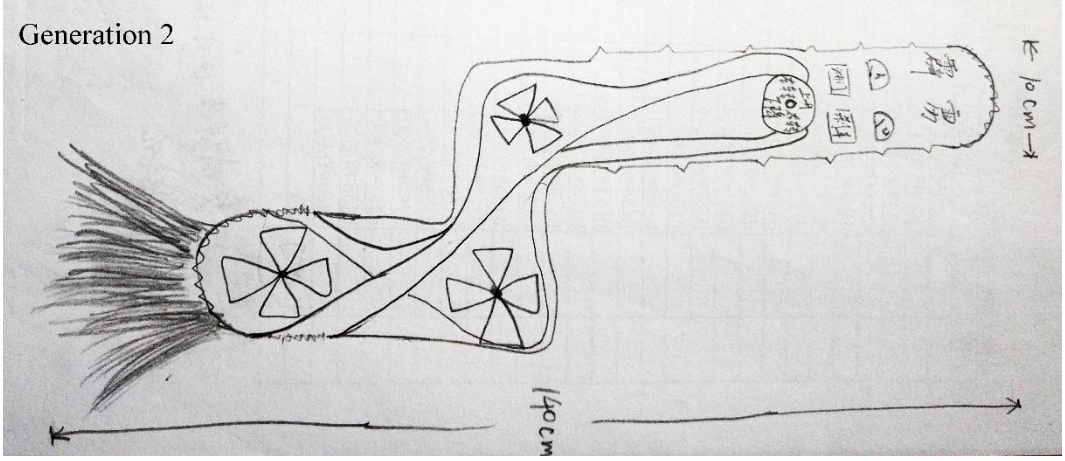
Q26: What is your job?
(1) Student. 20.18%
(2) Government employee. 13.21%
(3) Enterprise employee. 30.00%
(4) Government-affiliated company employee. 14.82%
(5) Free worker. 11.61%
(6) Farmer. 2.50%
(7) Solder 1.43%.
(8) Others. 6.25%

Questionnaire finishes.

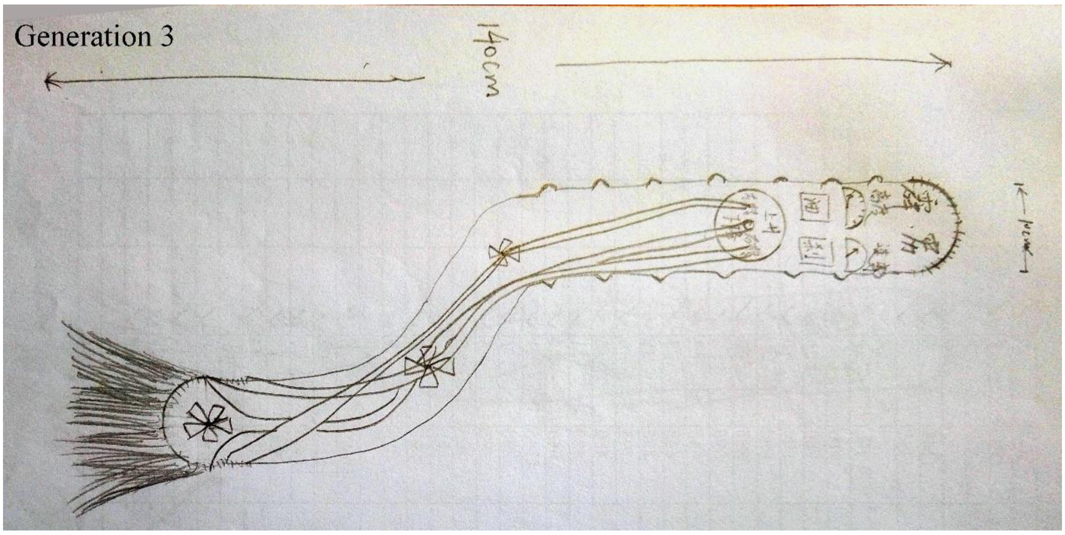
13 Appendix B

There are eight generations of analysis and design of flying broomsticks before this article was completed, among which many were simply drawn in the back of a draft paper when inspiration came. Just take a look at historical design:

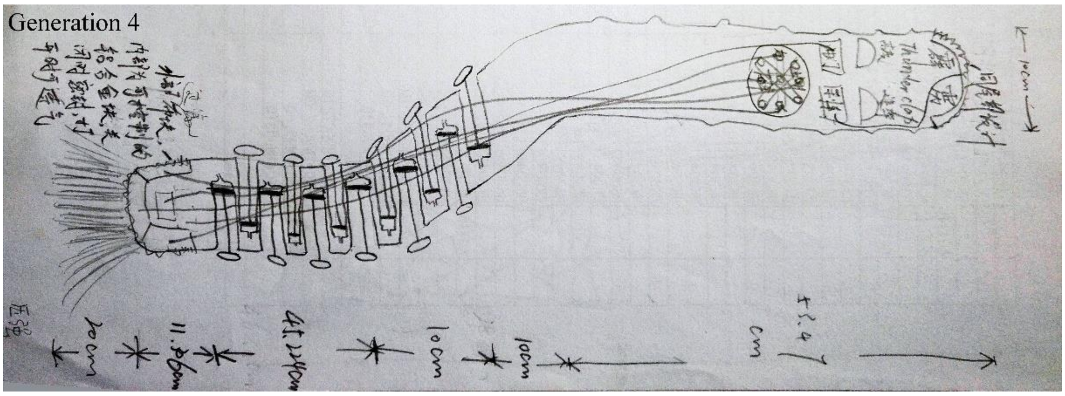




Generation 2



Generation 3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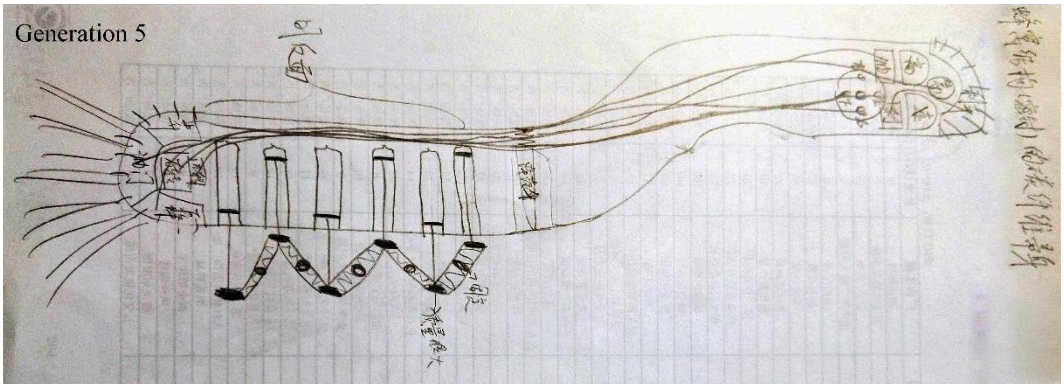
Generation 5

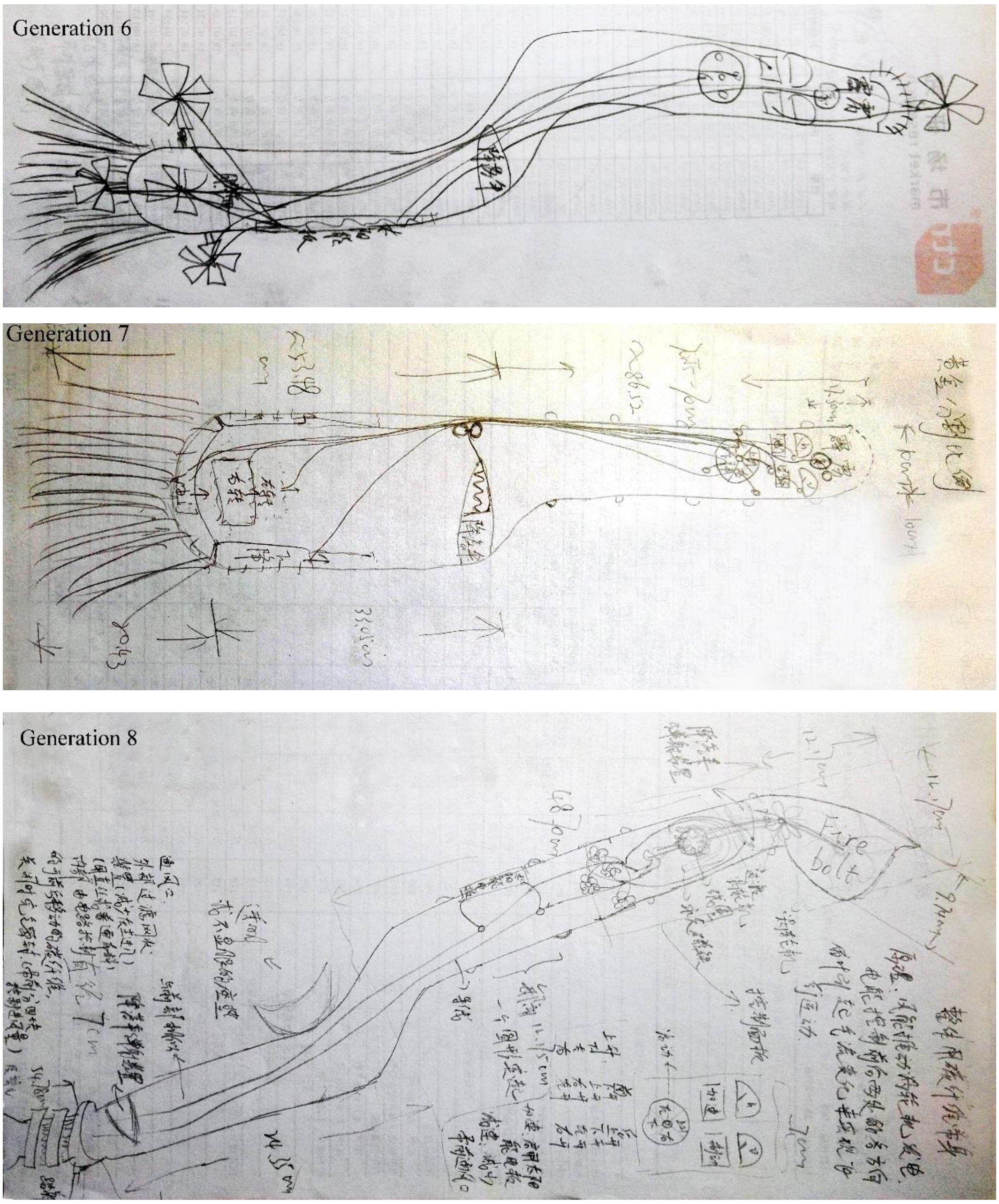

Fig. 13 Generation 1 to 8 of flying broomstick designs, all hand-draw drafts before age of eighteen, mostly inspired by principle of normal life objects or insects like dragonflies as suggested previously.