國立交通大學

機械工程研究所

碩士論文

變速自行車鏈條設計

Design of Chains on Multi-speed Bicycles

研究生：張崇銘

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摘要

本論文主要研究對象為自行車上傳動系統中的鏈條元件，由於自行車飛輪受到車架、騎乘姿勢所形成的空間限制，必須在有限空間內增加飛輪片數增加齒數比，達到變速換檔的舒適性。因此，為了配合這樣緊密的飛輪，鏈條寬度的縮減是必須的。經過專利的整理後，確定空間尺寸和強度為初步設計的主要需求；提出不同的概念設計，並利用新的鏈條連結機構來達到鏈條寬度的縮減。

本文提出概念設計較目前市面上自行車最窄的鏈條寬度更窄，強度部份利用有限元素分析法做定性分析，比較各個設計的相對強度；此外也經由原型的製作，檢視其機構的問題。

Design of Chain on Multi-speed Bicycle

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ABSTRACT

This study focuses on the chain for the multi-speed bicycle. Design space for the freewheel on bicycle is limited by frame, riding posture, etc. However, the number of gear ratios in this design space increased with added more sprockets are the trend on the bicycles. Therefore, reduction of chain width is necessary for working with this compact freewheel. Space and strength are main requirements in the beginning of design according to literatures and patents review. Several new concepts are proposed, and these concepts use the linkage mechanism to achieve the reduction of chain width.

Chain width of these concepts proposed in this study can be reduced under the assumption for fixed design space and thickness of sprockets. The finite element method is used to compare the trend of strength among these concepts. Mechanism problem for the concept design can observe from the prototype.

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1.1 Bicycle Transmission Systems

A bicycle transmission system uses to transmit energy from the pedals to wheel. There are several forms of bicycle transmission used today, and can be divided into three main types by transmission means. One is "derailleur transmission"; another is "hub transmission"; and the other is "continuously variable transmission (CVT)". Different type of transmissions is applicative in respective bicycle markets, for example, CVT is usually applicative on electric bicycles.

1.2 Motivation

In recent years, an obviously trend on new generation multi-speed bicycle is that more gear ratios are designed on both the derailleur transmission system and the hub transmission system. Fig. 1.1 shows the trend of freewheel, and number of sprockets increases with years. The maximum number of sprocket is ten, and will probably increase in the future. The advantages with more gear ratios are more comfortable, smooth shifting, and riders have more choices. As a result of above-mentioned, designer can design more gear ratios.

However, there are breakthrough and difficulties after 10-speed derailler transmission system-space and strength. Fig. 1.2 shows a brief top view of derailler transmission system and two ways that can increase gear ratios:

Left diagram: increases the number of sprockets of chain wheel directly; for example, if a bicycle transmission system has 27 gear ratios (3x9), one more sprocket of chain wheel will increase 9 gear ratios (although some transmission ratios maybe repeat). However, pedals also have to move outwardly. Cyclists feel uncomfortable because the outward pedals. Therefore, this method is unsuitable.

Right diagram: Increases the number of sprockets of freewheels directly; however, chain is over biased due to the added sprocket. Therefore, this method is also unsuitable.

Freewheel have the space limit, and added sprockets put in this space. Freewheel is more and more compact. Therefore, reduces width of bicycle chain is necessary. Traditional technique reduced width of each chain plate and achieved the total reduction. However, reduction of material also decreases strength of chain. This method can not go on when strength is not enough.

This study for "multi-speed bicycle transmission system" focuses on new chain to increase the number of gear ratios. Not like traditional technique, this study uses new chain mechanisms to form narrow chains.

1.3 Thesis Organization

In this study, Chapter 1 makes a brief introduction of bicycle transmissions, motivation and thesis organization; Chapter 2 lists reviews the transmissions and chains on bicycles in the literatures; Chapter 3 introduces some requirements and the theory of "TRIZ" when designing a chain; concept designs are introduced in Chapter 4; Chapter 5 presents the manufacture and discussion for the prototypes; Chapter 6 establishes a analysis process to determine tensile strength of chain plate; finally Chapter 7 is conclusions and future works.

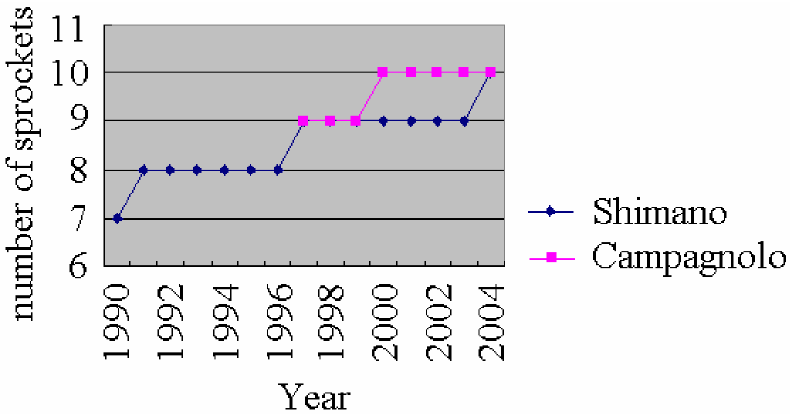


Fig. 1.1 Trend for number of sprockets of freewheel

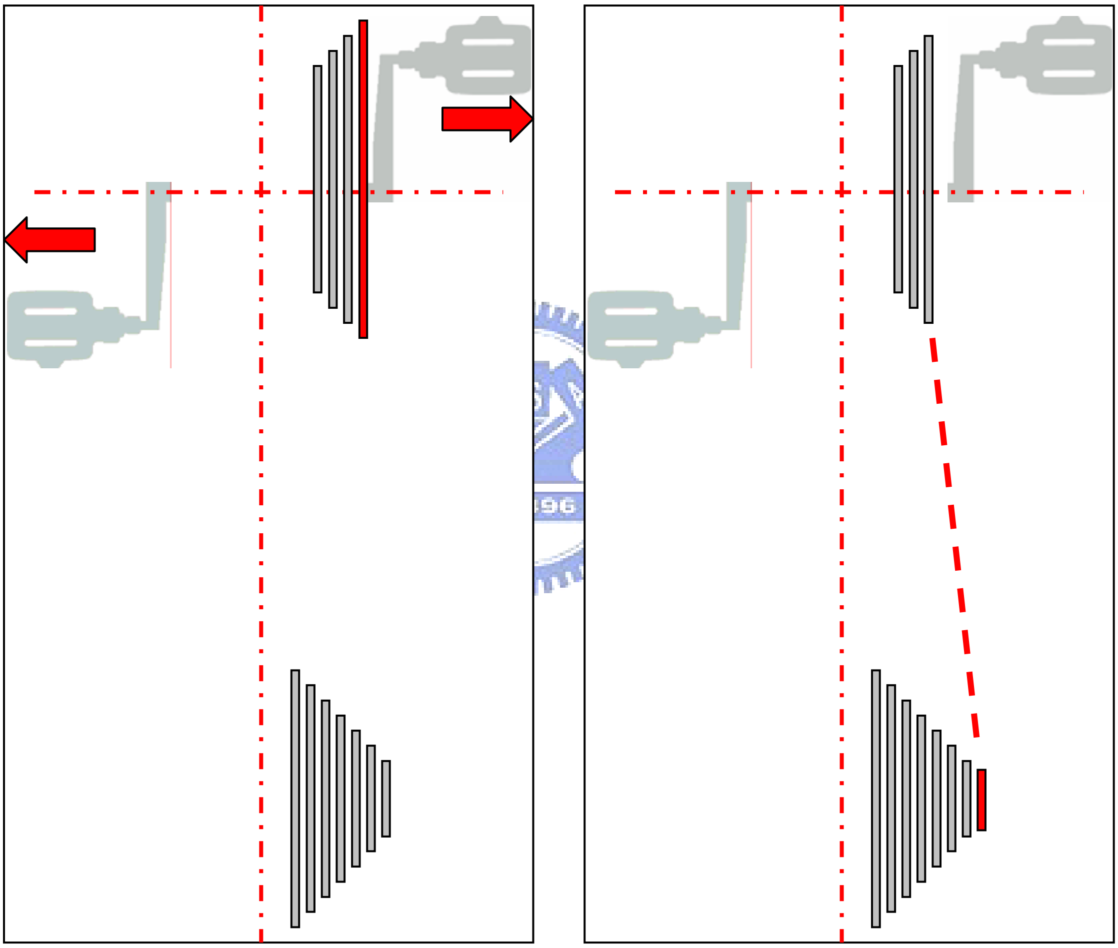


Fig. 1.2 Two ways can increase transmission ratios

Chapter 2 Literature Reviews

A transmission system is very important for a vehicle. For a bicycle, there are many types that can transfer human power to mechanical power. Most of transmission systems on bicycles use medium – chain to transfer power. This Chapter introduces the typical types of bicycle transmission systems and chains.

2.1 Bicycle Transmission

2.1.1 Derailleur Transmission

Derailleur transmission is in common used on bicycles in the world. As shown in Fig. 2.1, rider stamps on pedal (not shown in the figure) to rotate cranks and uses roller chain to connect the cranks to rear wheel. When rider wants to change gear ratio, he or she can use cable to control front and rear derailleurs. Derailleurs can shift the chain on the assigned sprockets and then change the gear ratio. Derailleur transmission has high efficiency than 95%.

2.1.2 Hub Transmission

Hub transmission is similar to derailleur transmission in operating, but derailleur transmission is outer transmission, and hub transmission is inner of bicycle. Hub transmission was proposed by Sturmey Archer in 1902 [1].

Hub transmission use epicyclic gear principle [2]. All gears rotate around a fixed pinion, the Sun Pinion. This is contained within a planet cage which also contains pinions, the Planet

Pinions, which rotate around the Sun Pinion. As shown in Fig. 2.2, if the planet cage is turned 90°, this moves the gear ring which rotates around the planet cage 90° plus extra 5 teeth due to the rotation of the planet pinions. These 5 teeth is 30° making a total of 120°. This means the gear ring always rotates faster than the planet cage in a proportion of 120:90, giving a gear ratio of 4:3.

Refer to Fig. 2.3, inputs and/or outputs can be connected to A, C, and D. In a bicycle hub gear, A is on a stationary shaft. In the low gear, the chain-sprocket input is connected to C and the output D is connected to the wheel hub. In top gear, these connections are reversed. The gear set is bypassed in middle gear, with the sprocket connected via the freewheel to the wheel hub.

Hub transmission is usually heavier and has lower efficiency than derailleur transmission.

2.1.3 Continuously Variable Transmission

Continuously variable transmission (CVT) is in common use on automatic vehicle, and rare on bicycle 錯誤! 找不到參照來源。. CVT usually use belt or other flexible elements, and has lower efficiency compares with derailleur transmission, about 80%~90%. As shown in Fig. 2.4, a CVT on bicycle in which the working diameter of the gearing mechanism is increased or decreased in response to various amounts of torque being applied to the pedals by the rider.

2.2 Chain

The greater part of bicycle use roller chain to transfer power, and few use other chain, like silent chain. Silent chain exists in industry for a long time. Therefore, this Chapter introduces these two chain type and list a comparison of roller chain and silent chain.

2.2.1 Roller Chain

A bicycle chain is arranged as a closed loop and engages one of the gears of the chain ring and one of the sprockets.

A conventional bicycle chain [4] according to the known technology is illustrated in Fig. 2.5. Fig. 2.5 shows a portion of a chain, comprising outer links “A” alternating with inner links “B”, mutually hinged about axes of articulation “C”. The two outer plates “D” have coaxial holes “E” within which the end of an articulating pin “F” are secured with an interference fit. Pin “F” supports, with articulation, two inner plates “G” constituting an inner link “B”. The inner plates “G” have coaxial portions “H” in the form of bushes, on which a roller “I” is mounted, free to rotate.

As mentioned in Chapter 1, recently developments in the pinion assembly associated with the rear wheel of the bicycle have led to the production of assemblies with an ever large number of pinions [5]. According to this trend, the chain becomes narrower and narrower. To minimize the thickness of bicycle chain is an object of this study.

2.2.2 Silent Chain

Silent chain [6], also called inverted-tooth chain, is used mainly for the transmission of mechanical power between rotating parallel shafts and for timing applications requiring high speed, no slip, and quiet operation. In the early history, silent chain was constructed of sets of links connected together at articulating joints by circular pins. Two-part joint comprising a pin and a rocker having abutting surfaces appeared with time [7].

Left figure of Fig. 2.6 shows the style of joint design used by the manufacturer, Ramsey Products Corporation and right one shows the engagement situation with sprockets.

Few applications of silent chain used on bicycles, Fichtel & Sachs AG, Schweinfurt have claimed a chain drive mechanism for a bike [8]. The chain is similar to silent chain. In face, it is a roller chain, but changes the profiles of link plates on one side roller chain, these link plates all have a pair of teeth.

2.2.3 Comparison

Some features of silent and roller chain are compared and list on Table 2.1. This table is according to the common use of chain. Obviously, silent chain has more advantages than roller chain. However, silent chain on bicycle has some difficulties like space requirement, and the development cost is a considerable problem. The transmission of bicycle may need to design whole system again due to the use of silent chain. Oppositely, the future transmission type of bicycle is unknown, silent chain is also a possible solution for multi-speed bicycle with more and more variable ratios.

2.3 Remarks

1. Most bicycle use derailleur transmission because of its high efficiency
2. Hob transmission is complex.
3. CVT usually has flexible parts. If flexible parts can be substituted by engaged parts, efficiency will increase.
4. Silent chain has many advantages compares with roller chain. However, both chains have similar space requirement; and then have similar number of gear ratios.

Table 2.1.   Comparison – silent chain versus roller chain

Chain types / Features	Silent chain	better than (>) worse than (<)	Roller chain
Efficiency		>	
Operating speed		>	
Noise		>	
Space requirement (present use)		≈	
Sprocket life		>	
Impact and sliding (engaging situation)		>	
Installation		<	

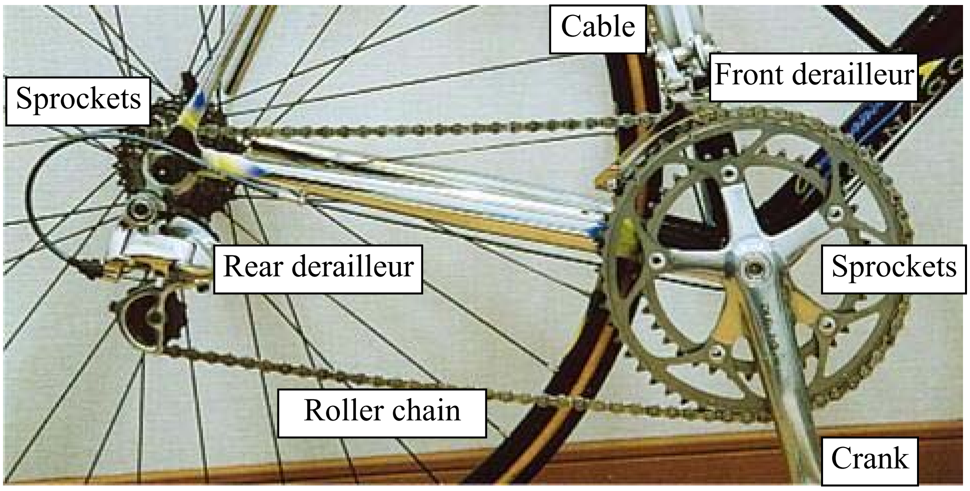


Fig. 2.1 Derailleur transmission

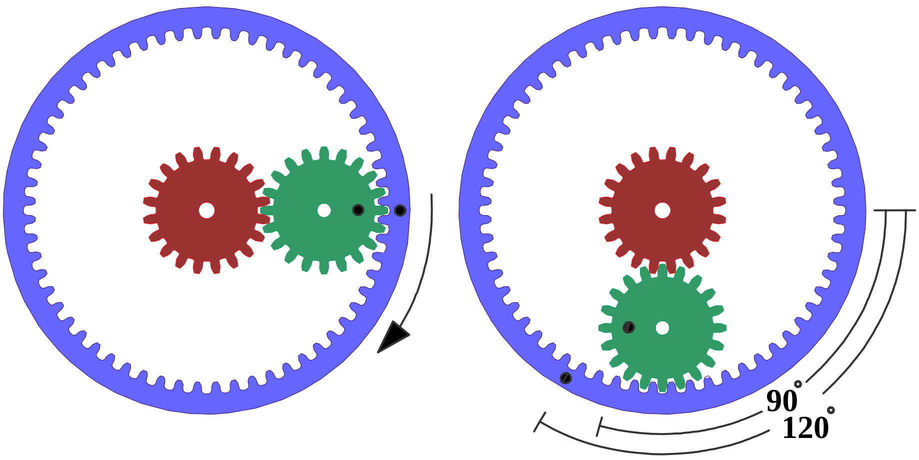


Fig. 2.2 Diagram of epicyclic gear principle

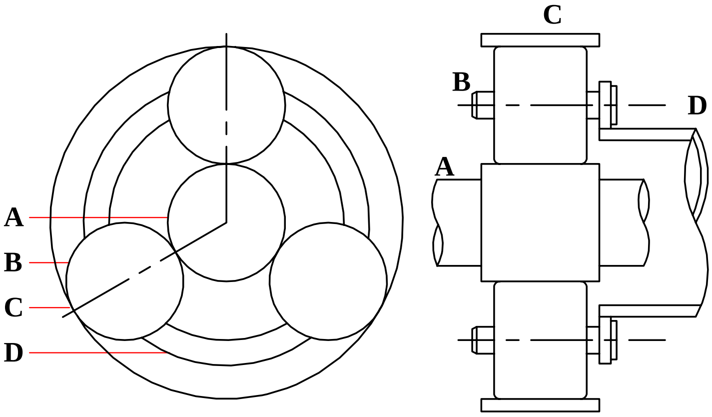


Fig. 2.3 Three speeds hub transmission

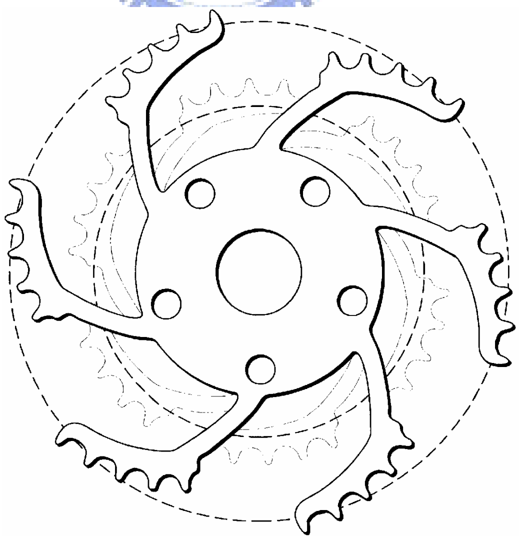


Fig. 2.4 CVT on bicycle 錯誤! 找不到參照來源。

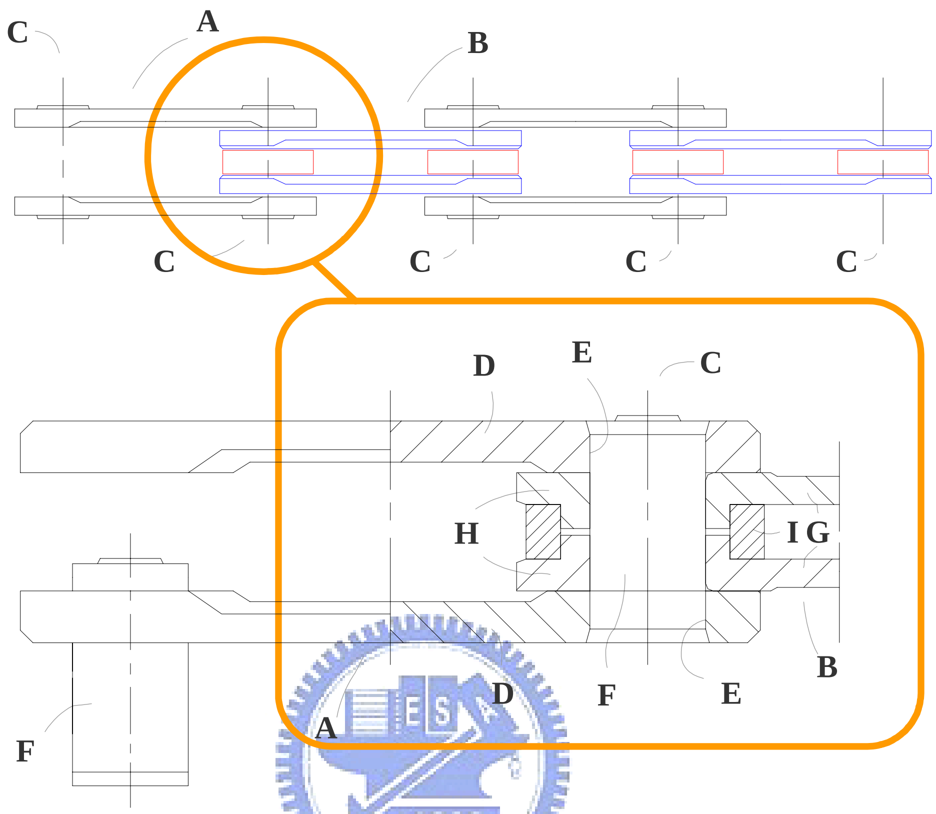


Fig. 2.5 Portion of a roller chain

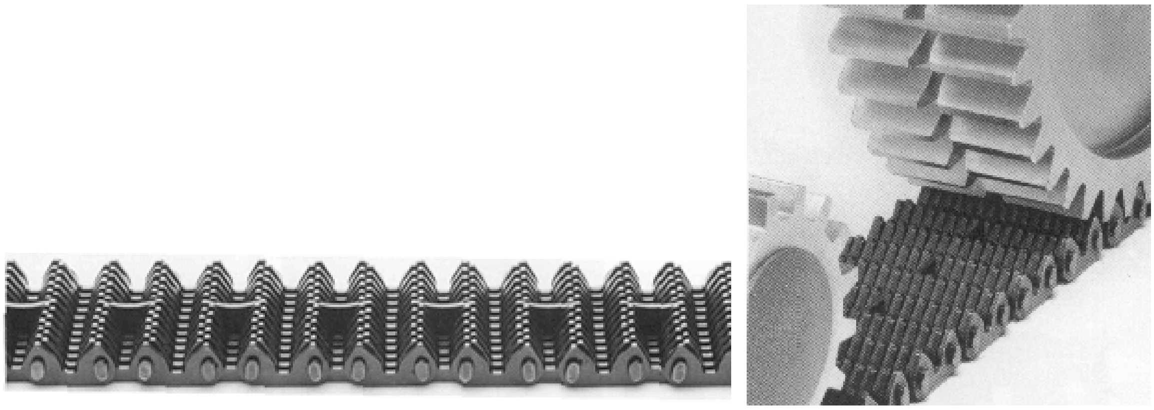


Fig. 2.6 Center guide assembly type of silent chain

Chapter 3 Design Method and Requirements

3.1 TRIZ

3.1.1 Introduction of TRIZ

"TRIZ" is the acronym for the same phrase in Russian. TRIZ was developed by Genrich Altshuller and his colleagues in the former USSR starting in 1946, and is now being developed and practiced throughout the world [10].

TRIZ research began with the assumption that there are universal principles of invention that are the basis for creative innovations that advance technology, and that if these principles could be identified and codified, they could be taught to people to make the process of invention more predictable. The research has proceeded in several stages over the last 50 years. Over 2 million patents have been examined, classified by level of inventiveness, and analyzed to look for principles of innovation. The three primary findings of this research are as follows:

- Problems and solutions were repeated across industries and sciences.
- Patterns of technical evolution were repeated across industries and sciences.
- Innovations used scientific effects outside the field where they were developed.

In the application of TRIZ all three of these findings are applied to create and to improve products, services, and systems.

3.1.2 Foundational Elements of TRIZ

As mentioned above, TRIZ is strictly not an algorithm; the method is not a single chain procedure. In fact, an algorithm for inventive problem solving also exists, called ARIZ is in a rapid and intuitive way. ARIZ is a simplified form of TRIZ [12].

TRIZ have many tools help people innovate [13]. This section proposes the classification of TRIZ, and some tools that will possibly use in chain design will be detailedly introduced.

Classification

The tool box of TRIZ can be classified into following four groups:

- analysis
- knowledge
- analogy and
- vision

Fig. 3.1 shows the four columns of the TRIZ method and its tools. This classification is a general type; there are other classifications defined. However, use these tools in the tool box with good flexibility is more important than the classification type. Several tools may be useful and convenient for a chain design, like "Problem Formulation Modeling", "Ideality", "Patents Data Base Research" and "Contradiction". These four tools are explained in the follows.

Problem Formulation Modeling

This method use "harmful function (HFn)" and "useful function (Ufn)" represent the drawbacks and main functions in a system. The definition of function is widely, anything you think can be defined as a function.

There are three relations between HFn and UFn:

UFn ⇒ HFn : UFn creates HFn.

UFn ─┼→ HFn : UFn eliminates HFn

UFn → HFn+1 : UFn supplies HFn+1

Furthermore, the item in a circle ○ is UFn and in a rectangle □ is HFn.

Some questions can help people define the functions. One confirmed answer represents at least one relation, and every confirmed answer guides other UFn or HFn. Repeat this procedure and build all relations.

Ideality

The aim of any technique is supplying functions, and in conventional thinking, machines or equipments must need to reach the aim. An ideal system does not need machines or technique to supply functions, this way can save cost, space and energy. Ideality is final target of inventions. There are six ways to find ideal system, and four processes to reach "Ideality"; list in the follows.

Six ways find ideal system

Remove assistant functions.

Remove system elements.

Find self-supply.

Replace elements.

Change operation.

Use resource.

Four processes to reach “Ideality”:

1. Describe the situation want improve.
2. Describe the ideal situation.
3. Do workable methods exist to realize ideality?

   If answer is “Yes”, write it down; if answer is “Yes” but also has drawbacks, than solve contradiction. If answer is “No”, think how to use resource; if there are difficulties, describe it.
4. What should change to overcome the difficulities?

Patents Data Base Research

Patents create rich technology database. By knowing the previous technique, and improve old technique. In this way, new generational product can be produced quickly. Some patent database is free, like USPTO, and there are over 6,600,000 patents in this database.

Contradiction

Contradiction analysis is a powerful tool. Contradiction can divide into engineering contradiction and physical contradiction. For engineering contradiction; improve a parameter may cause a bad effect to another parameter, and this type of contradiction is called engineering contradiction. For physical contradiction; certain parameter in a system must be in two contrary states, and this type is called physical contradiction.

(A) Solving engineering contradiction

After Altshuller analyzed more than 40,000 patents, he generalized 40 inventive principles [14]. Altshuller developed contradiction matrix in 1970s, the column and row of matrix include 39 features, as show in Table 3.1. First process of this method is to find the parameter want to improve in the column, than find the relational harmful parameter in the row. The intersection of two parameters includes some useful principles. All 40 principles are common concepts, as show in Table 3.2; and designers must use creativity to let these principles apply questions.

(B) Solving physical contradiction

The main technique of solving physical contradiction is “separation”: separate factors in different space or time. Use math model to describe as follows: assume physical contradiction has form like parameter $A > 0$, $A < 0$ at time $t = t_i$, position $X = (x_i, y_i, z_i)$. The method is let $A > 0$ at time $t = t_j$, position $X = (x_j, y_j, z_j)$; $A < 0$ at time $t = t_k$, position $X = (x_k, y_k, z_k)$. This way can solve contradiction $A > 0$ and $A < 0$ simultaneously.

3.2 Requirements

Some requirements must be conformed when designing a chain on bicycle. For example, material, tensile force, length of chain, lateral curve, assembly, manufacture, wear, fatigue, cost, etc. In the beginning of design, force and space requirement are important. Therefore, in this Chapter, these two requirements for "force" and "space" are indicated.

3.2.1 Force Standard

A brief force equilibrium diagram is shown in Fig. 3.2, tensile force T result from downward force F due to rider pedal. The distance between center of chainwheel and point of application of force is l; and the diameter of chainwheel is D.

Base on the model, tensile force T can be calculated from equation (3.1), and the force standard JIS D 9417 on Table 3.3 shows the minimum necessary tensile force of two standard bicycle chains [11].

$$T = \frac{F \times l}{\frac{D}{2}} \tag{3.1}$$

Analyses of tensile force are introduced in Chapter 6.

3.2.2 Space Limit

There are space limits in designing bicycle transmission. First, the present chain ring has 3 sprockets. To increase the number of sprockets can increase gear ratios, but unfortunately, the riding pose is also changed and this can not be used by riders.

Another space limit locates at freewheel. Chain ring has set 3 sprockets; if freewheel increase the number of sprockets outwardly, transmission direction of chain will be over oblique between chain ring and added sprockets of freewheel, shown in Fig. 3.3. The balance performance will also be worse due to the added sprockets.

Since the design space is limited, the thicknesses of chain and sprocket determine the number of gear ratio. The thickness of one sprocket in present products is 1.8mm, and to consider the strength problem, the reducible thicknesses are few. Therefore, the thickness or width of chain is an important key to improve the bicycle transmission.

D : total design space

N : number of sprockets

t : sum of gap between chain and adjacent sprockets

Wc : width of chain

Ws : thickness of each sprocket

Wss :distance between adjacent sprockets

According to Fig. 3.4,

$$\frac{(Wc+t)-Ws}{2}=Wss \tag{3.2}$$

Total design space D is limited; therefore, an inequality equation (3.3) is led due to the geometry relation.

$$\frac{D-(Ws \times N)}{(N-1)} \geq Wss \tag{3.3}$$

Finally, the variable N that designer and market concern can be calculated by following equation.

$$N \leq \frac{D+Wss}{Ws+Wss} \tag{3.4}$$

How many pieces of rear sprockets of freewheel can be put on for a new narrow chain? The answer depends on the width of chain. As mention above, if the width of chain is defined, than the number of sprockets of freewheel will be defined, too. From equation (3.2) to equation (3.4), the relation of width of chain Wc and number of sprockets N is found.

From Fig. 3.4, Wss can be calculated by equation (3.2), note that width of chain Wc is included in this equation. In following equations, all variables are known before calculating except Wc and N. Wc is the input and N is the output.

Table 3.4 lists some calculated results of space requirement. For example, if number of sprockets N is 12, then the width of chain Wc will be less than 4.83 mm. These values maybe need to re-calculate, because the total design space D may increase due to new wheel design or what.

In this study, some dimension requirements are fixed. Thickness of sprocket Ws is 1.8 mm and the total design space D is 4.1 mm.

3.2 Remarks

1. TRIZ solves engineering contradiction problems with contradiction matrix. 39 parameters and 40 principles are in the contradiction matrix. Principles are related to design parameters.
2. In the beginning of design, force and space requirement are important.
3. In this study, thickness of sprocket and total design space are fixed. These dimensions maybe change in the future. For example, total design space could increase if spokes of wheel move inward.

Table 3.1. 39 features of system

1. Weight of moving object	2. Weight of stationary object
3. Length of moving object	4. Length of stationary object
5. Area of moving object	6. Area of stationary object
7. Volume of moving object	8. Volume of stationary object
9. Speed	10. Force
11. Stress or pressure	12. Shape
13. Stability of the object's composition	14. Strength
15. Duration of action by a moving object	16. Duration of action by a stationary object
17. Temperature	18. Illumination intensity
19. Use of energy by moving object	20. Use of energy by stationary object
21. Power	22. Loss of Energy
23. Loss of substance	24. Loss of Information
25. Loss of Time	26. Quantity of substance/the matter
27. Reliability	28. Measurement accuracy
29. Manufacturing precision	30. External harm affects the object
31. Object-generated harmful factors	32. Ease of manufacture
33. Ease of operation	34. Ease of repair
35. Adaptability or versatility	36. Device complexity
37. Difficulty of detecting and measuring	38. Extent of automation
39. Productivity	

Table 3.2. 40 principles

1	Segmentation	21	Skipping
2	Taking out	22	"Blessing in disguise" or "Turn Lemons into Lemonade"
3	Local quality	23	Feedback
4	Asymmetry	24	'Intermediary'
5	Merging	25	Self-service
6	Universality	26	Copying
7	"Nested Doll"	27	Cheap short-living objects
8	Anti-weight	28	Mechanics substitution
9	Preliminary anti-action	29	Pneumatics and hydraulics
10	Preliminary action	30	Flexible shells and thin films
11	Beforehand cushioning	31	Porous materials
12	Equipotential	32	Color changes
13	'The other way round'	33	Homogeneity
14	Spheroidality - curvature	34	Discarding and recovering
15	Dynamics	35	Parameter changes
16	Partial or excessive actions	36	Phase transitions
17	Another dimension	37	Thermal expansion
18	Mechanical vibration	38	Strong oxidants
19	Periodic action	39	Inert atmosphere
20	Continuity of useful action	40	Composite structures

Table 3.3. JIS D 9417

JIS	Pitch	Diameter of roller	Thickness of inner link	Maximum thickness	Ultimate load
No.	(mm)	Max. (mm)	Min. (mm)	Max. (mm)	Min. (kgf)
1/2 x 1/8	12.70	7.75 ± 0.08	3.4	9.5	820
1/2 x 3/32	12.70	7.75 ± 0.08	2.4	8.5	820

Table 3.4. Some calculated results of space requirement

N	9	10	11	12	13	14
Wc	7.5	6.41	5.54	4.83	4.23	3.73

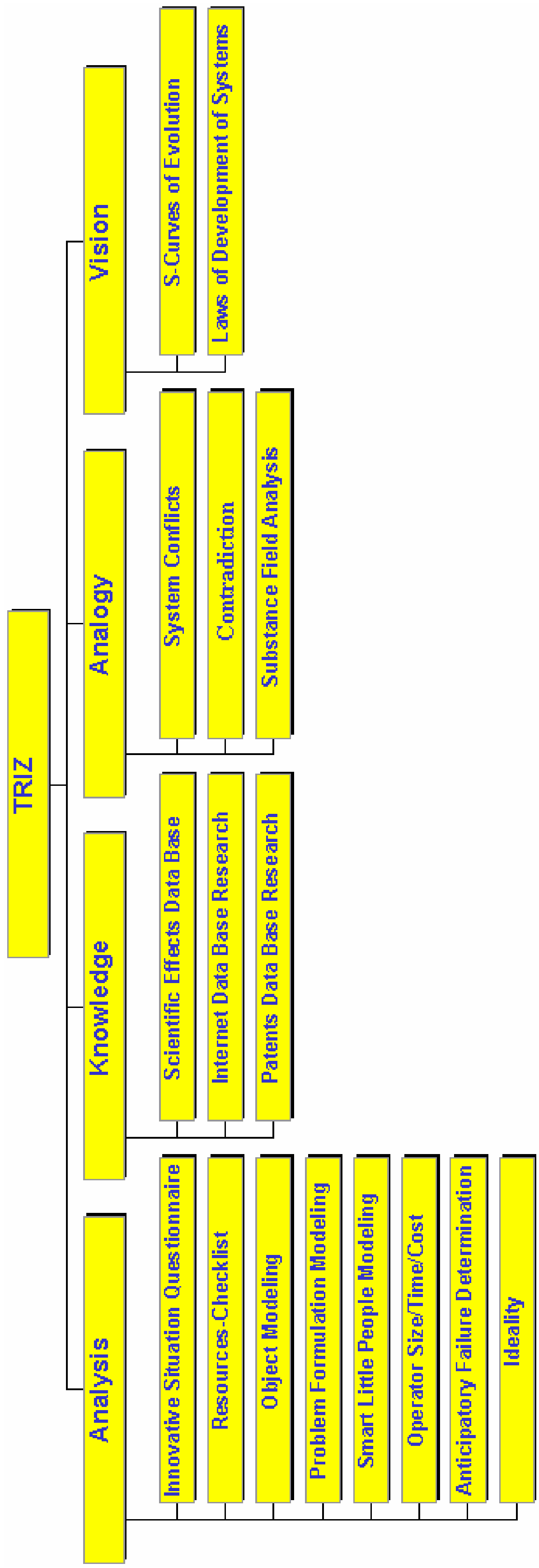


Fig. 3.1 Four columns of the TRIZ method and its tools

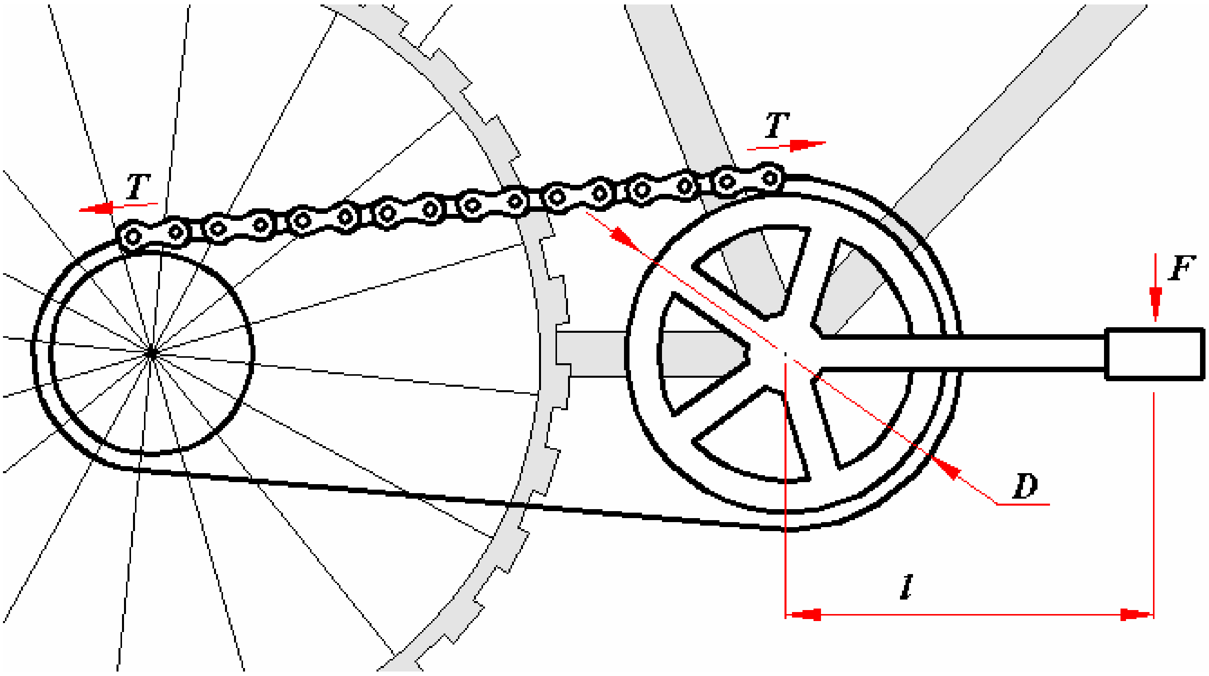


Fig. 3.2 Force equilibrium diagram of bicycle transmission

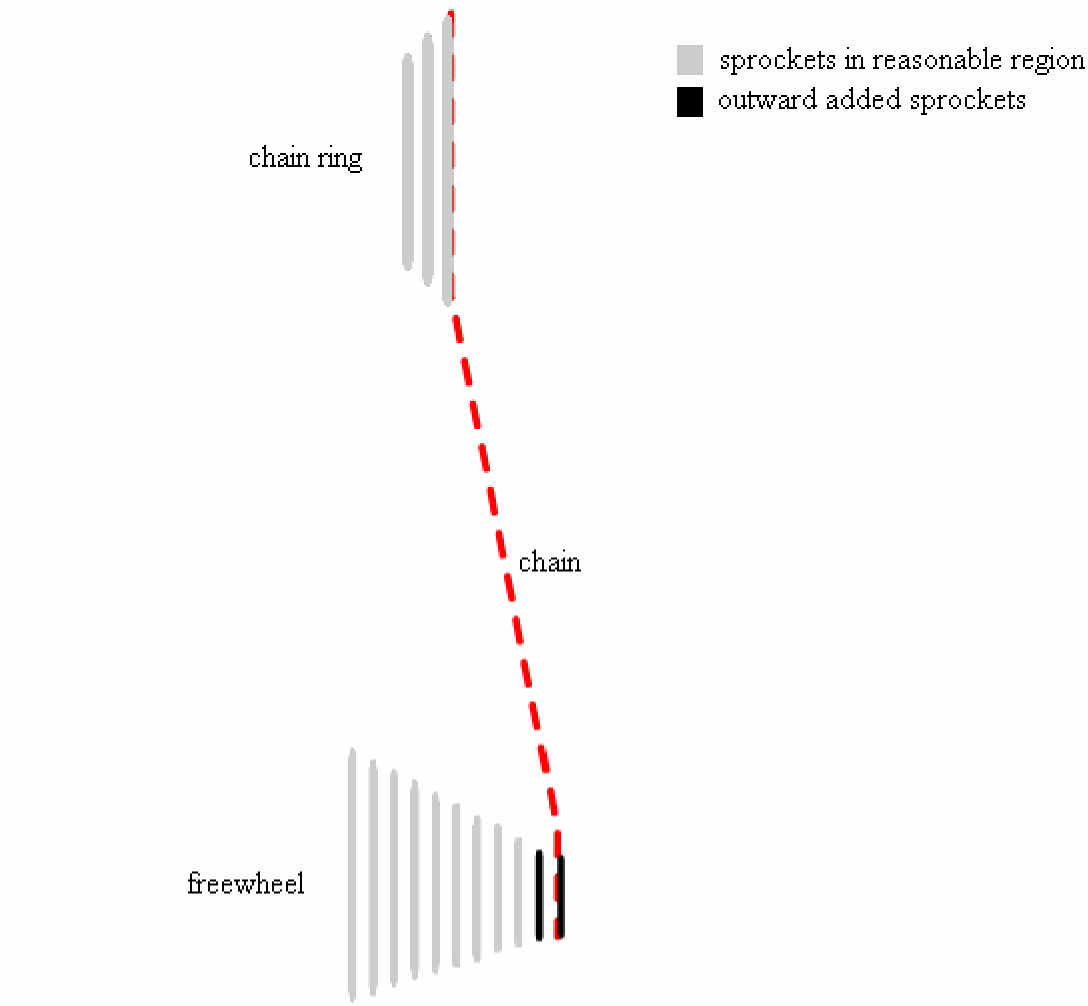


Fig. 3.3 Over oblique situation due to added sprockets

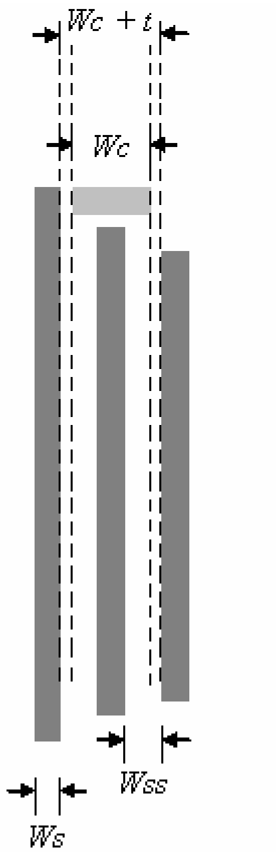


Fig. 3.4 Brief diagram of relation of chain and sprockets

Chapter 4 Concept Design

4.1 Present Design

Avoid infringing present products or designs on published documents, searching related information is necessary. The number of patents about bicycle chain is a small amount, and most patent focus on shifting or preventing dust. There are some patents are about narrow chain [15] [16], and the techniques focus on eliminate pin protrusion.

Table 4.1 shows width of different bicycle chain products, the narrowest chain product is “Shimano CN-7800” – 5.6 (mm). The assembly of “Shimano CN-7800” is the same as current bicycle chain; but thickness of each chain plate is thinner. However, the method can not go on because decrease of chain strength. New mechanism is one method to reduce width of chain.

One patent is worth of mention: US NO.5, 921,881 proposed a new mechanism of chain [17]: “Narrow bicycle chain with inner links that receive sprocket teeth within a bottom recess”. From Fig. 4.1, the shape of inner chain plates have concave portions. The important advantage of this type of narrow chain is its composition. One section of chain comprises two outer link plates, two inner link plates and one roller, total five elements. In other words, there are five thicknesses needed for bicycle chain from the top view. However, there are only three thicknesses needed for the narrow chain in Fig. 4.1. And Fig. 4.2 is the top view of narrow chain, and three thicknesses can be seen clearly in this figure.

The concave plate has a bottom recess, and this is the key of this technique. The bottom recess contains the teeth of sprocket so that outer link plates in past design can be decreased. The number of components also reduces.

Because the concave plate has a bottom recess, the strength of chain is worse than current one. The problems about strength of the concave plate and current chain plate are discussed in following Chapter.

4.2 Concept Designs

In this section, several concept designs for narrow roller chain are proposed. Some concept designs emphasize the bicycle chain itself; others emphasize the transmission system.

4.2.1 Concept 1

The concept 1 shown in the Fig. 4.3 is similar to current bicycle chain. This concept includes outer plates, inner plates and pins. The outer plate is similar to the outer plate on current bicycle chain, but cut some region of both arc ends; the inner plate has two curved sides and two circular parts. The outer plates and inner plates connect alternately with pins; pin fixes with outer plate and revolves with inner plate.

Fig. 4.4 shows the situation that inner plate rotate around pin. When chain is stretched, θ is 60˚. Maximum θ is 120˚ and can make chain operate regularly. This range can be used to current bicycle transmission system.

Besides the angle range, chain design on current bicycle system must be workable when chain is reverse, because chain need to reverse on one guide gear of rear derailleur. Concept 1 is the same whether chain is reverse or not. The bicycle chain design in 4.1 is different due to its bottom recess. Therefore, the re-designed guide gear shown in Fig. 4.5 is different from current one. [17]

Concept 1 and the chain design in 4.1 both have the same property, roller is not existed. Roller on current bicycle chain rolls when it gets into or leaves tooth of sprocket, this action can reduce the sliding between roller and tooth of sprocket. That is one reason why the efficiency of roller chain is high. The two designs use solid part to replace roller, so the sliding produces absolutely. Except efficiency, the life of the two chains also decreases due to the wear between solid part and tooth of sprocket.

There is still one problem on concept 1 – manufacture. The inner is difficult to manufacture because it is a closed part and that will increase the cost.

4.2.2 Concept 2

On the whole, concept 2 is the same with concept 1. However, concept has the manufacturing disadvantage. This bicycle chain concept 2 also includes outer plates, inner plates and pins. The outer plate is the same with concept 1, but the inner plate is half of concept 1. The outer plates and inner plates connect alternately with pins; pin fixes with outer plate and revolves with inner plate.

The inner plate is easier to manufacture than the one in concept 1, it perhaps manufacture by sheet metal stamping.

Manufacture for bicycle chain is important because bicycle chain is made up of repeated components. Therefore, sheet metal stamping or forging is common in chain manufacture. There is another way to down the cost –decrease the number of components. Form this direction, concept 3 is proposed.

4.2.3 Concept 3

As mentioned above, the design of concept 3 is for cost. The method "SCAMPER check list" is used to decrease the number of components. The technique "combine" is suitable for solving this problem. The outer plate and inner plate can combine and produce a new part.

Fig. 4.7 shows the exploded view of concept 3; this bicycle chain is made up of uniform chain plates. The uniform chain plates connect alternately with pins; pin fixes with the smaller end and revolves with the curved end.

From concept 1 to concept 3, it is similar. The chain concepts improve for manufacture and cost considerations. However, the three concepts have one common problem, the strength reduce due to the curved parts. Obviously, the chain plate will bend if the tensile force is more and more large.

4.2.4 Concept 4

One design method can be seen at above narrow chains. Number of components decreases and approximately three components is in cross section. Previous method reduces thickness of each chain plate and chain width also reduces. However, this method can not go on, the strength of chain plate also reduces when cutting down thickness of chain plate.

Fig. 4.8 shows opposite position of teeth on sprocket and engaged parts, engaged parts may be roller or solid parts as above concepts. Base on above method; draw the top cross section shown in Fig. 4.9, use two link parts to connect those engaged parts. But link parts have to revolve to each other, this problem must be solved.

TRIZ introduced in Chapter 3 can provide some principles for solving this problem. Fig.. 4.1 shows a part of contradiction matrix. For narrow chain design, dimensions roughly decrease and strength hence reduces too. According to Table 4.2, the worsening parameter assigns to 14(strength) and the improving parameter assigns to 3(length of moving object). Four principles are provided, and Table 3.2 shows what those principles are.

Principle 8: Anti-Weight

Principle 35: Parameter Changes

Principle 29: Manufacturing precision

Principle 34: Discarding and Recovering

Use principle 35(parameter changes) to solve the problem of link part. Link part can be flexible, and the engaged parts can revolve to each other. Fig. 4.10 shows basic assembly of concept 4, it is made up of engaged parts and flexible link parts; the flexible link part can be cable or otherwise. However, concept 4 in Fig. 4.10 has so many degrees of freedom that can't limit chain in transmission direction.

For decreasing the degrees of freedom, concept 4 can add boards, shown in Fig. 4.11. Those boards are fixed to those engaged parts, and chain is limited in transmission direction when it works.

4.2.5 Concept 5

Four principles of TRIZ are led out in 4.2.4 and concept 4 uses principle 35 to change parameter of part. Therefore, three principles remain on the table. This section finds out whether another useful principle exists.

Principle 34 is "Discarding and Recovering", the definition is [14]:

A. Make portions of an object that have fulfilled their functions go away (discard by dissolving, evaporating, etc.) or modify these directly during operation.

B. Conversely, restore consumable parts of an object directly in operation.

Discard rollers and outer plates of bicycle chain as step A, and restore outer plates to the position between inner plates. Concept 5 shown in Fig. 4.12 is made up of inner plates and recovered outer plates and pins. The function of roller is substituted by recovered outer plate.

In fact, concept 5 is similar to double pitch chain. Double pitch chain is common in industry. Double pitch roller chain has essentially the same application characteristics as standard pitch roller chain; generally used on lighter duty applications such as conveyor drives and slower speed drives.

Use concept 5 on current bicycle transmission causes problems, and the most obvious one is the compatibility with sprockets. Sprockets need matching up the double pitch. However, the advantage of concept 5 (compares with previous concepts) is its strength. The plates have no bend; the recovered plates shown in Fig. 4.12 can be even thicker than current bicycle chain plates.

4.2.6 Concept 6

From concept 1 to concept 5, these concepts are related to designs of chain itself. Following concepts are not single chain design, but system design. System design here means bicycle transmission design, especially means rear transmission system design.

In concept 6, bicycle chain becomes a sprocket. The basic operated way is shown in Fig. 4.13. Chain encircles and forms a sprocket, therefore, another chain still need to drive the sprocket shown in Fig. 4.13. There is flexible part in the inner space of sprocket; flexible part always pushes outward and keep the sprocket become a circle. The upper sprocket shown in Fig. 4.13 is larger than lower one.

Fig. 4.14 shows the improved concept 6. "A" is the base; "B" is guided board, guide the chain plates when cable puts or pulls; "C" is cable; "D" is screw and roller, the position of roller can extend or shorten by screw; "E" is a flexible part (similar to disk spring), enable the sprocket become a circle.

The chain plate also shows in Fig. 4.14. The chain plate have two extrusions because the chain plate also need engages when the sprocket changes it diameter.

4.2.7 Concept 7

Concept 7, as said above, is also a system design. It is similar to current bicycle transmission. Sprockets of current bicycle are coaxial but not coplanar. However, sprockets of concept 7 are coaxial and coplanar. This is unreasonable because there are interferences between different sprockets. Following, the question is explained.

The interferences said above are due to the shift action changes to up and down, not previous axial direction. Therefore, solving the shifting problem can let chain shifting on coaxial and coplanar sprockets.

Fig. 4.15 shows front view of concept 7, there are only half sprockets in the figure. That is the key of concept 7, and half sprockets can eliminate interferences between different sprockets. Teeth of sprockets have inclined planes.

Fig. 4.16 shows exploded view of concept 7. Transmission disk has many holes to contain teeth of sprockets, connect by springs; fixed disc has arc slots. When chain drives transmission disk, teeth bounce in the slots and compress in other area of fixed disk. Inclined planes can force teeth of sprockets compress rapidly.

Fig. 4.17 shows an example of chain with concept 7, the chain shifts from B to A. However, when chain extents to shift from A to B, the upper link touch B first and cause failed shifting. Fig. 4.18 shows another example of chain of concept 7, and it includes link plates, engage plates and pins. Engage plates have engage slots; these slots engage teeth shown in Fig. 4.16.

4.3 Remarks

1. The first five concepts are chain designs and the last two concepts are freewheel designs.
2. From concept 1 to concept 3, curved plates are used to form narrow chains. However, curved plate has lower strength than flat plate oppositely.
3. Concept 4 uses cables to link parts and form a narrow chain. Strength of cable is high, but the fixed method between cables and parts is main problem.
4. Concept 5 changes the pitch of bicycle chain, and this involves the compatibility with sprockets. Pitch of sprocket must be the same with pitch of chain.
5. Concept 6 proposes a new sprocket, and main part of this sprocket is a chain linkage. However, this concept is in the beginning, this study just proposes several main parts. The flexible part maintains this circle of sprocket, and efficiency also losses due to the deformation.
6. Concept 7 is a design of freewheel; the most different is the sprockets of freewheel is co-axial and co-planarity. Chain can shift on different sprocket because half teeth of each sprocket hide.
7. Widths of chains of first five concepts are all 4.4 mm.
8. Analyses of tensile force of several concepts are introduced in Chapter 6.

Table 4.1. Width of different chain products

Production type	**Width**
Shimano CN-7800	5.6 mm
Campagnolo C10	6.1 mm
KMC X10	6.2 mm
Wippermann connex 10-speed	6.2 mm

Table 4.2. Part of contradiction matrix

worsening Parameter / improving Parameter		…	14	15	…
		…	strength	duration of action of moving object	…
ʃ	ʃ	ʃ	ʃ	ʃ	ʃ
2	weight of stationary object	…	28,2,10,27	-	…
3	length of moving object	…	8,35,29,34	19	…
4	length of stationary object	…	15,14,28,26	-	…

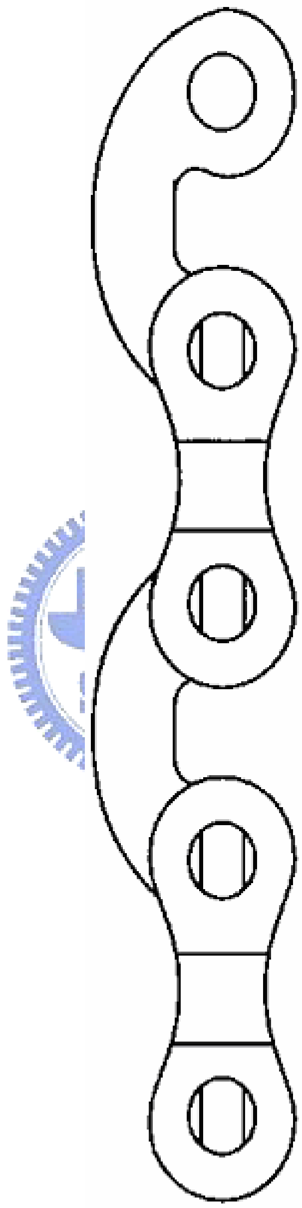


Fig. 4.1 Shape of narrow chain US5, 921,881

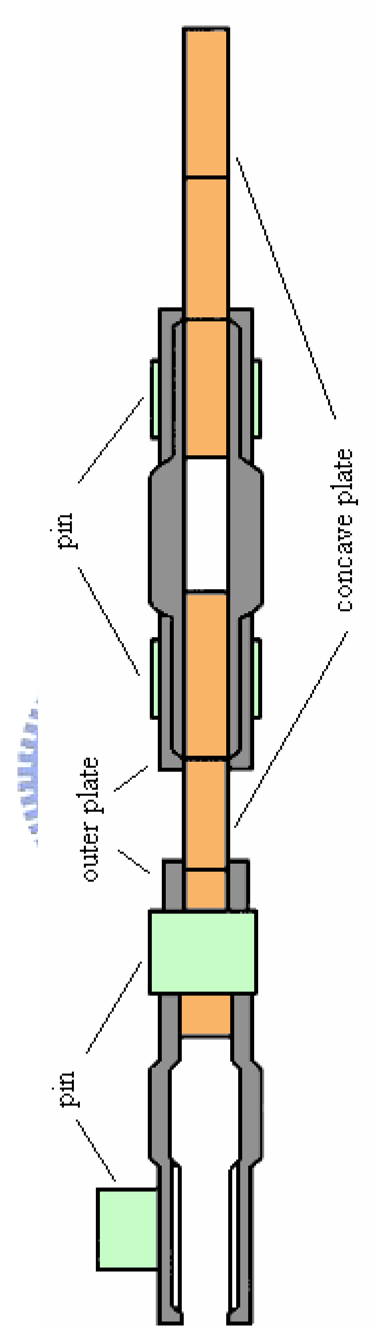


Fig. 4.2 Top view of narrow chain US5, 921,881

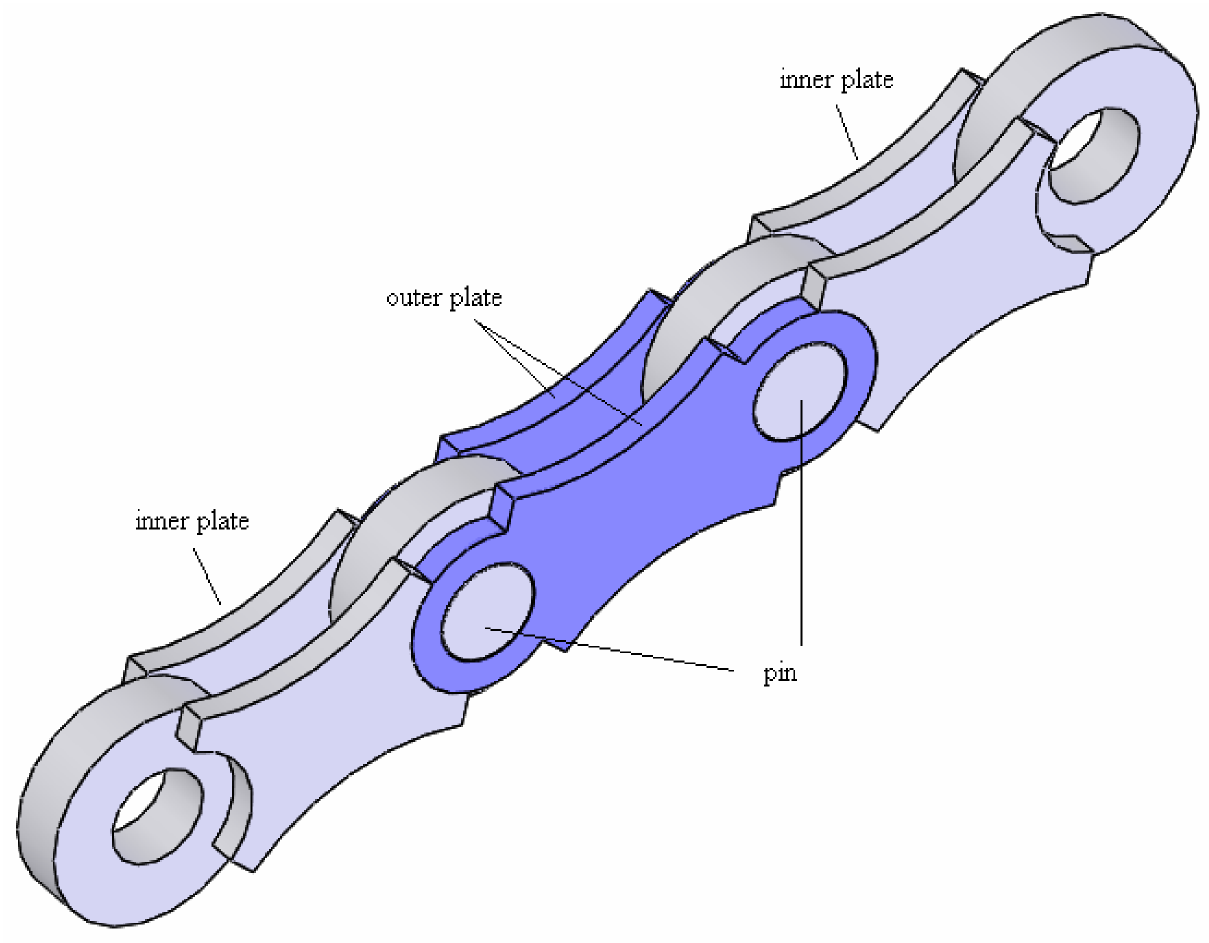


Fig. 4.3 Assembly view of concept 1

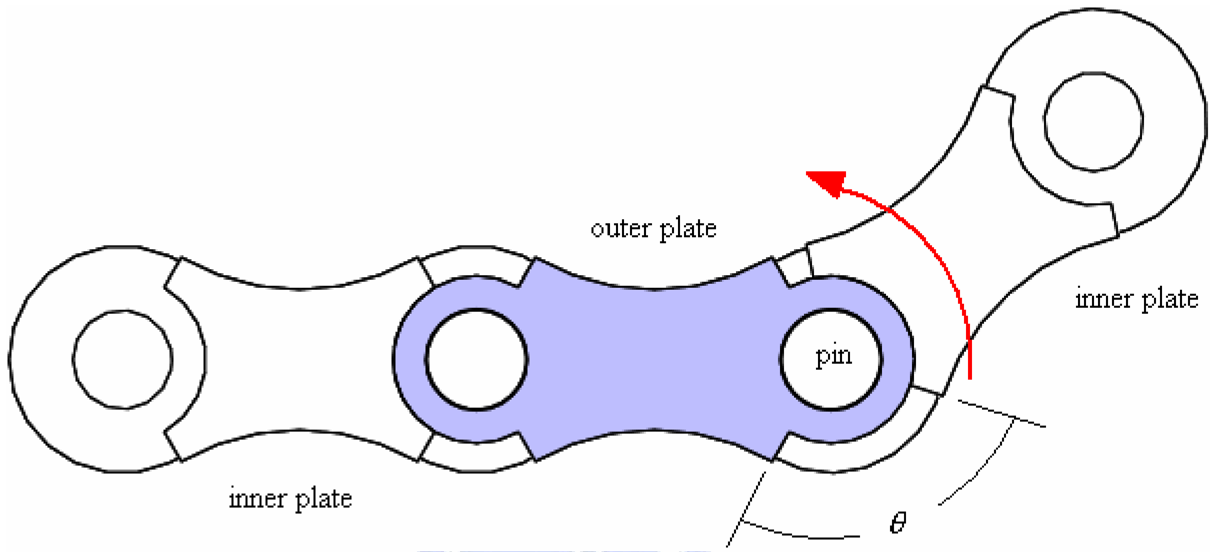


Fig. 4.4 Inner plate rotates around pin

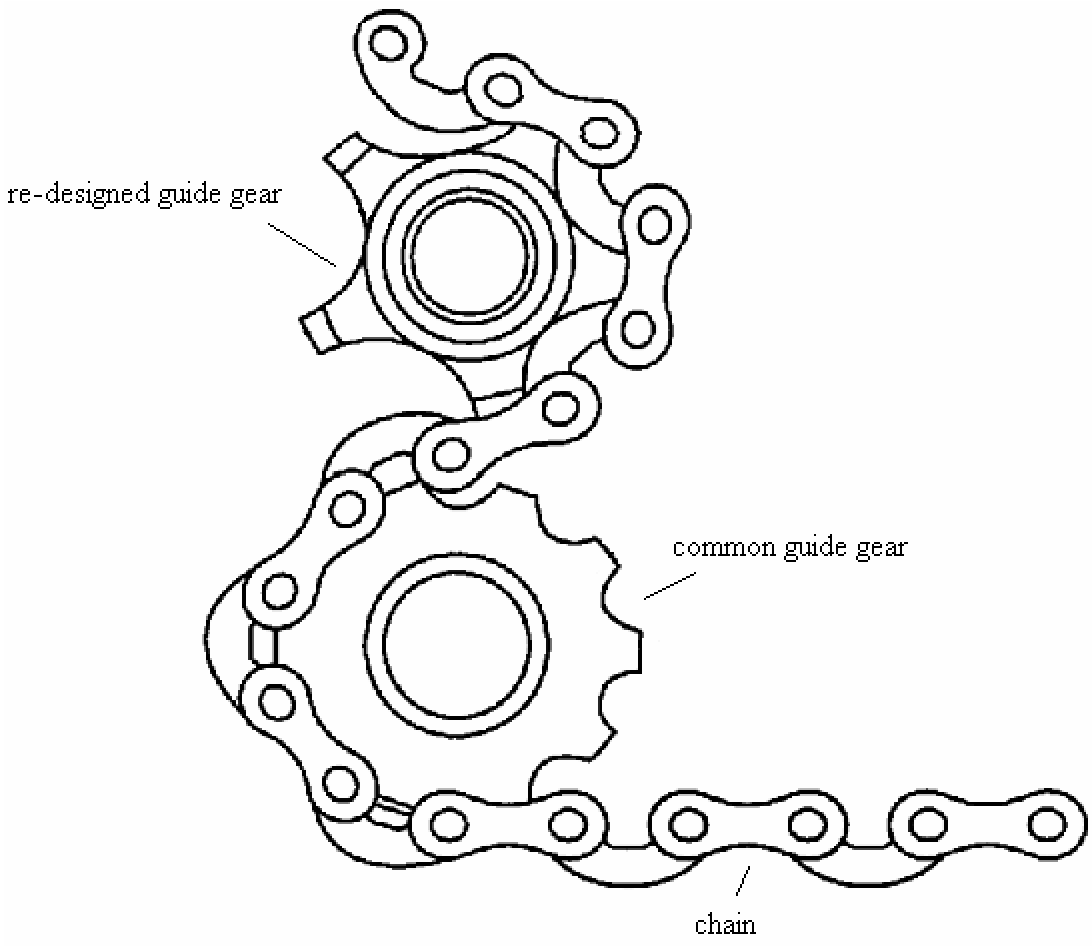


Fig. 4.5 Re-designed guide gear

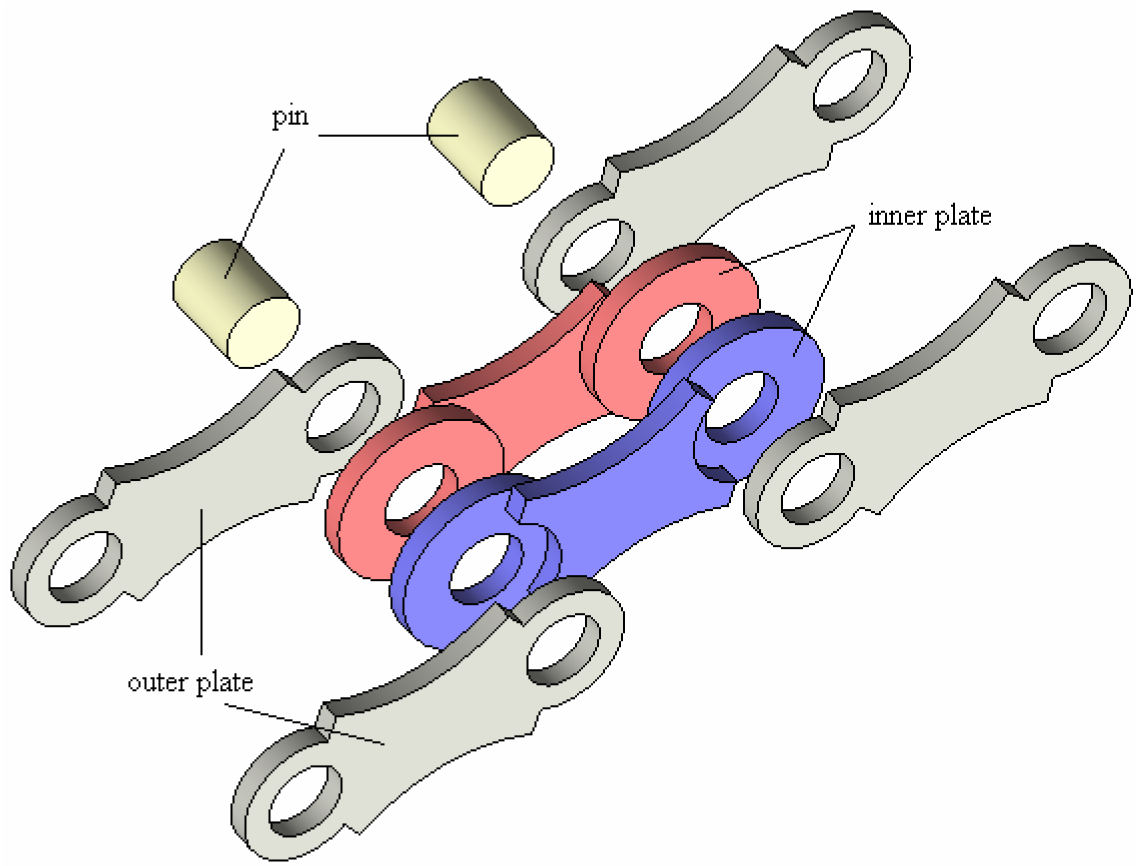


Fig. 4.6   Exploded view of concept 2

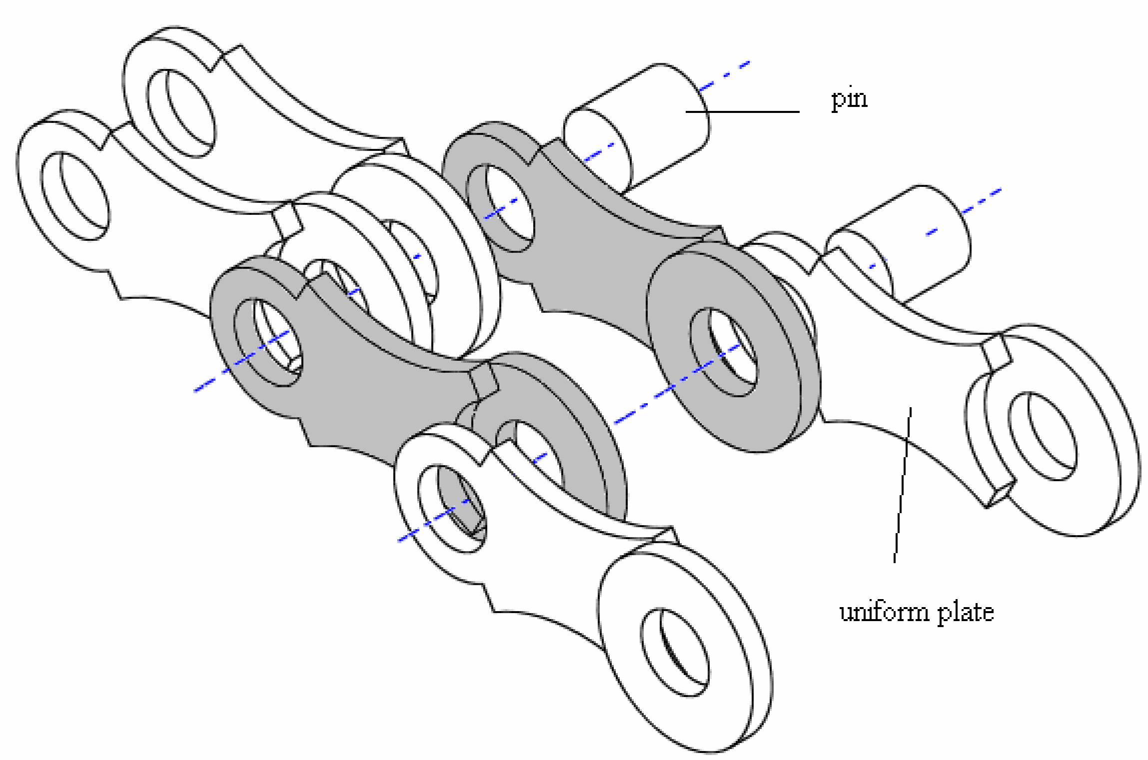


Fig. 4.7 Exploded view of concept 3

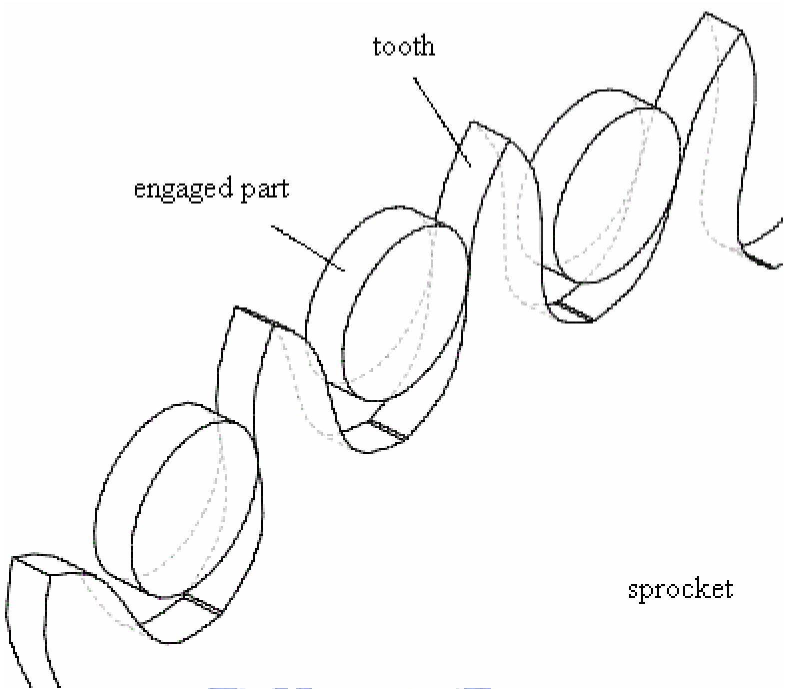


Fig. 4.8　Opposite position of teeth and engaged parts

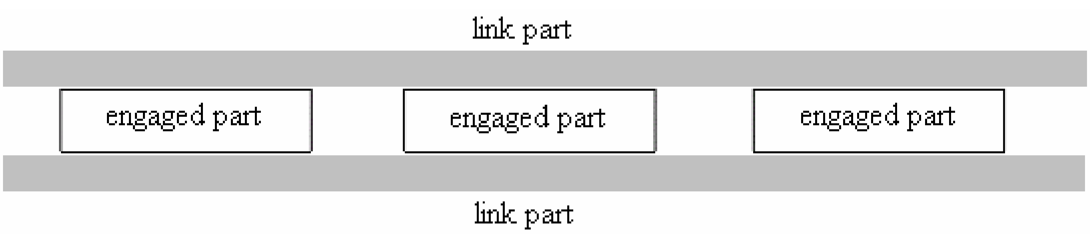


Fig. 4.9　One method of narrow chain

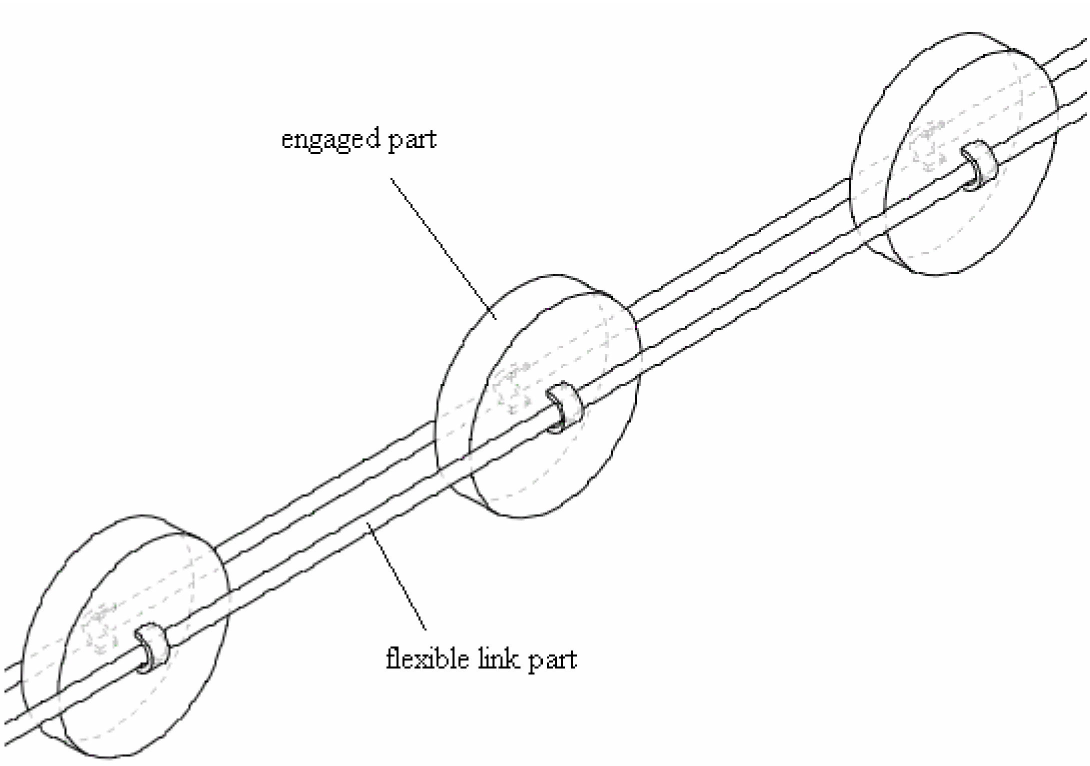


Fig. 4.10 Basic assembly of concept 4

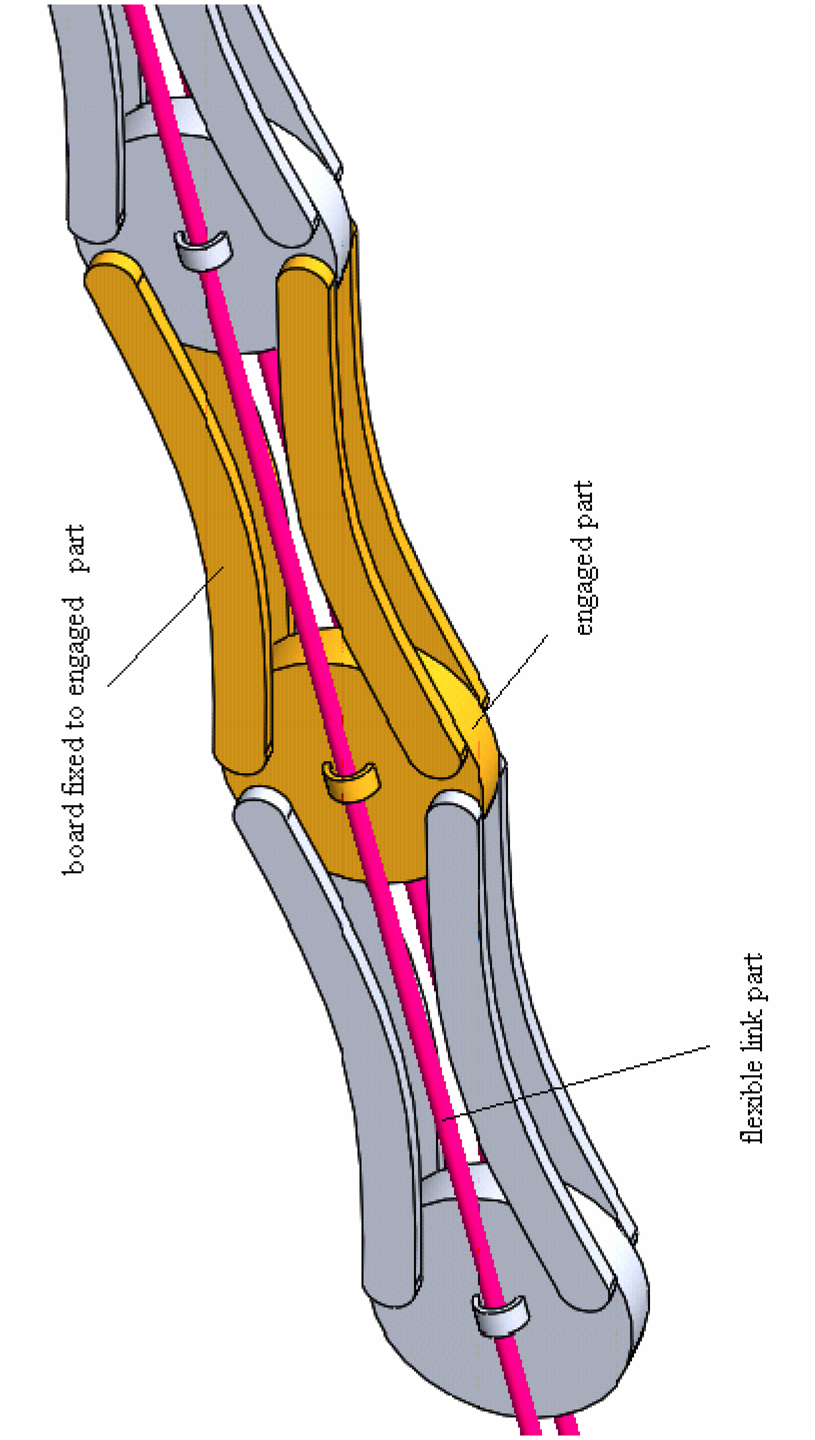


Fig. 4.11 Concept 4 with boards fixed to engaged part

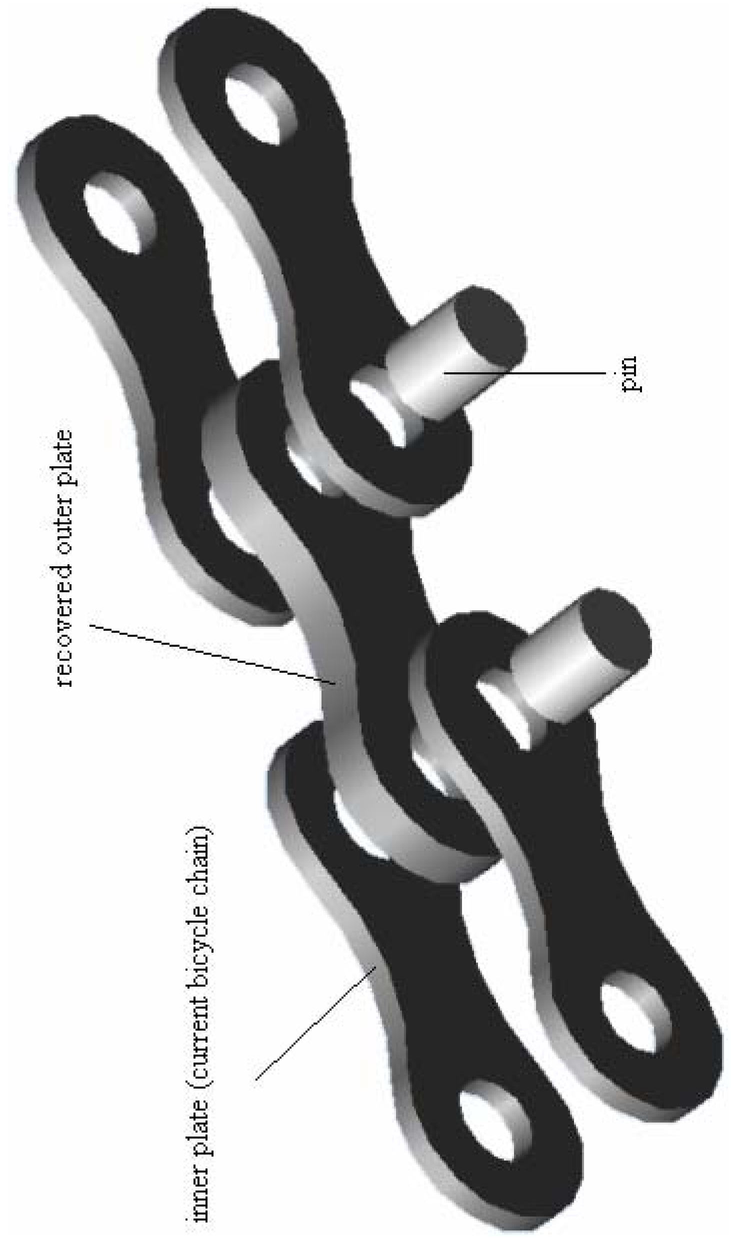


Fig. 4.12 Exploded view of concept 5

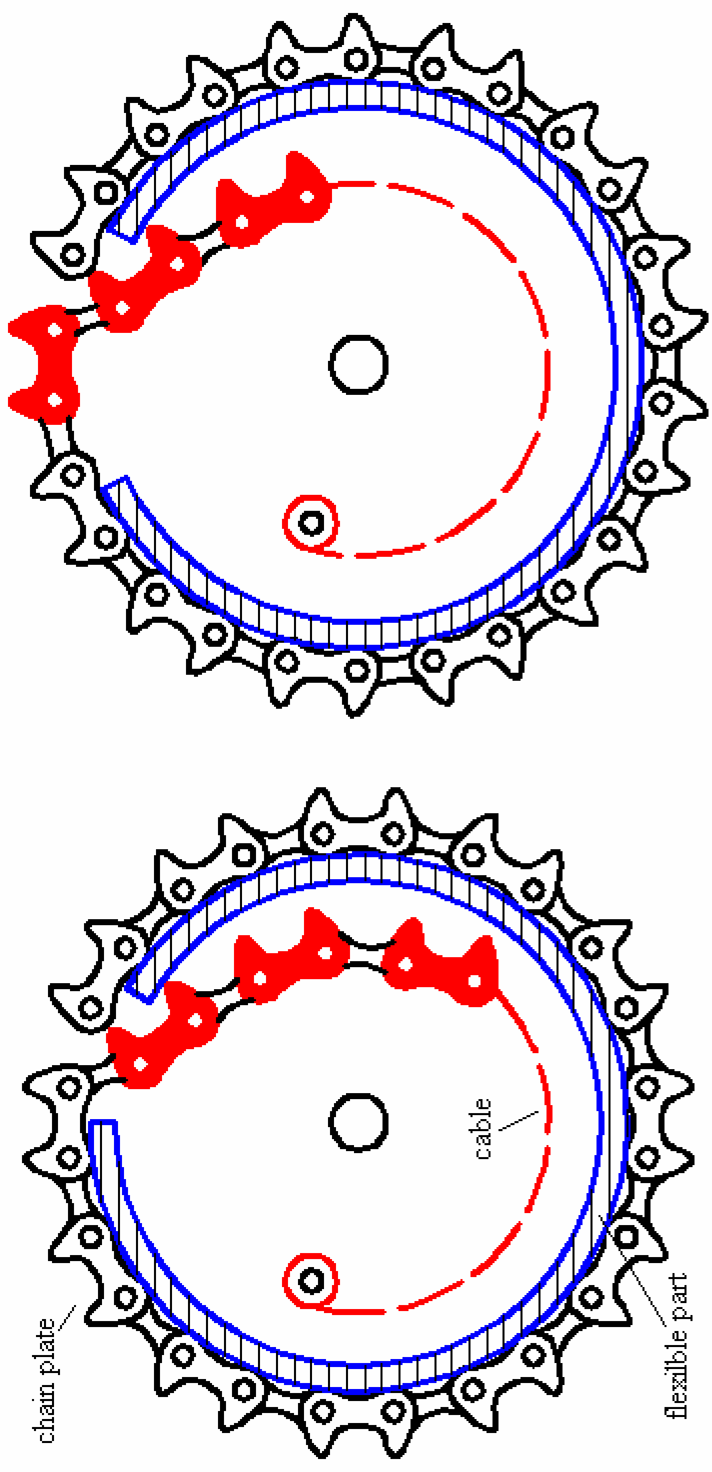


Fig. 4.13 Basic operation of concept 6

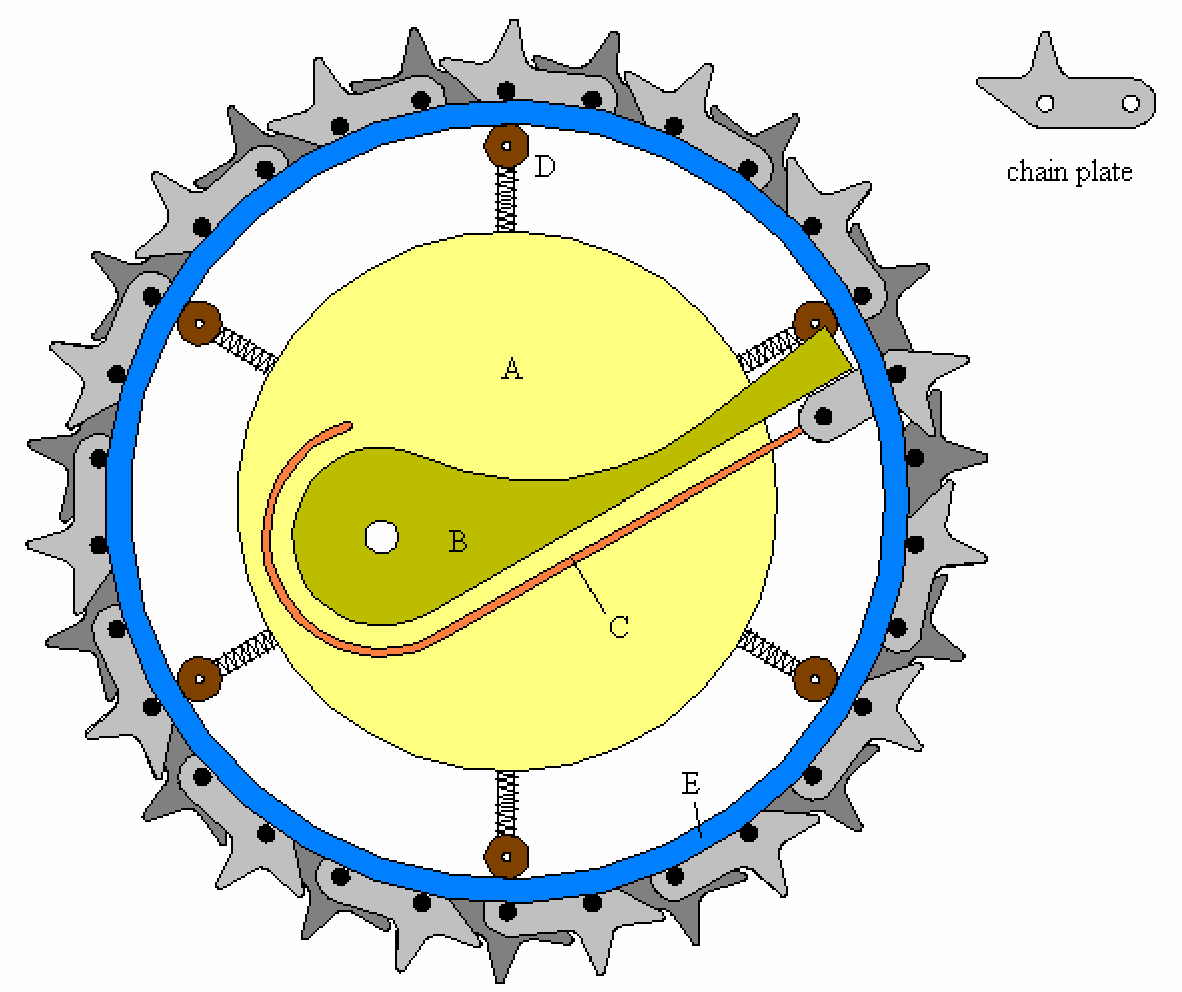


Fig. 4.14 Improved concept 6

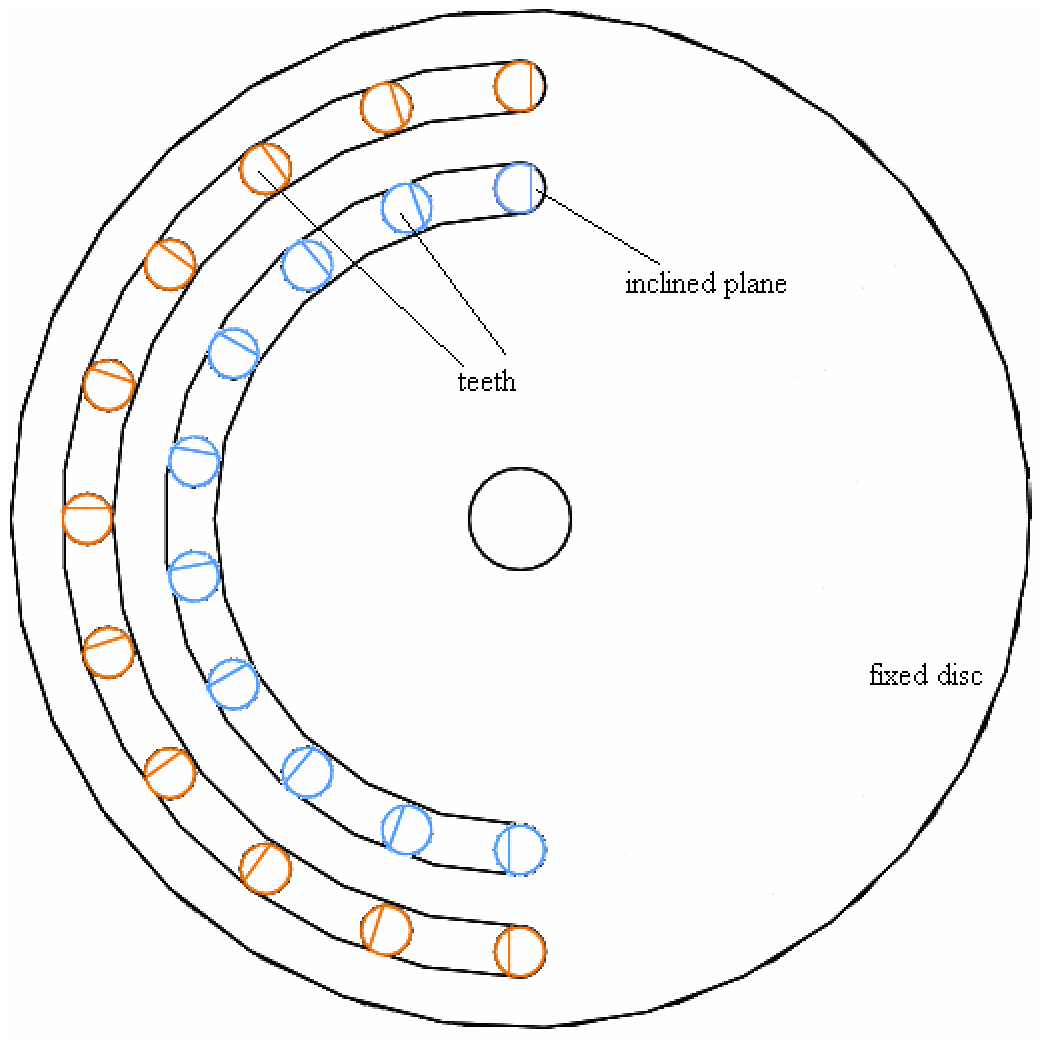


Fig. 4.15 Front view of concept 7

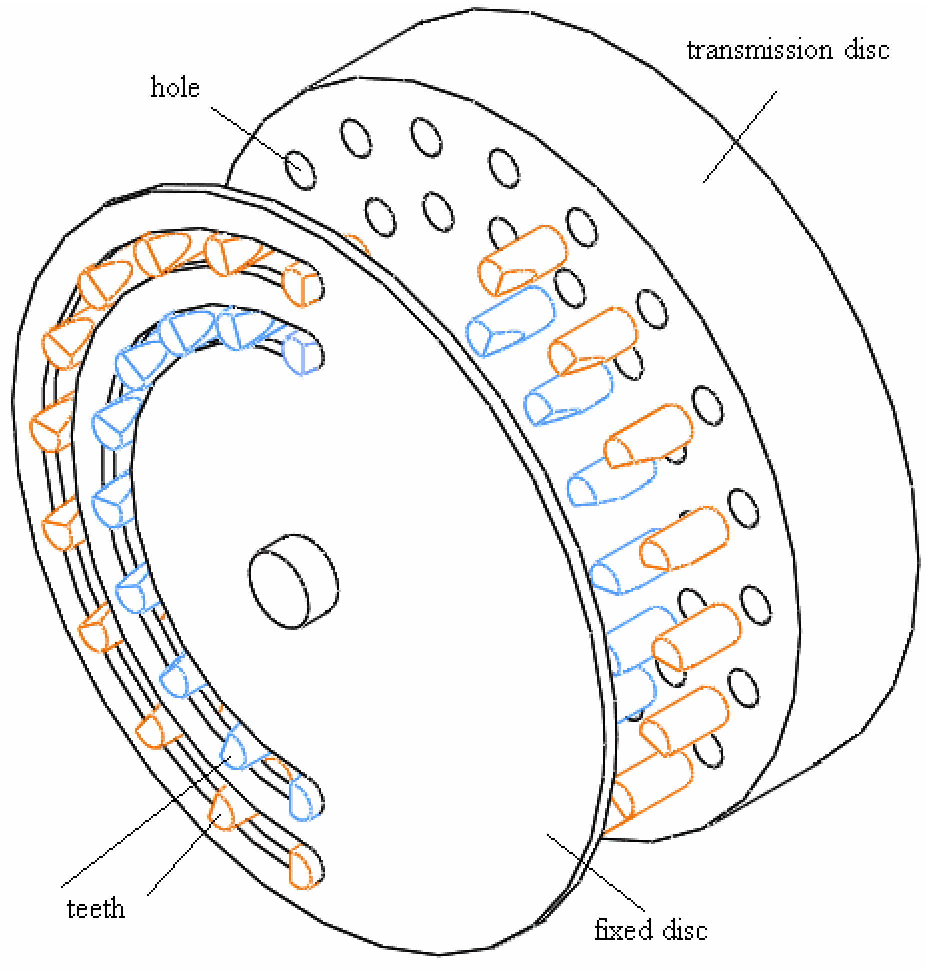


Fig. 4.16 Exploded view of concept 7

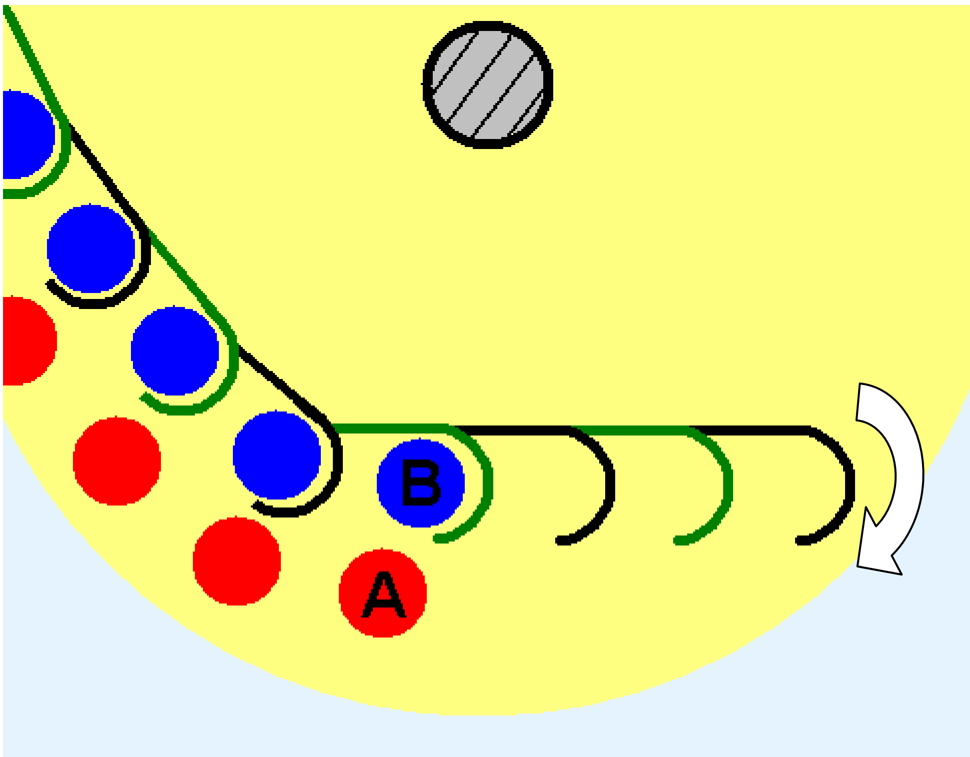


Fig. 4.17 An example of chain with concept 7

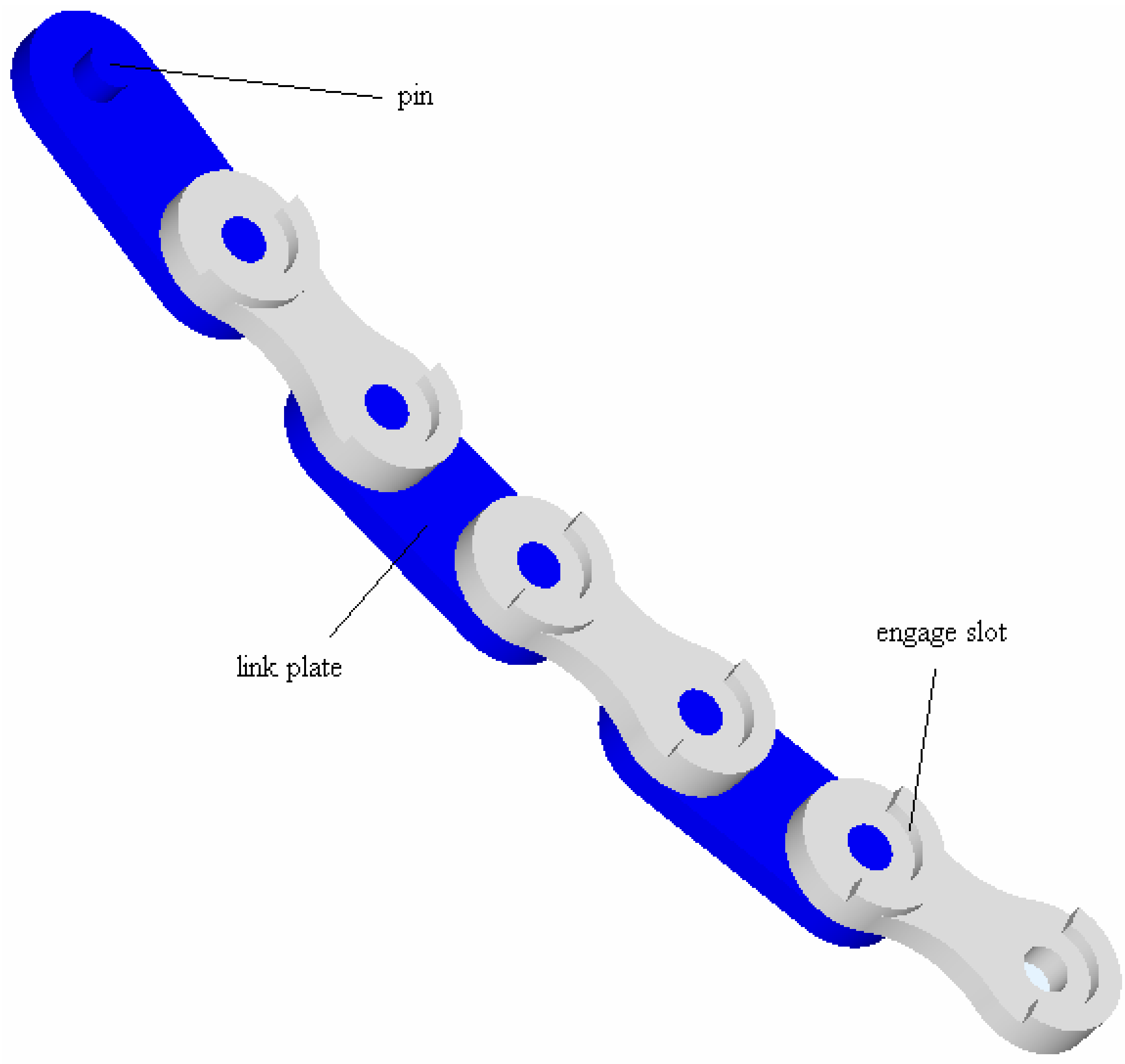


Fig. 4.18 Another example of chain of concept 7

Chapter 5 Prototype

This Chapter introduces embodiment and prototype of narrow bicycle chain. After producing concepts, some concepts can be chosen and embody in detail dimensions. The prototype of embodied concepts can be manufactured, and some problems of mechanism or assembly can be observed.

Chapter 4 lists concepts of narrow bicycle chain. Concept 1 to concept 3 is a series of curved plates; except the strength problem, this type of chain can be manufactured. Concept 4 is related to flexible material; however, it is hard to fix on engaged parts. Concept 5 is easiest to manufacture, however, it also need modifying the tooth profiles of sprockets. Other concepts are designed as systems, and the derivative problems are more than chain design itself.

Therefore, from the view of manufacture, concept 3 is chosen to make embodiment and prototype. 5.1 introduce the detail drawing of embodiment; 5.2 introduce the mold used to make the prototype; 5.3 introduce the assembly of chain; and the last section of this Chapter discusses some problems observed from prototype.

5.1 Embodiment

Concept 3 shown in Fig. 5.1 is base on current chain design; the pitch of chain is also 12.7 mm. Diameter of pin is 3 mm; diameter of right hole is 3.06 mm and left one is 2.96 mm. Different diameters are due to that right side plate is used to engage with teeth of sprocket, therefore, pin has to rotate with this hole. The left hole is outside and fixed with pin. Hatched area shown in Fig. 5.1 is curved by pressing and distance between two holes shortens to

12.7mm.

The chain plates are manufactured by water jet because this type of manufacture is cheap. However, the precision of water jet is not very good. Fig. 5.2 shows the manufacturing chain plates; material of chain plate is brass (copper). Edges of chain plates are rough because of both material and manufacture.

5.2 Mold

The plate shown in Fig. 5.1 is curved by pressing, and this section introduces the mold. Fig. 5.3 shows the cad drawing of mold assembly; the mold is made up of pressing cylinder, upper template and bottom template. Material of mold is carbon steel. The prototype is used to observe the mechanism and manufacture problem, and not used to test the strength. Therefore, material of chain plates is brass and the mold need not to do heat treatment.

Bottom template has a long slot and a deep circular slot. Long slot contains the chain plate shown in Fig. 5.2 and deep circular slot receives the pressing cylinder. The drop height between long slot and deep circular slot is 1mm.

Upper template has a hole used to contain the pressing cylinder and limit the pressing cylinder in the axial direction. Hole on upper template and deep circular slot on bottom template are axial. Bottom template and upper template are connected with four screws. Pressing cylinder presses the chain plate through the hole on upper template. Chain plate puts on the long slot, and then connects two templates, finally press the chain plate by pressing cylinder. The pressing force comes from vise clipping.

Fig. 5.4 shows parts and assembly of the mold. Fig. 5.4(a) list three parts; Fig. 5.4(b) shows the drop height 1mm and Fig. 5.4(b) shows the assembly of mold.

Fig. 5.5 shows the pressed chain plate, and right side in the Fig. 5.5(a) is the pressed area. The pitch of chain plate is also indicated in the Fig. 5.5(a) – 13.2 mm. This value of pitch does not conform to expected result (12.7 mm). This is a mistake on the dimension of chain plate; the original pitch before pressing (13.7 mm) is designed too much that can't shorten the pitch to 12.7 mm. If the original pitch is designed to 13.2 mm, the pitch after pressing will reach expected result.

5.3 Assembly

After manufacture of mold and chain plate, the parts are assembled. Feature of concept 3 is uniform chain plate, therefore, it only need pins to join chain plates.

Fig. 5.6 shows the chain assembly, Fig. 5.6(a) is front view of chain and Fig. 5.6(b) is top view of chain. The thickness of chain is about 4.5 mm without pin protrusion. Some problems occurred when assemble:

First, chain plates have neck at the pressed circular area. The shape of chain plate shown in Fig. 5.5 is not smooth as concept 3.

Second, pitch is not expected length; and this can be solved by modifying the pitch of original chain plate.

Finally, the material of chain plate is copper, and copper is softer than the material of pin. Pins can fix on outward chain plates and rotate on inner chain plates. However, the fixed pairs separate while rotating several times due to the different material. Therefore, rubber cubes insert the holes on chain plates before insert pins.

5.4 Remarks

This section discuss the advantages and drawbacks of the prototype introduced in 5.3. If drawbacks can be improved, the better design will be also produced. Principal discussion focuses on mechanism, manufacture, and operating with sprocket.

For mechanism, concept 3 have limit of degree while rotating. This limit is expanded in the prototype because the tolerance of pitch and pressed shape. As said in last section, the pitch of prototype is 13.2 mm. This tolerance of pitch causes center of hole not to locate in center of pressed area (see in Fig. 5.5(a)). Another reason is pressed shape; it means that the wall of pressed area is not obvious like concept 3. However, in fact, the wall can be made with press equipment and fine mole design.

For manufacture, the prototype proves the feasibility of concept 3, and this type of mechanism decreases the width of chain successfully.

For operating with sprocket, the prototype has no rollers, and rollers are substituted for two wall of chain plate, shown in Fig. 5.5(b). While operating with sprocket, chain plates will separate by engagement. This transverse force is very disadvantageous for applying in transmission system. One improved method is that adding a part of chain, a ring in the outward wall of pressed area.

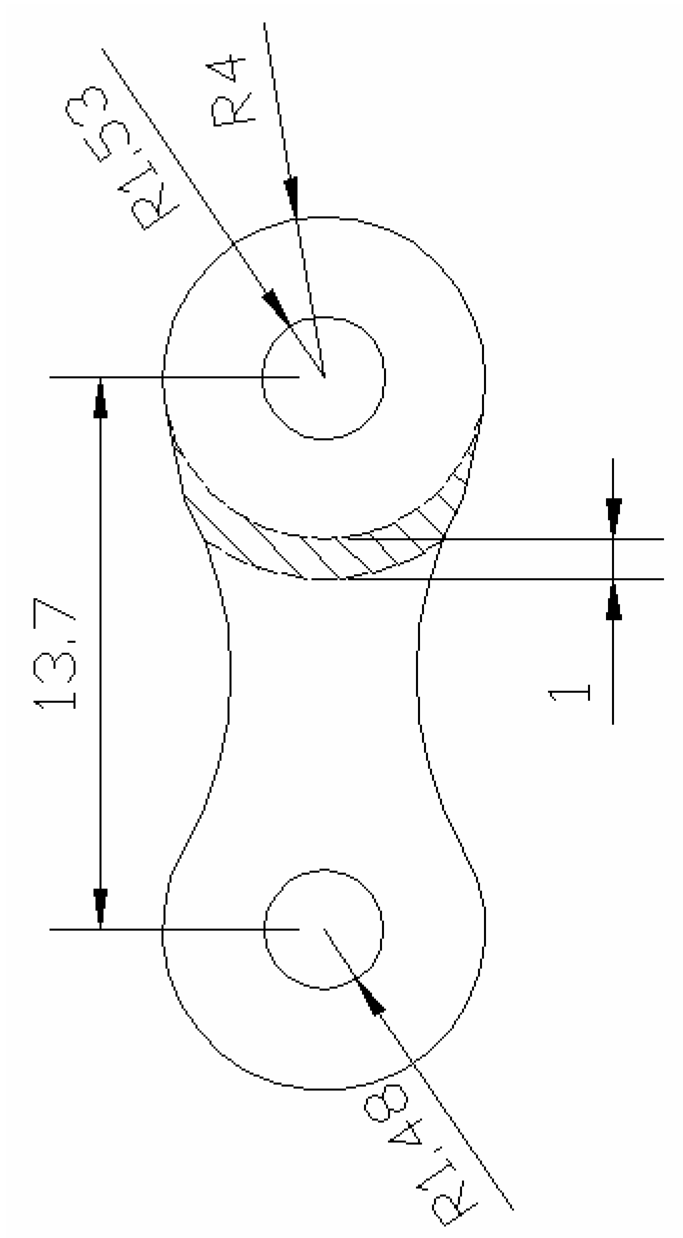


Fig. 5.1 Dimension of chain plate

Fig. 5.2   Chain plates manufactured by water jet

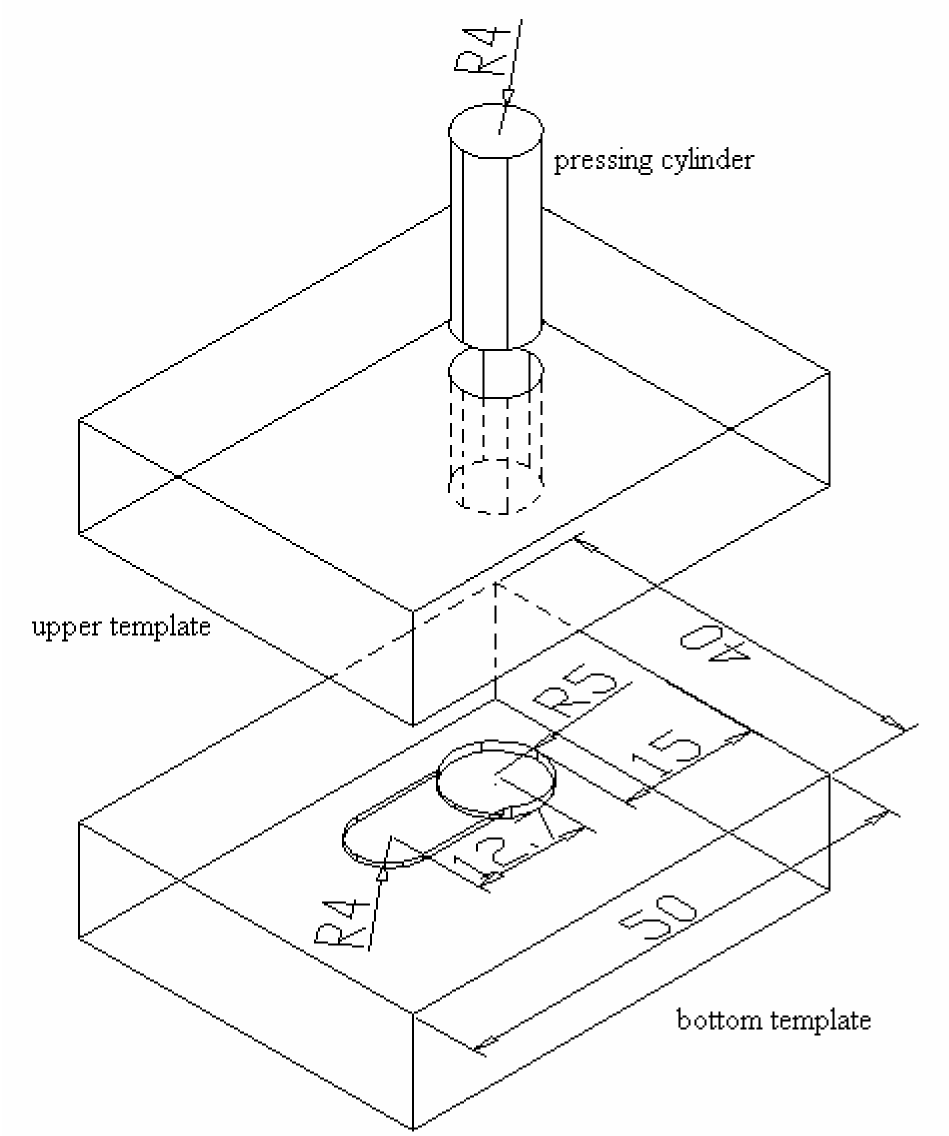
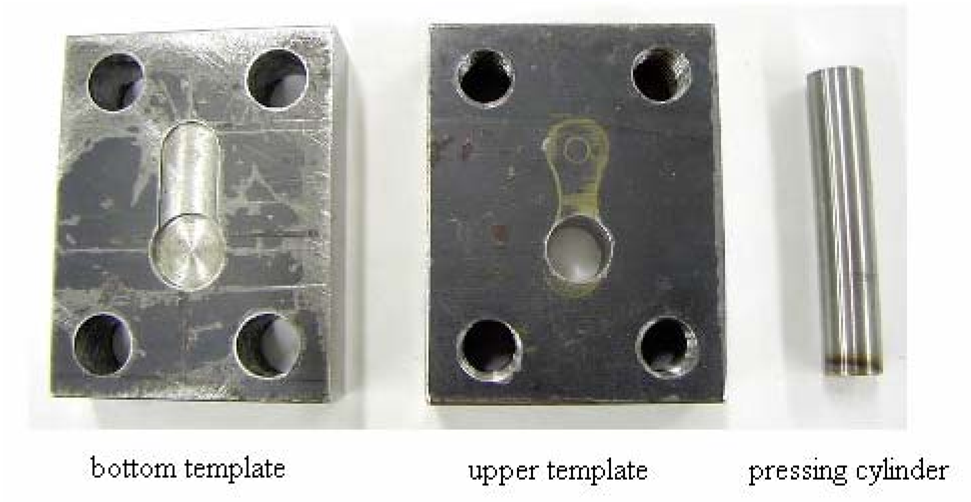
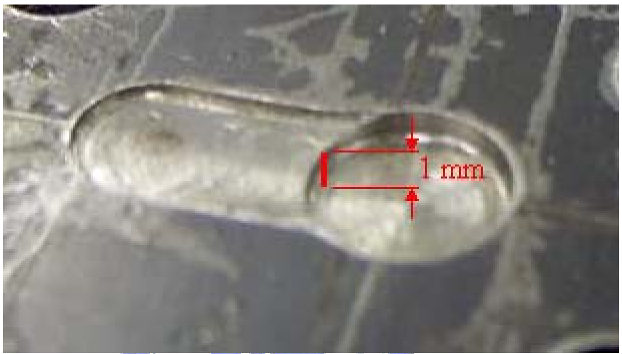


Fig. 5.3 Cad drawing of mold assembly



(a)

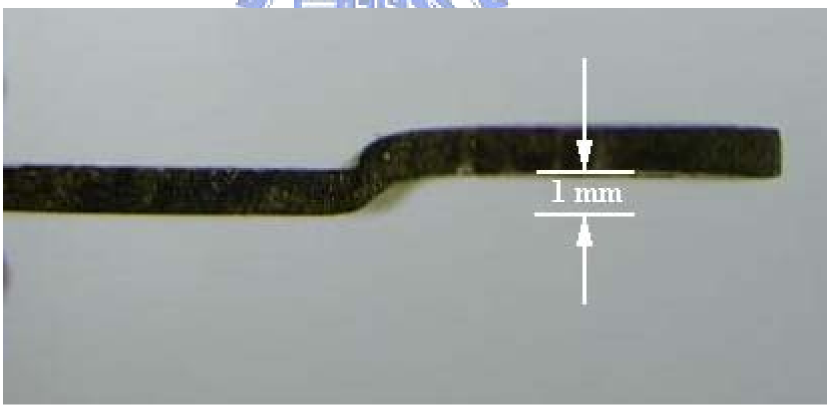


(b)

(c)

Fig. 5.4 Parts and assembly of mold

(a)



(b)

Fig. 5.5 Pressed chain plate

(a)

(b)

Fig. 5.6 Chain assembly

Chapter 6 Analysis

Chapter 3.2.1 brings up the force standard. Fracture of chains occurs in non-linear segment of stress-strain diagram. In this chapter, some chains are analyzed; however, the purpose of analysis is to compare some designs and concepts. Therefore, this study use loading under yield strength to be an index. Index case analyzes a chain of product – X9 chain of KMC chain industrial co, ltd.

This section introduces six chain analyses; case1 in Chapter 6.1 is the index, and uses the index to compare other results.

6.1 Case1 – Analysis of X9 chain of KMC chain industrial co. ltd.

This section analyzes a chain product – X9 chain of kmc chain industrial co., ltd [19]. According to information supplied by KMC, some features of X9 chain list in the following:

Material of outer chain plate: SCM 435

Elastic module: 2.17 x10^{11} (Pa)

Poisson ratio: 0.286

Profile of outer chain: shown in Fig. 6.1. (Simplified drawing, without X-Bridge side plate configuration)

Table 6.1 shows JIS table of mechanical properties Cr-Mo, Ni, Ni-Cr, and Ni-Cr-Mo Steel [21]. Yield strength of SCM 435 is over 80 (kgf/mm^2), equal to 784 (MPa). And then simulate the value of tensile force that von Mises stress achieve 784 (MPa).

Fig. 6.2 shows simulation of outer plate of X9 chain. Use half outer plate because this chain is symmetrical. Left face is fixed, and a distributed force loads on the hole. Fig. 6.3 shows simulation of pin of X9. It is not full pin; width of this pin is 4.1 mm, the same with inner link of X9 chain (inner link means that assembly of two inner plates and rollers). This analysis simulate that pin is fixed with outer plates and load a distributed force on middle round face.

Table 6.2 shows simulation results of outer plate and pin of X9. Stress of outer plate achieves yield stress 784 (MPa) when tensile force is 160 (kgf), equal load a chain 320 (kgf) tensile force. Stress of pin achieves yield stress when tensile force is 290 (kgf). These values are index values, and simulation results of other designs can compare with these index value.

6.2 Case2 – Analysis of US patent NO. 5,921,881

This section analyzes US patent NO. 5,921,881 – "Narrow Bicycle Chain with Inner Links that receive sprocket teeth with a bottom recess" [17].

Fig. 6.4 shows profile of inner plate of case2, and this profile is drawn base on patent drawings. Pitch of this chain is 12.7 mm.

Fig. 6.5 shows simulation inner plate of case2, left hole is fixed and a distributed force load on right hole. Fig. 6.6 shows simulation pin of case2. The width of pin is 2.1 mm, and different form pin of X9, because chain of case2 just has two outer plates. Pin is fixed with outer plates and a distributed force loads on middle round face.

Table 6.3 shows simulation results of outer plate and pin of case2. Stress of inner plate achieve yield stress when tensile force is about 68 (kgf); and stress of pin achieve yield stress when tensile force is about 260 (kgf). Load on inner plate of case2 is equal to the total load on a chain, so the tensile force 68 (kgf) is about one-fifth of index value 320 (kgf). Strength of pin 260 (kgf) decrease than index value 290 (kgf), but difference is small.

6.3 Case3 – Analysis of concepts

Fig. 4.3 shows assembly of concept 1; Fig. 4.6 shows concept 2 and Fig. 4.7 shows concept 3. Assemblies of these three concepts look the same. However, parts of each concept are different. Therefore, the simulation results are also different.

Table 6.4 shows simulation result of plates and pin of concept 1. Stress of inner plate achieves yield stress when tensile force is about 350 (kgf), similar to index value 320 (kgf); stress of outer plate achieves yield stress when tensile force is about 110 (kgf) and stress of pin achieves yield stress when tensile force is about 260 (kgf), the same as case 2.

Table 6.5 shows the simulation results of concept 2, and Table 6.6 shows the simulation results of concept 3. Analysis of are all the same because the dimension is the same as case 2.

According to these results, strength of inner plate of concept 1 is close to index value; however, strength of outer plate is poorer than index value.

Inner plate of concept 2 is half inner plate of concept 1, but strength of concept 2 is very poorer than concept 1. Outer plate of concept 2 are the same with concept 1, therefore the results are the same. Concept 3 use uniform plates form a chain. Strength of this uniform plate is very poorer than index value.

Table 6.7 shows simulation results of concept 5. Fig. 4.12 shows assembly of concept 5. Concept 5 uses a solid inner plate to substitute roller. Therefore, width of this inner plate is also 2.1 mm. Stress of inner plate achieve yield stress when tensile force is about 400 (kgf). This value is higher than index value.

6.3 Remarks

After comparing results with index value:

1. Use analysis results of X9 chain to be index values.
2. Patent US 5,921,881 uses inner plate with bottom recess. This bottom recess cause poor performance on strength.
3. Results of pins are about the same. Pin for a narrow chain that use new linkage mechanism is shorter than pin for current chain.
4. Strength of open curved plate is poor; however, strength of closed curved plate (inner plate of concept 1) is about the same with index value.
5. Concept 5 has better performance on strength.

Table 6.1. JIS table of mechanical properties Cr-Mo, Ni, Ni-Cr, and Ni-Cr-Mo Steel[21]

JIS	Yield strength (kgf/mm^2)	Tensile strength (kgf/mm^2)	Impact value ($kgf.mm/cm^3$)	Hardness(Hb)
SCM432	>75	>90	>9	255~321
SCM430	>70	>85	>11	241~293
SCM435	>80	>95	>8	269~321
SCM440	>85	>100	>6	285~341
SCM445	>90	>105	>4	302~363
SNC236	>60	>75	>12	212~255
SNC631	>70	>85	>12	248~302
SNC836	>80	>95	>8	269~321
SNCM431	>70	>85	>10	248~302
SNCM625	>85	>95	>8	269~321
SNCM630	>90	>110	>8	302~352
SNCM240	>80	>90	>7	255~311
SNCM7	>90	>100	>5	293~352
SNCM439	>90	>100	>7	293~352
SNCM447	>95	>105	>7	302~363

Table 6.2. Simulation results of outer plate and pin of X9 chain

X9		
Part / Force (kgf)	outer plate	pin
100	494 MPa	-
150	740 MPa	-
160	789 MPa	-
200	-	596 MPa
300	-	808 MPa
290	-	781 MPa

Table 6.3. Simulation results of outer plate and pin of case2

Case2		
Part / Force(kgf)	inner plate	pin
50	577 MPa	-
100	1154 MPa	-
68	784 MPa	-
200	-	598 MPa
250	-	746 MPa
260	-	777 MPa

Table 6.4. Simulation results of plates and pin of concept 1

Concept 1			
Part / Force(kgf)	inner plate	outer plate	pin
50	110 MPa	-	-
100	220 MPa	714 MPa	-
110	-	784 MPa	-
250	550 MPa	-	-
350	770 MPa	-	-
260	-	-	777 MPa

Table 6.5. Simulation results of plates and pin of concept 2

Concept 2			
Part / Force(kgf)	inner plate	outer plate	pin
50	758 MPa	-	-
100	1517 MPa	-	-
110	-	784 MPa	-
260	-	-	777 MPa

Table 6.6. Simulation results of plates and pin of concept 3

Concept 3		
Part / Force(kgf)	uniform plate	pin
50	870 MPa	-
40	700 MPa	-
45	785 MPa	-
260	-	777 MPa

Table 6.7. Simulation results of plates and pin of concept 5

Concept 5		
Part / Force(kgf)	inner plate	pin
100	193 MPa	-
200	386 MPa	-
400	770 MPa	-
260	-	777 MPa

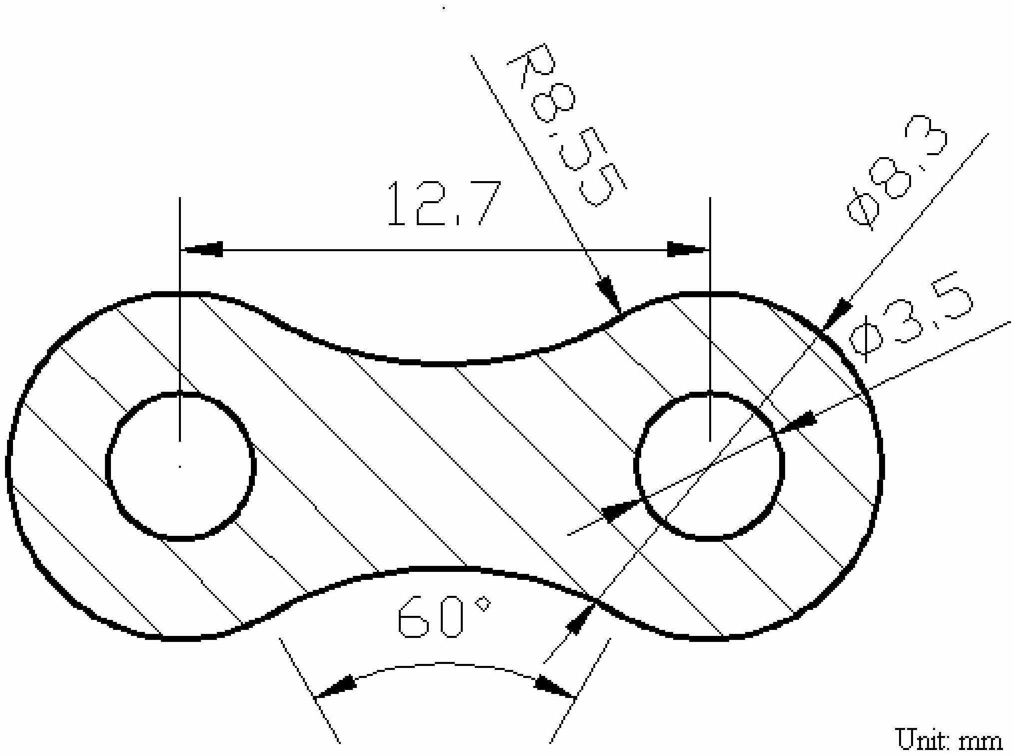


Fig. 6.1 Profile of outer plate of X9

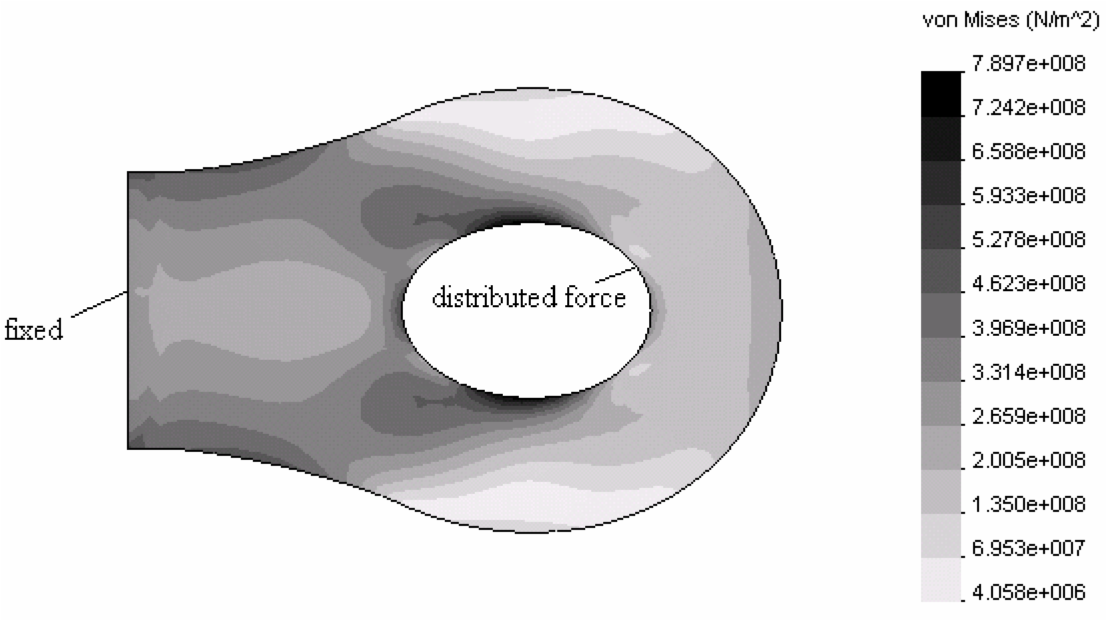


Fig. 6.2 Simulation of outer plate of X9

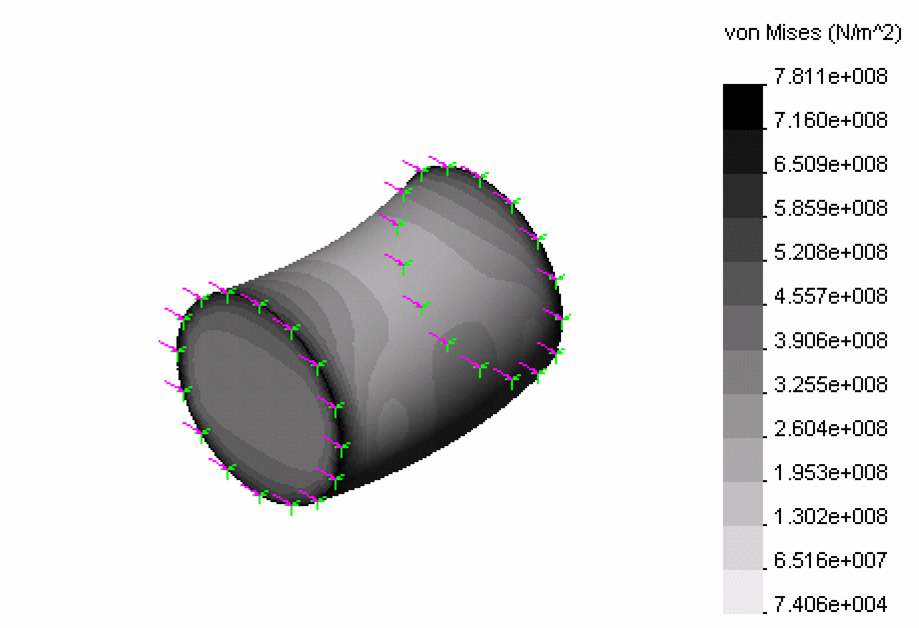


Fig. 6.3 Simulation of pin of X9

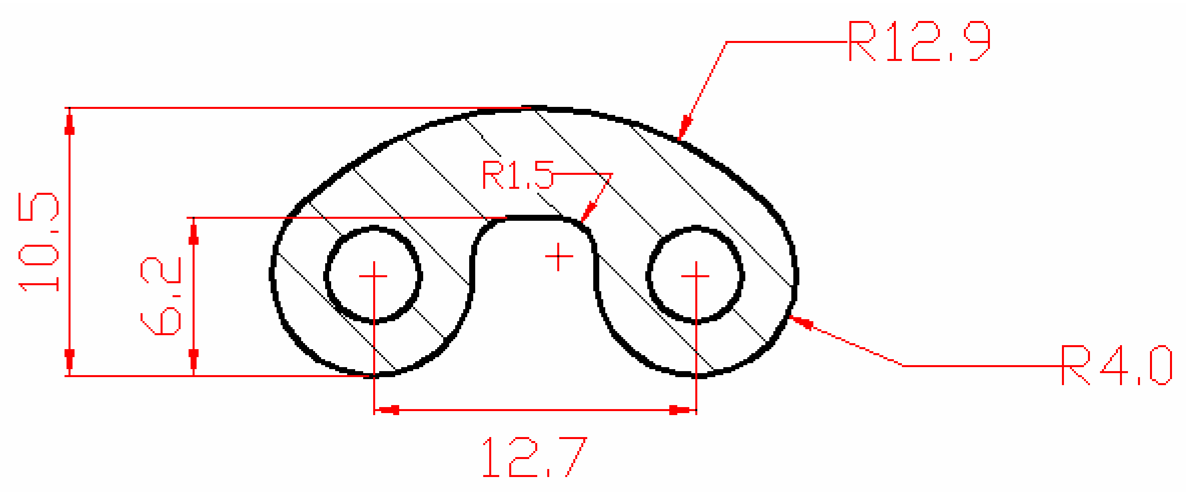


Fig. 6.4 Profile of inner plate of case2

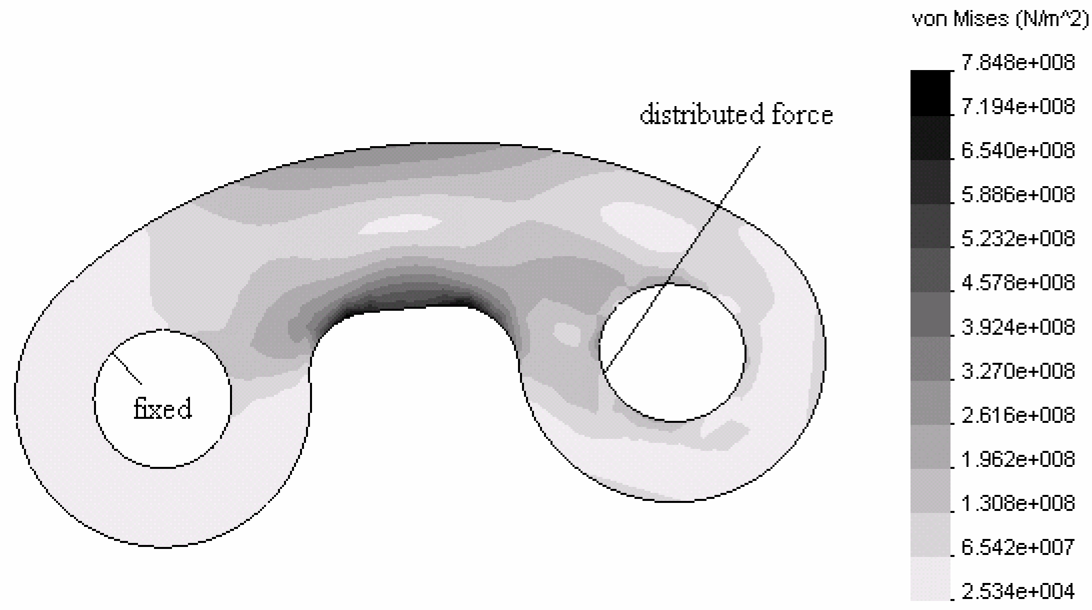


Fig. 6.5 Simulation of inner plate of case2

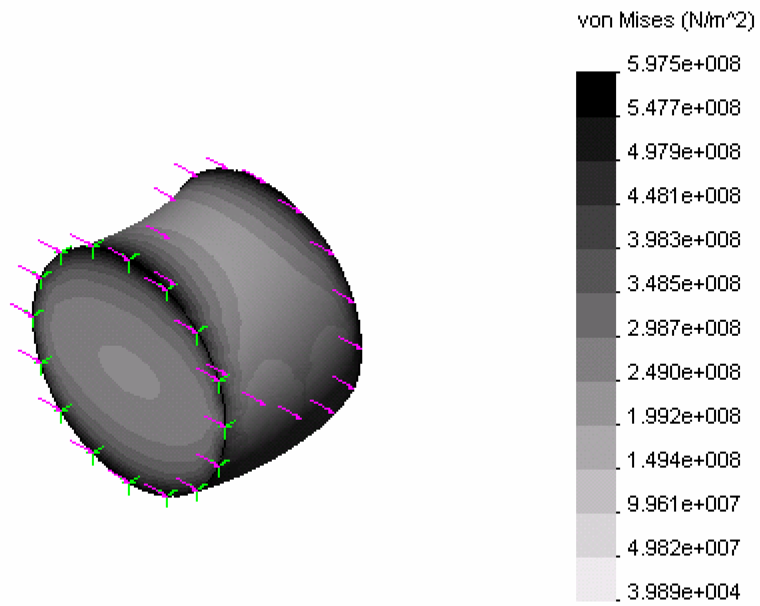


Fig. 6.6 Simulation of pin of case2

Chapter 7 Conclusions and Future Works

7.1 Conclusions

1. TRIZ provides principles to designer, and these principles are related to design parameters. Therefore, these provided principles are usually suitable. This is different with checklist method; designer use principles of checklist method by his/her own. Therefore, using checklist method needs more creativity.

2. Narrow chain has few components, and solid parts substitute rollers. In this study, widths of narrow chain concepts are all about 4.4 mm. To compare with current narrowest bicycle chain, shown in Table 4.1, reduction of width achieves about 1.2 mm.

3. To compare different concepts, concept 5 has better performance and analysis results of other chain concepts are poorer than index values.

7.2 Future Works

1. Search related information. Patents are important sources, and the search method can change for new search result. Other production for patents related to chain will be also searched, like necklace, jewel, etc.

2. Propose new concepts.

3. Shape optimum. Some concepts have curved plate or curved shape. Use strength to be the cost and get better design dimensions.

4. Change material. Chapter 3 mentions two requirements, and one is strength. Materials of chain components also influence the strength.

5. Sprocket design. Because of concepts of chain are different with current chain. Therefore, sprockets need to modify for working with new chain.

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