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報告題名：

最佳滑雪場地設計

Report Title: Design of Optimal Snowboard Course

作者：徐子健
系級：航太與系統工程學系
學號：D0324221

開課老師：翁明材

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中文摘要

單板滑雪是一項極具挑戰性的精彩體育賽事，並於 1998 年正式成為國際冬季奧林匹克運動會的比賽項目。當前，這項比賽主要有三種形式：單板平行大回轉，單板越野競逐，半管滑板。本文主要研究半管滑板場地的設計。

本文從能量的角度對滑雪場地參數及其特性進行分析設計，其中心是根據末端動能來衡量運動員最大騰躍高度，並認為最大騰躍高度是評判運動員表現的重要方面。通過合理的假設，本文建立了動力學模型，用以探究各參數之間的相互關係。基於受力分析與能量分析，建立了運動與能量方程並得到末端能量的表達式。

根據所建立的模型，首先對場地不同組成部分對最大騰躍高度進行研究。藉助 Matlab 軟體模擬可以發現，平底段與垂直段對其沒有較大影響，而坡度角以及過渡段曲率半徑對其有顯著影響。然後，通過採取不同的曲線對過渡段進行模擬，可以得到理論最佳過渡段曲線為。通過進一步的模擬仿真，可以得到理論最佳曲線方程中。最後，本文討論了安全性、建造難度、外界環境等影響因素對場地的影響，並對各因素進行權衡與調整。

最終得到最佳滑雪場地設計方案。平底段長度為 18 公尺，垂直段高度為 1 公尺，坡度角為 18 度，過渡段曲線方程為，其頂端夾角為 86 度。在文章的結尾，對模型之優缺點進行了客觀地分析。

關鍵字：單板滑雪　U 形管　動力學模型　能量方程

Abstract

Snowboarding is an adventurous and exciting sport that has been contested at the Winter Olympic Games since 1998. Nowadays, the events are usually held in three specialities: parallel giant slalom, snowboard cross and halfpipe. What we are interested here is the halfpipe, in which athletes perform tricks while going from one side of a ditch to the other.

In our paper, we study the design of a snowboard course and its factors from the view of energy. The main idea is to measure the "vertical air" by final energy. By making several assumptions, we build the dynamic model, which reveals essential interactions among different factors. Based on force analysis and energy analysis, we set up energy equations and obtain the general form of final mechanical energy.

Based on our model, we firstly study the each part's influence on the vertical air respectively and change each parameter. We find that the flat-bottom and the height of vert don't have an obvious effect on the change of vertical air, while the slope angle, the curvature radius of transition have obvious effect on the vertical air. Then, by simulating of different type of curves, we find out that when the transition's geometric function is $y = ax^4$, snowboarder can reach the maximum vertical air. After further simulation, we obtain that $a = 0.005$.

At last, the adjustments and tradeoffs to develop a practical course are discussed. After taking consideration of construction difficulty, snowboarder's safety and their maximum twist, we adjust the parameters of the halfpipe to make our result more practical.

In conclusion, we find a most optimal design of snowboard course, with the length of flat bottom is 0.4m, the height of vert is 1m, the slope angle is 18 degrees, the geometric function of transition is $y = 0.005x^4$ and the edge angle is 86 degrees. At the end of paper, we discuss the strengths and weaknesses of our model.

Keyword：**Dynamic Model Energy Equation Halfpipe Snowboard**

Contents

1 Introduction

1.1 Restatement of the Problem

Snowboarding is an adventurous and exciting sport that has been contested at the Winter Olympic Games since 1998. Since then snowboarding has taken off with perfecting ramps and slopes to enable a variety of tricks and stunts. Some of these stunts require a simple slope, others a rail. Nowadays, the events are usually held in three specialities: parallel giant slalom, snowboard cross and halfpipe. What we are interested here is the halfpipe, in which competitors perform tricks while going from one side of a ditch to the other. [1]

The half-pipe consists of six parts: the distance between the two crowns, width of deck, height, transition, flat-bottom and vert. In a halfpipe the vert and transition allow for back and forth motion using the force of gravity to give the snowboarder a velocity. A snowboarder uses the flat to regain balance as well as a time to pump. Pumping adds work to the system and gives the boarder a greater velocity to make it up the opposite vertical and obtain a higher vertical air. [2]

To maximize the production of “vertical air” by a skilled snowboarder, the shape of the halfpipe is of vital importance. Besides, some other tradeoffs, such as safety and building difficulty, also have great influence of the halfpipe’s designing.

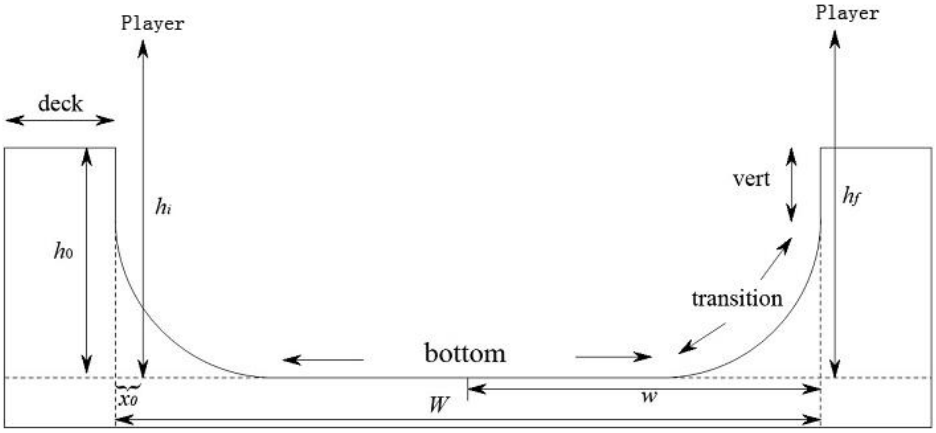

Figure 1 A snowboard halfpipe

Figure 2 A sliding route of snowboarder

It is usually accepted that the half-pipe is 100 to 150 meters long, 17 to 19.5 meters wide and has a height of 5.4 to 6.5 meters (from floor to crown). The slope angle is 16 to 18.5 degrees. In addition, the FIS (International Ski Federation) recommended that the Width (*W*), Height (*H*), Transition (*T*) and the Bottom Flat (*B*) could be 15m, 3.5m, 5m, 5m, respectively. [3] But it is obviously that it is not the most optimal design. To maximize the production of "vertical air" by a skilled snowboarder, ensure his safety and reduce the building difficulty, we must redesign the shape of this halfpipe.

In this article, we first determine the shape of a snowboard course which can generate the highest jump above the edge of the halfpipe. Then, we optimize the shape to satisfy other requirements of the trick. At last, we analysis what properties of the halfpipe should be abandoned in practical.

1.2 Notation

Table 0 Notation

Symbol	Meaning
h	The height of vert.
ρ	The curvature radius of transition.
l	The length of flat bottom.
α	The slope angle.
β	The angle between course side and sliding route.
S	The length of sliding route.
v_0	The snowboarder's initial velocity.
v_t	The velocity of taking off from the halfpipe.
W_f	The energy which is consumed by friction.

1.3 Assumptions

- We treat the snowboarder as a mass point and whose mass is m. We also ignore body twists of snowboarder and some other geometrical properties.
- We assume that the mass point moves right on the snow surface rather than traveling along the track of the gravity center of a snowboarder.
- We only consider sliding friction, collision and air resistance in energy analysis, while other sources of energy loss are ignored.

• We treat the halfpipe as a perfectly rigid body. And its motion can be modeled by curve lines.

• The collision time is ignored and we treat the collision between snowboarder and halfpipe as perfect inelastic collision.

• The effects of environment, climate and some other geographical factor are ignored.

2 The Models

2.1 Geometric Distributed Function

As the figure above, we can divide the motion into three parts: Flat bottom motion, Transition motion and Vert motion. We first extract the line of the halfpipe's section. Then we define the line of the section as the shape of the half-pipe which is called as the orbit of the halfpipe. At last, put the orbit onto the coordinate surface consists of grids, then the orbit can be matched with a distributed function.

For each part of motion, we can figure out a geometric distributed function. The matched function can be used to describe and compare the shape of different halfpipes quantitatively.

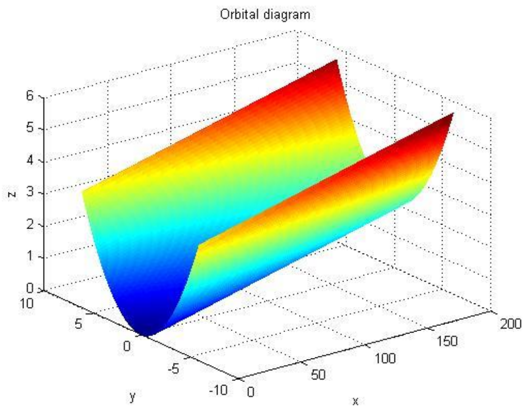

Figure 3 A design of snowboard course

In flat bottom motion, the distributed function $y_1(x)$ of flat bottom is determined by the length of flat bottom because the flat bottom is a horizon line. In transition motion, the distributed function $y_2(x)$ is determined by "the wall angle" and the length of curve. Where the wall angle is determined by the halfpipe's height and width and $\theta_{wall} = 2h/w$. In vert motion, the distributed function $y_3(x)$ is determined by the length of vert because the vert is a vertical line.

We represent the slope profile in the coordinate system by track function $y(x)$. The distributed function determines the geometric construction of the track. Besides, we know about that the halfpipe is symmetrical, so we only need to consider one side of the halfpipe. We can obtain the following geometric distributed

$$y(x) = \begin{cases} y_1(x), & x \in Flat\ bottom \\ y_2(x), & x \in Transition \\ y_3(x), & x \in Vert \end{cases} . \qquad (1)$$

2.2 The Dynamic Model

2.2.1 The Force Analysis

In our model, the snowboarder and his snowboard are seemed as a single rigid structure. We also assume that the snowboarder will keep still in the air, so that we can obtain the maximum vertical air. In the three parts of motion process, lat bottom motion, Transition motion and Vert motion, the snowboarder and his snowboard are affected by four forces: gravity, braced force of snow surface, the sliding friction and air resistance.

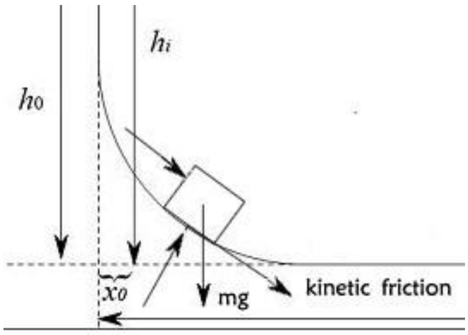

Figure 4　The Snowboarder's Force Analysis

Besides, to simplify our model, we assume that the sliding friction coefficient, air friction coefficient are all constant. In the real situation, they change with the snowboarder changing his sliding track.

According to the Newton Second Law, we let ***r*** to be the snowboarder's center of mass position vector and we can obtain the dynamic equation.

On the surface,

$$\frac{d^2\vec{r}}{dt^2} = -mg\overrightarrow{y_0} + (\vec{n} - \mu\overrightarrow{v_0})N - \eta v^2\overrightarrow{v_0}. \quad (2)$$

In the air,

$$\frac{d^2\vec{r}}{dt^2} = -mg\overrightarrow{y_0} - \eta v^2\overrightarrow{v_0}. \quad (3)$$

where, *m* is the mass of the snowboarder; *g* is the acceleration of gravity; $\overrightarrow{y_0}$ is unit vector in direction *y; v* is the velocity of the snowboarder, and its unit vector is $\overrightarrow{v_0}$;

$\vec{n}$ is the velocity's unit normal vector; *N* is the snow surface's pressure to the snowboarder; μ is the friction coefficient between the snowboard and the snow; η is the air friction parameter.

According to the research in physics, we can know about that friction coefficient μ is range from 0.03 to 0.11. And the air friction parameter can be calculated by the following equation,

$$\eta = \frac{1}{2}\rho SC \tag{4}$$

where, ρ is the air density; S is the area confronting to the wind; C is the air friction coefficient and it range from 0.03 to 0.11. [4]

During the motion on the surface, the snowboarder is subjected to the gravitational force and the frictions generated by the normal pressure and air. While the snowboarder leaves the surface, the sliding friction disappears because there is no contact surface. The component of the gravitational force normal to the surface is $mg\cos\theta$, where ε is the angle the normal to the course surface makes with respect to the vertical. Approximately,

$$\theta(x) = \arctan(y'_c(x)). \tag{5}$$

The centripetal force term is proportional to the inverse radius of the osculating circle or the radius of curvature $\rho(x)$,

$$\rho(x) = \frac{(1+y'(x)^2)^{\frac{3}{2}}}{|y''(x)|}. \tag{6}$$

The pressure between the snow surface and snowboard is provided by the gravity and centripetal force.

$$N = m(g\cos\varepsilon + v^2/\rho(x)). \tag{7}$$

According to the force analysis, we can obtain the instantaneous velocity of snowboarder which is important to calculate the vertical air.

2.2.2 The Energy Analysis

Based on the force analysis, we can know about that the velocity of snowboarder is related to the sliding route. Obviously, there are minimum consume of energy when the route is a straight line. The angle between the side of snowboard course and the route also has influence to the velocity.

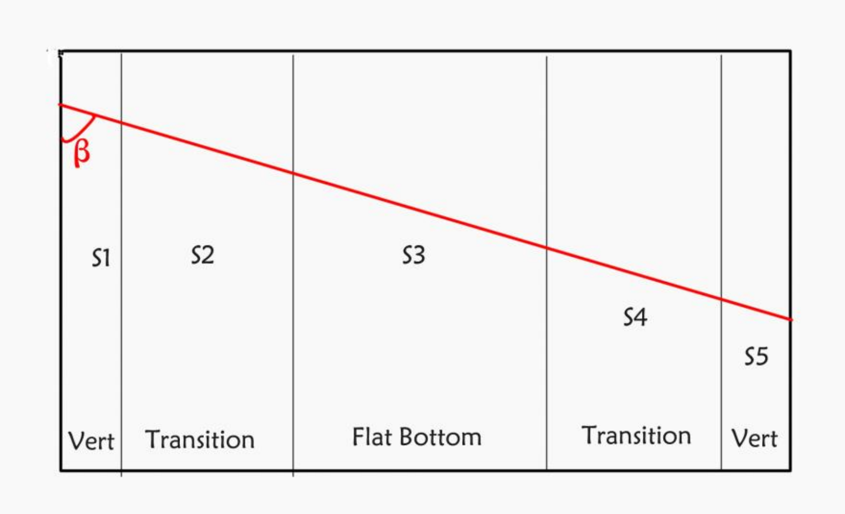

Figure 5　Surface development of halfpipe

We develop the halfpipe to a surface as Figure 4, and we can divided the whole process into 5 parts: the vert of sliding down, the transition of sliding down, the flat bottom, the transition of sliding up, the vert of sliding up. We analyse the energy consume of each part.

To the whole process, according to the the law of conservation of energy, we can obtain the equation,

$$mgH+\frac{1}{2}mv_0^2=mgH'+\frac{1}{2}mv_t^2+W_f \tag{8}$$

where, H is the height of start point; v_0 is the snowboarder's initial velocity; H' is the height of take off point; v_t is the velocity of taking off ; W_f is the energy which is consumed by friction.

Based on this energy equation, we can obtain the velocity of taking off v_t and the height difference ΔH between the start point and take off point.

$$v_t^2=2g\Delta H+v_0^2-\frac{2W_f}{m} \tag{9}$$

$$\Delta H=\frac{2h+\pi\rho+l}{\tan\beta}\sin\alpha \tag{10}$$

where, h is the height of vert; ρ is the curvature radius of transition; l is the length of flat bottom; α is slope angle; β is the angle between course side and sliding route.

During the whole motion process, each part consume energy because of the sliding friction and air residence. To calculate the the velocity of taking off v_t and the height difference ΔH, we need analysis the W_f in each part. Based on the force analysis, we can obtain the following equations.

A. In the vert of sliding down

$$W_{f_1} = f_1 S_1 = f_1 \frac{h}{\sin\beta} \tag{11}$$

where, S is the length of sliding route in the vert of sliding down.

B. In the transition of sliding down

Based on the force analysis in the transition, we can know about that

$$G\cos\alpha\sin\theta - f = m\frac{dv}{dt} \tag{12}$$

$$N - G\cos\alpha\cos\theta = m\frac{v^2}{\rho}. \tag{13}$$

Using the method of variation of constant, we can obtain the following equation of the pressure between the snow surface and snowboard,

$$N = \frac{3mg\cos\alpha}{1+4\mu^2\sin^2\beta}e^{2\mu\sin\theta\sin\beta+\sin\beta} + Ce^{-\mu\sin\beta(\frac{\pi}{2}-\theta)}. \tag{14}$$

At the initial moment, we can know about that $\theta = 0$, and at this moment the pressure $N = m\frac{(v_0\sin\beta)^2}{\rho}$. Then we can obtain the value of *C*,

$$C = m\frac{(v_0\sin\beta)^2}{\rho} - 2m\sin\beta\frac{3mg\cos\alpha}{1+4\mu^2(\sin\beta)^2}. \tag{15}$$

Based on the analysis above, we can obtain the consuming energy in the transition of sliding down.

$$W_{f_2} = \int f dS = \int_0^{\frac{\pi}{2}} f \rho d\theta \tag{16}$$

where, μ is the friction coefficient between the snowboard and the snow; β is the angle between course side and sliding route.

C. In the flat bottom

$$W_{f_3} = \mu mg \cos\alpha \frac{l}{\sin\beta} \tag{17}$$

where, l is length of flat bottom; α is slope angle.

D. The transition of sliding up

Similar to the the transition of sliding down, we can obtain the pressure between the snowboard and the surface,

$$N = \frac{3mg\cos\alpha}{1+4\mu^2\sin^2\beta} e^{2\mu\sin\theta\sin\beta+\sin\beta} + Ce^{-2\mu(\frac{\pi}{2}-\theta)\sin\beta}. \tag{18}$$

According to the initial moment, we can obtain the value of *C*,

$$C = e^{\pi\mu\sin\beta}\left[mg\cos\alpha + m\frac{(v\sin\beta)^2}{r} - \frac{3mg}{1+(4\mu\sin\beta)^2} \right]. \tag{19}$$

Then, we can obtain the consuming energy in the transition of sliding up,

$$W_{f_4} = -\int_{\frac{\pi}{2}}^{0} f\rho d\theta. \tag{20}$$

E. The vert of sliding up

$$W_{f_5} = \mu \frac{h}{\sin\beta}\left(\frac{3mg\cos\alpha}{1+4\mu^2\sin^2\beta} e^{2\mu\sin\beta+\sin\beta} + C\right). \tag{21}$$

2.3 The Effect of Slope Angle

Usually, every halfpipe has a slope angle θ, and it will generate a certain drop height $\Delta h = L\sin\theta$. As a result, when a snowboarder slides on the halfpipe, the drop height Δh will make the kinetic energy E_k become much larger. Apparently, the change of slope angle will have a certain effect on the velocity of the snowboarder when he take off from the halfpipe.

Based on the analysis of energy transform process, we can know about that the existence of the slope angle will increase the start point's gravitational potential energy. Besides, the gravitational potential energy will transform into applying work by overcoming the resistance and the snowboarder's increase of kinetic energy.

$$E_p = \Delta E_k + w \tag{22}$$

where, E_P is the start point's gravitational potential energy; ΔE_k is the snowboarder's increase of kinetic energy; w is the applying work by overcoming the resistance.

According to the effect of slope angle, the velocity of leaving the halfpipe should be adjusted as following:

$$v_t' = v_t + \Delta v \tag{23}$$

where, Δv is determined by the drop height which is caused by the slope angle.

$$\Delta v = \sqrt{\frac{2(mgL\sin\theta - w)}{m}} \tag{24}$$

2.4 Maximum the Vertical Air

Based on the force analysis and the energy analysis above, we can obtain the vertical distance H_v, which is the maximum vertical air.

$$H_v = \int_{\Delta t} v_t' dt \tag{25}$$

where, v_t' is the velocity during the rising process which is adjusted; Δt is the time to rising to the highest point.

3 Model Implementation

3.1 The Influence of Different Variable

In order to find the optimum design of the snowboarder course, we first study the each part's influence on the vertical air respectively, and then change each parameter to find out the suitability and stability.

3.1.1 The Analysis of the Flat Bottom

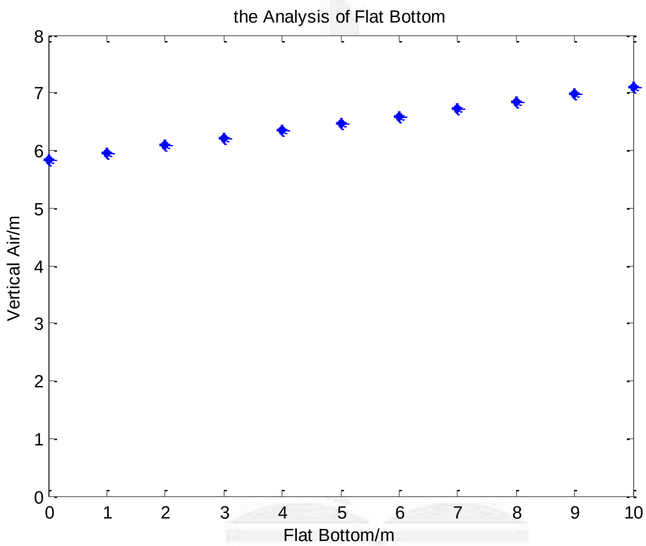

Figure 6 The analysis of flat bottom

From the Figure 6, we can obtain the relation between the flat bottom and the vertical air. The length of the vertical air will increase with the increase of flat-bottom. There is a positive correlation between them. But the change of the flat-bottom doesn't have an obvious effect on the change of vertical air.

3.1.2 The Analysis of Transition

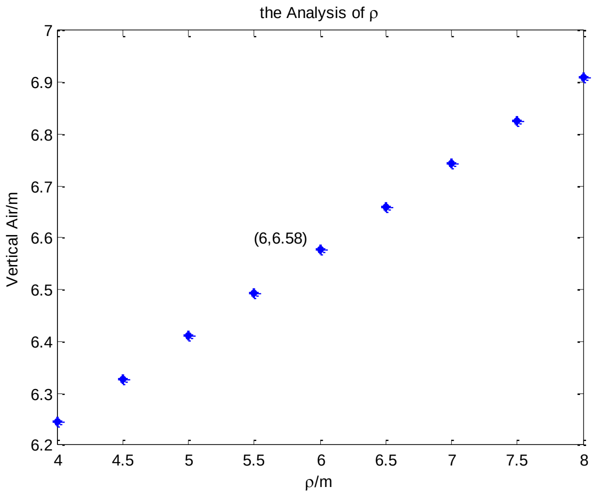

Figure 7 The analysis of transition ($\mu = 0.05$)

Firstly, we assume that the transition is a standard arc to simplify our model. As a result, the curvature radius of transition is the radius of arc. According to the Figure 7, the analysis of transition, the air vertical raise with the rising of the curvature radius of transition. As a result, there are positive correlation between the vertical air and curvature radius of transition, and the effect is impressive.

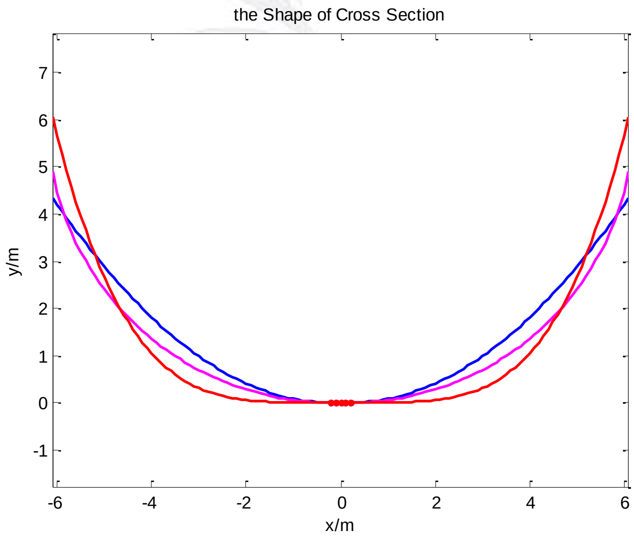

Figure 8 Comparison of different types of transition

Obviously, this assumption is not accurate but it provide the a approximate relationship between the vertical air and the curvature radius of transition. By simulating of different type of curves, we find out that when the transition's geometric function is $y = ax^4$, snowboarder can reach the maximum vertical air. After further simulation, we obtain that $a = 0.005$. In this situation, the maximum vertical air can reach to 7.3m.

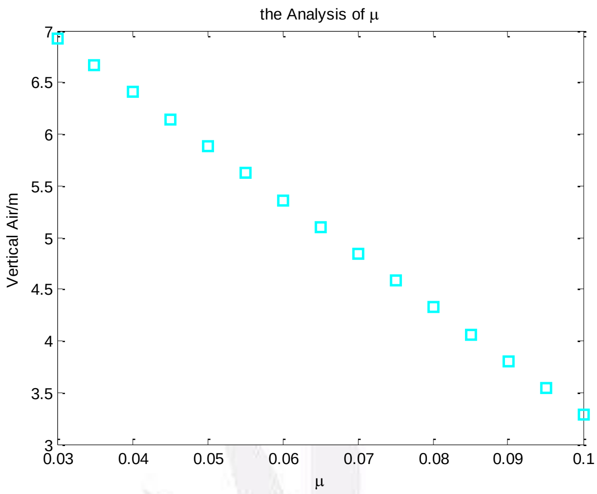

Figure 9　The sensitivity analysis of friction coefficient

What's more, the friction coefficient between snowboard and snow surface μ also has influence on the vertical air. The value of μ affect the friction on the surface, which will lead to the consume of energy. From Figure 9， we can see that with the rise of μ the vertical air decrease obviously. When the μ is large, the relationship between the vertical air and curvature radius of transition will change completely, just as the Figure 10 shows.

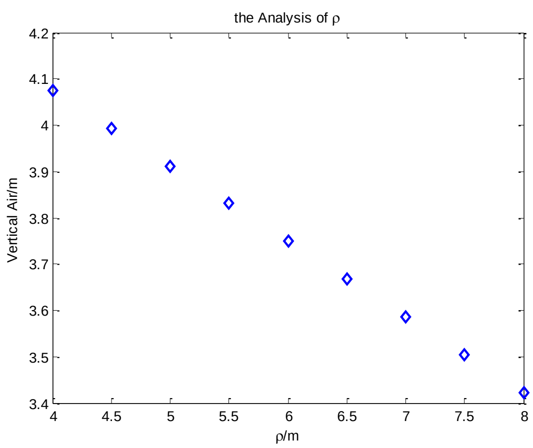

Figure 10 The relationship between ρ and vertical air ($\mu = 0.1$)

3.1.3 The Analysis of the Slope Angle

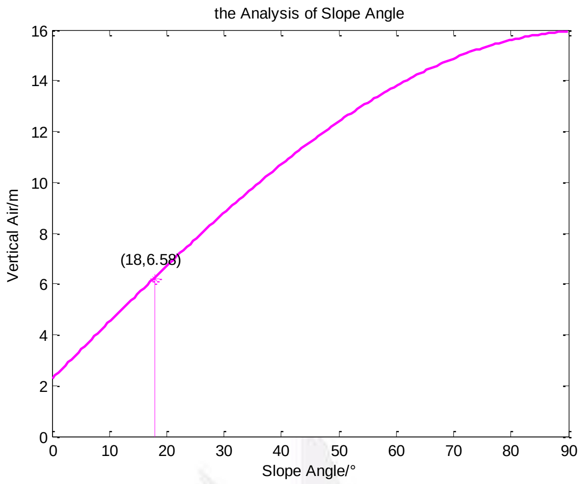

Figure 11 The analysis of slope angle

From the Figure 11, we find out that slope angel has an impressive positive correlation to the vertical air. Meanwhile, the degree of the correlation falls down with the increase of the slope angle. The reason may be explained as the following: with the angle increasing, the kinetic offered by the gravity increases, causing the vertical to increase. But in the real life, the angle is impossible to rise to $60°$. Because the vertical air is too high for human being to suffer, this may cause many serious injuries.

3.1.4 The Analysis of the Height of Vert and Angle β

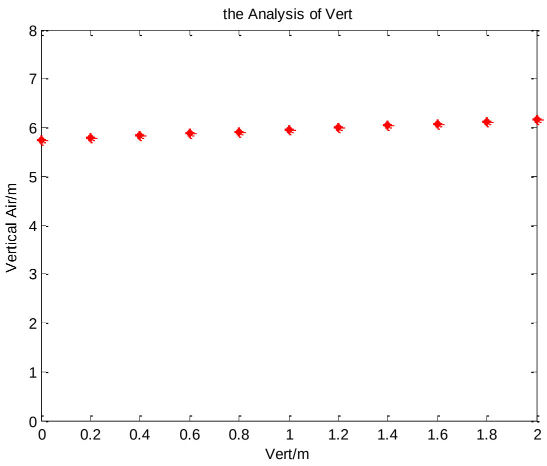

Figure 12 The analysis of vert

In a snowboard course, the vert is used to change the snowboarder's direction of taking off. With the vert, snowboarder can ensure his taking off direction is vertical, or he will be out of the course and injured. But according to our analysis, the height of vert doesn't has obvious influence to the value of the vertical air. Just as the Figure 12, we make the height of vert is 0.4m.

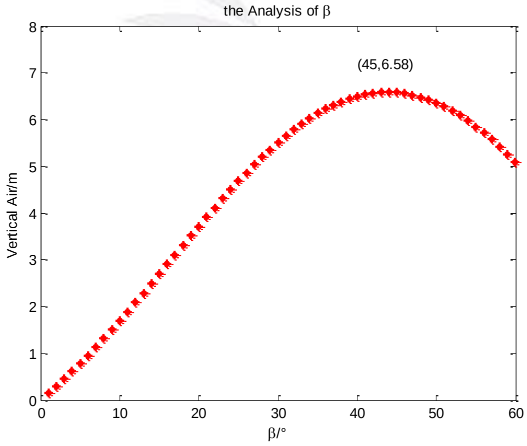

Figure 13 The analysis of β

Based on the force analysis, we can know about that the velocity of snowboarder is related to the sliding route. Obviously, there are minimum consume of energy when the route is a straight line. The angle between the side of snowboard course and the route β also has influence to the velocity.

3.2 The Result of Implementation

From the analysis of each variable, we can obtain the relationship between the vertical air and every variable. And some variables have great influence on the vertical air , while some other variables have less influence. According to “The International Snowboard Competition Rules” , we know that each part of the half-pipe has a certain range. [5] It is usually accepted that the half-pipe is 100 to 150 meters long, 17 to 19.5 meters wide and has a height of 5.4 to 6.5 meters (from floor to crown). The slope angle is 16 to 18.5 degrees. In this range, we simulate the possible types of course and find the most optimal design.

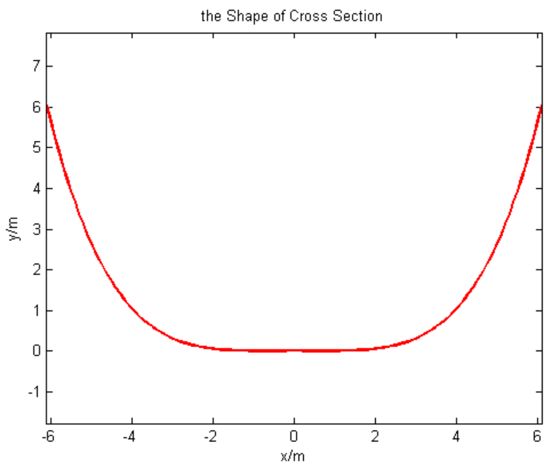

Figure 14　The most optimal design of halfpipe

At last, we find a most optimal design of snowboard course, with the length of flat bottom is 0.4m, the height of vert is 1m, the slope angle is 18 degrees, the geometric function of transition is $y = 0.005x^4$ and the edge angle is 86 degrees.

3.3 Adjustments and Tradeoffs

Our analysis of the dynamic model is purely theoretical, based on some ideal assumptions. While in the real world, the player is not a mass point without rotation, and the goal is not simply to reach the highest point. Practical situations are much more complicated and more factors should be taken into consideration. So we have to adjust the design of halfpipe to optimize various requirements.

3.3.1 Snowboarder's Safety

The safety of athletes is the most important takeoff in the design of course. The safety requirements should always be put in the first place. Take the design of edge angle as an example. In theoretical halfpipe the angle θ at the top of transition is the higher the better, and it should be close to 90 degrees. However, such large θ means less holding force from halfpipe to player, which will increase the possibility for player to fly away the track too early.

In contrary, when the player falls onto the surface of the halfpipes edge from air, the shock is in proportional to $\cos\theta$. So a too small θ may increase the shock, hurting players or making them lose their balance. In conclusion, θ should neither be too large nor too small. Usually this is set from 83 degrees to 88 degrees. [6]

The slope angle of the halfpipe α is another factors related to safety. Larger α means higher jump but also higher danger. Therefore, while adjusting α in our design, we could only slightly increase it from the theoretical value 17.1 degrees to about 17.5 degrees. This is also the actual slope angle used in regular game nowadays.

Besides, the change of the flat-bottom doesn't have an obvious effect on the change of vertical air. To minimize the energy loss caused by friction, the bottom part should be abandoned. However, if the flat bottom is abandoned, athlete will not have enough time to prepare for the next take off. As a result, we retain the flat bottom which has a short length to minimize the energy loss.

3.3.2 The Maximum Twist

In regulation games, players are demanded to play more twists in the air. The angular velocity for twists is obtained by wriggle the waist and stomp the ramp. To help players perform more twists, we should provide them more time in the air, and offer them a more safe vert to step on. But according to our analysis, the height of vert doesn't has obvious influence to the value of the vertical air. If we just consider the minimum loss of energy, the height of vert is the lower the better. Obviously, a lower vert will influence the twist of athlete.

So on one hand, we could increase α to speed the player up within the safe range. On the other hand, the height of vert should be reasonable.

3.3.3 Construction Difficulty

The shape of curve is not a big problem challenge in actual construction. However, the building of vertical ramp may increase the difficulty, since the vertical surface can not hold the snow firmly on its surface. Therefore, decreasing θ from nearly 90 degrees to 85 degrees can also meet construction requirements. [7]

4 Conclusion

In our paper, we study the design of a snowboard course and its factors from the view of energy. The main idea is to measure the “vertical air” by final energy. By making several assumptions, we build the dynamic model, which reveals essential interactions among different factors. Based on force analysis and energy analysis, we set up energy equations and obtain the general form of final mechanical energy. This final energy is used to measure the vertical air.

Based on our model, we firstly study the each part's influence on the vertical air respectively and change each parameter to find out the suitability and stability. We find that the flat-bottom and the height of vert don't have an obvious effect on the change of vertical air, while the slope angle α, the curvature radius of transition ρ and the angle β have obvious effect on the vertical air.

Then, by simulating of different type of curves, we find out that when the transition's geometric function is $y = ax^4$, snowboarder can reach the maximum vertical air. After further simulation, we obtain that $a = 0.005$.

At last, the adjustments and tradeoffs to develop a practical course are discussed. After taking consideration of construction difficulty, snowboarder's safety and their maximum twist, we adjust the parameters of the halfpipe to make our result more practical.

In conclusion, we find a most optimal design of snowboard course, with the length of flat bottom is 0.4m, the height of vert is 1m, the slope angle is 18 degrees, the geometric function of transition is $y = 0.005x^4$ and the edge angle is 86 degrees.

5 Strengths and Weaknesses

Like any model,the one present above has its strengths and weaknesses. Some of the major points are presented below.

5.1 Strengths

- We build a simple dynamic model first and then introduce corrections step by step. Therefore, it is easier to analyze the effect of different factors separately.
- We have taken many kinds of different factors into consideration and made all the

analyses systematically and comprehensively.

- A lot of figures are set to illustrate the relations between different variables. This is more accessible and easier to analyze than those complicated function expressions.
- The halfpipe size and the slope angle obtained by our model fit the real data well. That's to say, our model is successful in application.
- Based on some additional factors, the safety, construction difficulty and maximum twist, we adjust our design of this course and make it more practical.

5.2 Weaknesses

- To simplify our model, the direction of velocity is considered unchanging though out the movement. However, in fact, one skilled snowboarder may change his moving direction to achieve some complex tricks.
- We ignore the influence of snowboarder's movement on the height of vertical air, which may reduce the computational accuracy.

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