An innovative piston retractor for bicycle hydraulic disc braking systems

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Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering 2004 218: 295
DOI: 10.1243/095440704322955812

An innovative piston retractor for bicycle hydraulic disc braking systems

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Abstract: Hydraulic disc brake systems offer various advantages over other braking systems, including a good heat dissipation rate, a high force enlargement ratio and a constant braking force in various environments. However, they have an important defect as the lining pads remain at a small clearance from the disc rotor, occasionally producing judder, noise and power loss when freely running. This study proposes an innovative piston retractor by utilizing the theory of innovative problem solving. The prototype is manufactured and installed in a commercial brake caliper. Experimental results are obtained and demonstrate the feasibility of applying the proposed design in a bicycle hydraulic disc braking system. Retraction performance of the proposed design is superior to a current product with a ring seal as its retractor and another product with a retractor that does not contain an automatic adjustment mechanism. The clearance between the lining pad and disc rotor is successfully kept at a larger value than these products regardless of the pad wear.

Keywords: hydraulic braking system, piston, retraction, TRIZ, test rig

1 INTRODUCTION

Disc brake systems for vehicles provide several advantages over drum brake systems in operating performances. These advantages include a better heat dissipation rate and little variation in braking torque in moist, muddy and dry environments. Lining pads wear bicycle wheel rims in rim brake systems, whereas disc brake systems do not produce wear of this type. The pipelines in hydraulic disc brake systems provide lower frictional loses during pressure transmission, while the mechanical brake systems need the rider to apply an extra force to compensate the friction in the cable line. Moreover, the force enlargement mechanism and the wear compensation function are easily achieved in hydraulic systems. These features are making hydraulic disc brake systems increasingly popular in the bicycle brake system and component markets.

However, the hydraulic disc brake system has an important defect that judder, noise and power wastage may occur when wheels are running freely if lining pads and the disc rotor are not kept apart [**1**–**3**]. There are two main forces that retract the piston apart from the disc after the braking process ends, namely the pressure difference acting on the piston and the deformation force in the elastic sealing ring between the piston and the caliper cylinder. The pressure difference between atmospheric pressure outside the piston and the hydraulic pressure inside the caliper produces the first part of the retraction force acting on the piston, and is not discussed in this work. The ring seal, acting as the piston retractor, produces the other part of the retraction force. The seal deforms by the friction force between the piston and the seal when the piston is pushed outwards to the press lining pads against the disc rotor for braking. After the hydraulic pressure is removed, the deformed ring seal retracts the piston. If the retraction force is not large enough to retract the piston and pads apart from the disc surface, friction and vibration problems occur. Unnecessary attrition of the lining pads and disc rotor during a long period of free running will increase the operating temperature and reduces the coefficient of friction, which may reduce the braking performance and cause a safety problem when the rider really needs to brake. The unnecessary friction and wear will require the lining pads to be replaced frequently.

A feasible solution to the above-mentioned problems is to increase the clearances between pads and the disc rotor when the brake system is inactivated. Nevertheless, the clearance between the pad and disc when the brake system is idle is not designed to be excessively large because a larger clearance will increase the lever stroke, establishing sufficient braking force when braking starts

The MS was received on 23 June 2003 and was accepted after revision for publication on 29 October 2003.
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and hence delaying the maximum braking force [4]. Thus a clearance adjustment device is necessary for riders to maintain a constant clearance according to the pad wear.

Several piston retraction devices are proposed in patents, as shown in Fig. 1. Figure 1a shows the contour of recess that contains the ring seal between the piston and cylinder which is modified to recondition the retraction force provided by the deformed sealing ring, such that a larger clearance between the pad and the disc is kept [5]. Adjusting the chamfer size of the recess in which the sealing ring lies enables the distance of retraction to be enlarged as the fluid pressure is removed [6], as represented in Fig. 1b. A flexible sleeve and spring represented in Fig. 1c are used to exert a larger retraction force [7]. A support rod and sliding rings are proposed in reference [8] to provide the retraction force with an automatic adjustment mechanism, as indicated in Fig. 1d. Figure 1e shows that a screw and a spring are mainly employed to achieve the automatic clearance adjustment function of the piston [9]. However, the many components of these apparatuses increase manufacturing costs and fabrication time.

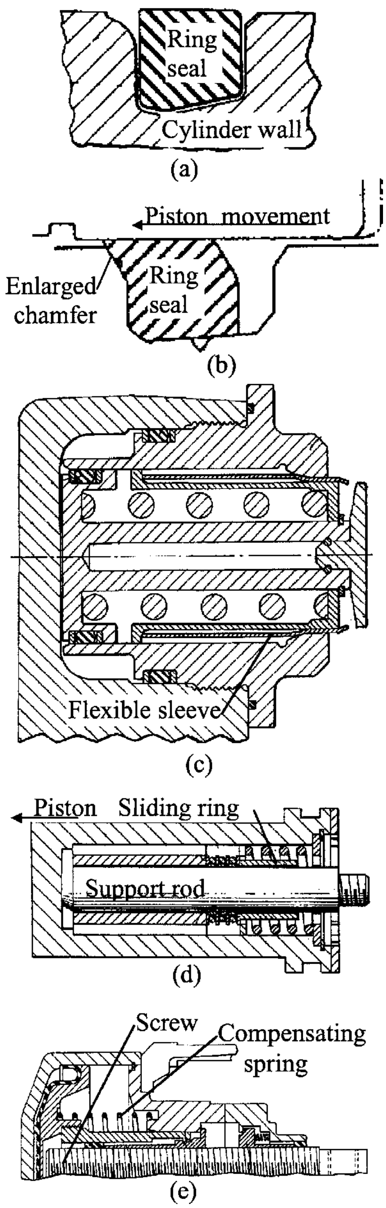

Fig. 1 Several piston retractor designs revealed in patents

A piston retractor with an automatic adjustment function is considered in this study. The theory of innovative problem solving (TRIZ) is involved in the concept generation stage to provide innovation principles and possible concepts. The proposed design improves convenience of use and is maintenance-free for riders. The number of components of the retractor is also reduced in order to keep the manufacturing cost low. Accuracy requirements on manufacturing and fabrication are also minimized. The definite values of the appropriate clearances need to be evaluated in other experiments that involve the performance of experienced and beginning riders, but these experiments relate to another issue not covered in this study. This paper confirms the clearance of the proposed design, causing it to be larger than a commercial product with only the ring seal as the retractor. The clearance of the proposed design is also verified to be a constant compared with a commercial product without the automatic adjustment mechanism that produces excessive large clearances.

This paper is organized in the following way. Section 2 states the technical background of the piston retractor and defines the main goal of this study. An innovative piston retractor with a US Patent pending proposes utilizing the suggested principles from TRIZ. Section 3 details the prototype and a test rig with experimental procedures for testing the piston retractor. Experimental results are presented herein to verify the effectiveness of this apparatus. Section 4 draws conclusions.

2 DESIGN AND ANALYSIS

2.1 Technical backgrounds

This study assumes that lining pad displacements are the same as the piston displacements during all braking processes, i.e. the pad is fixed on the piston. The caliper is considered as fixed. Only one side of the caliper with a single piston is discussed, since the results can be simply applied to an entire caliper of double pistons on opposite sides. Fluid dynamics and the temperature effect are not considered in this study.

Definitions of piston strokes during a single braking operation are schematically represented in Fig. 2. The piston is located at the initial position when a new pad is installed in the brake system. As the fluid pressure is energized, the piston will be pushed out, the pad is

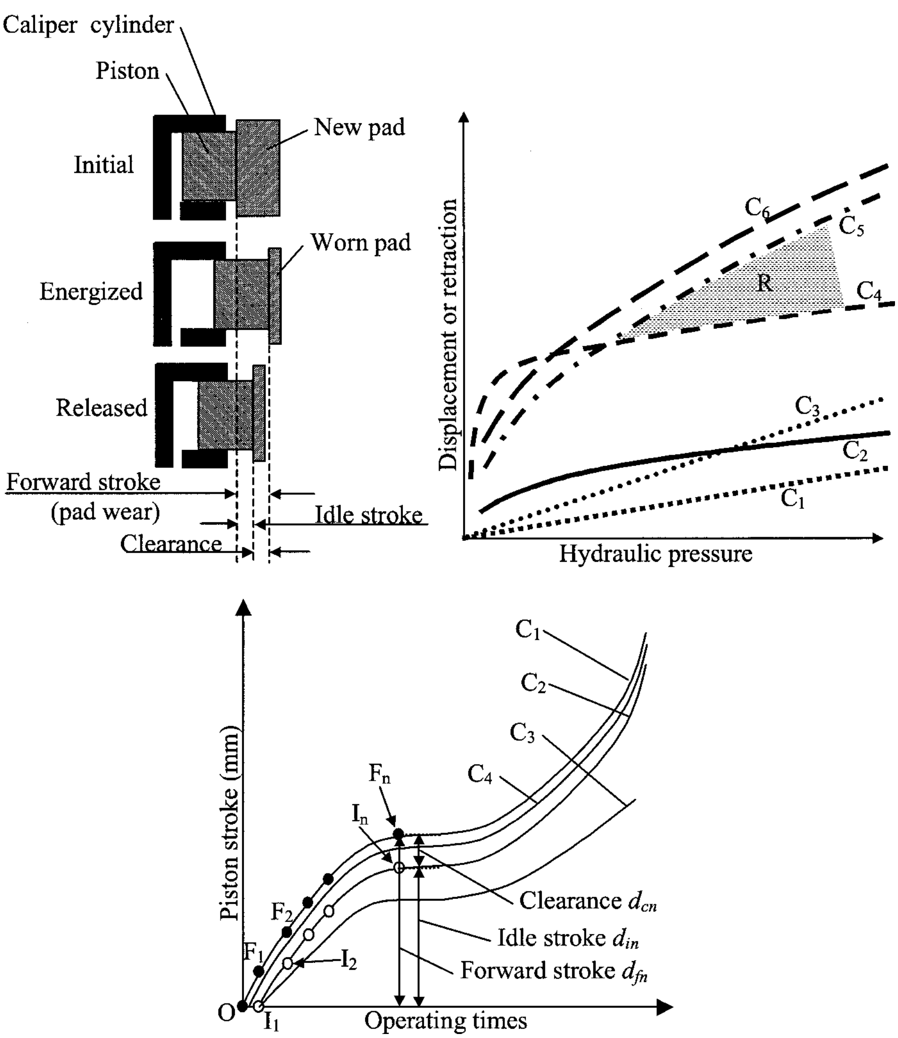

Fig. 2 Piston stroke definitions during a single braking operation

pressed against the disc rotor and wear occurs on the pad. This operation produces a forward stroke d_f, which equals the pad wear under the above-mentioned assumptions. The retractor pulls the piston and pad back to an idle position and produces an idle stroke d_i. The absolute value of the difference between d_f and d_i is the clearance d_c kept by the retractor. A pair of d_f and d_i exists during each braking operation; thus an individual d_c is calculated after each braking operation.

The lining pad wear grows as it is pressed against the disc rotor during braking, hence generating increasingly larger forward strokes. A piston retractor without automatic adjustment retracts the piston to a predefined initial position and produces the same idle strokes for the variable forward strokes. Therefore, increasingly larger clearances are generated as the wear grows. Larger clearances will cause defects of braking force delay, as mentioned in section 1. An ideal retractor keeps a constant clearance by adjusting idle strokes according to the actual pad wear. This study proposes a piston retractor design that adapts to the pad wear automatically.

2.2 Engineering requirements

According to the above-mentioned backgrounds, this study addresses the functions of braking performances and manufacturing considerations for the piston retractor:

1. Assisting the retraction of the piston. The piston is retracted after the braking lever is released so that the clearance between the pad and disc is kept larger than a commercial product without a retractor.
2. Automatic adjustment for lining pad wear. Without automatic adjustment, clearances between the pad and disc will grow increasingly larger as the pads wear.
3. Cost and manufacturing efficiency. The design of the apparatus will be simplified as much as possible to minimize the costs of production and fabrication.

With the automatic adjustment function, clearances between the lining pad and disc rotor can be defined in the design and manufacturing processes. In this manner, it is not necessary for a rider to possess a good skill on adjusting the clearance. Frequent adjustments of the clearance are thus eliminated.

2.3 Concept generation

This study involves TRIZ to serve as the concept generator for proposing a feasible piston retractor design. This subsection provides a brief description of this theory. TRIZ is the acronym for 'theory of inventive problem solving' in Russian, which was developed by Altshuller and his colleagues, starting in 1946 [**10**]. This theory is based on the analysis of over two million patents and classifications by different levels of inventiveness. The principles of innovation are extracted and collected under the hypothesis that there are universal principles for creative innovations that advance technologies.

TRIZ translates technical system characteristics into 39 engineering parameters, such as masses of moving objects, the energy to move, forces, maintenance conveniences, manufacturing complexities and so on [**11**]. Engineers may meet contradictions when they try to solve a problem because some characteristics of a technical system deteriorate while engineers attempt to improve others. TRIZ provides a 'Contradiction Table' of size 39 $\times$ 39. The columns and rows of the table indicate the parameters to be improved and those that have deteriorated while trying to solve the problem. Each cell of the table contains a set of possible solutions. These solutions are collected and selected from a total of 40 invention principles, such as segmentation, vibration, softening or thinning out, etc. In this way TRIZ suggests several invention principles that are needed to solve the technical problem by requesting engineers to translate the technical system characteristics into engineering parameters. For example, increasing the disc rotor size can enlarge the braking force of a disc brake system. However, this solution induces a problem where the disc rotor mass is excessively large. The technical problem in this case can be identified as 'to improve a force without increasing the mass of a moving object'. The Contradiction Table suggests a set of invention principles, including 'segmentation', 'mechanical vibration' and so on. Among these principles, the 'segmentation' principle gives engineers the idea of boring holes in the disc, therefore reducing the disc rotor mass while enlarging its size.

The problem to be solved in this study is to produce an automatic adjusting piston retractor design. The moving piston will be pulled back to a position where the clearance between the lining pad and disc is larger than the current design without an additional retractor. The number of components needs to be minimized, hence reducing the manufacturing and fabrication costs. This problem can be translated into a statement from the TRIZ viewpoint, 'to provide the energy for a moving object (the piston) without complicating the manufacturability'. The Contradiction Table provides three principles to solve the problem, including 'mechanics substitution', 'copying' and 'flexible shells or thin films'. The third principle explains that flexible shells or films can be used to replace the three-dimensional structures, and gives a concept of utilizing disc springs and a thin extensional ring. Disc springs can provide the energy to retract the piston. The extensional ring, which is frictionally fixed on the inner wall of the piston, serves as an automatic adjuster for the pad wear. The proposed piston retractor design is basically composed of these components.

2.4 Conceptual design

The retractor design involving disc springs, an extensional ring, a support rod and a plate is proposed to achieve the desired functions, as illustrated in Fig. 3. The extensional ring is formed with a ring-shaped base, a fringe and several tongues protruding from the ring-shaped base. The fringe exists for the disc spring to act on. The tongues tilt outwards and serve as compressible springs along the radial direction. The fabrication is indicated in Fig. 4 and the assembly procedures are described as follows:

1. The extensional ring is placed inside the caliper cylinder, coaxial with the support rod in the cylinder.
2. The disc springs are placed inside the extensional ring and are coaxial with the support rod. The bottom disc spring is in contact with the fringe of the extensional ring.
3. The support plate is fixed on to the support rod with its screw section, and is in contact with the top disc ring and compresses the disc springs. At this moment, the extensional ring is resiliently pressed to the bottom of the caliper cylinder by the disc springs.
4. The piston is pressed into the caliper cylinder. Normal forces between the tongues and inner wall of the piston are established since the tongues are compressed along the radial direction by the wall. The normal forces generate the friction force between the ring and piston. The tongues hold the piston by friction forces between the tips of the tongues and the inner wall of the piston. The total normal force between the extensional ring and inner wall of the piston is changeable by applying different numbers of tilts at the tongue tips, thus making the friction force modifiable.

Figure 5 represents the operations of the proposed design. When the lining pad (not shown) is new and installed in the brake system, the piston is settled at the bottom of the caliper cylinder, as shown in Fig. 5a. The piston is pushed outwards when the fluid pressure is energized, as shown in Fig. 5b. The friction force f_r

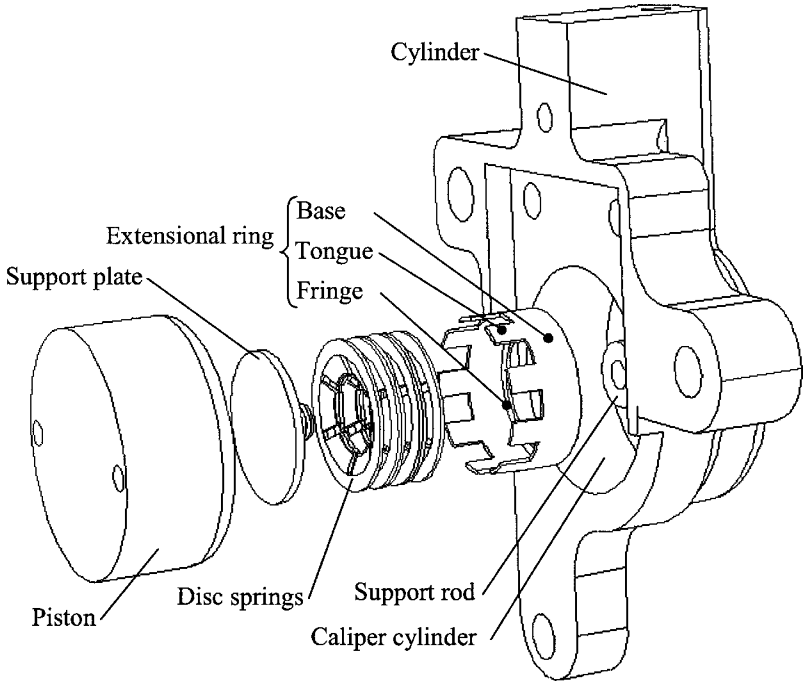

Fig. 3 Composition of the proposed piston retractor (US patent pending)

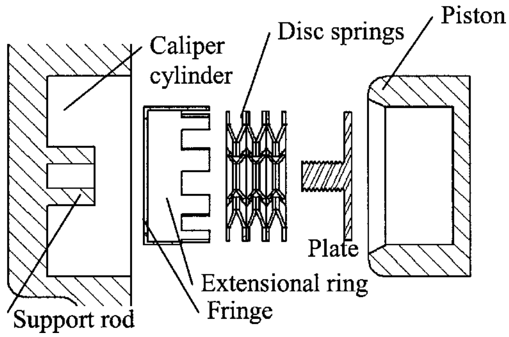

Fig. 4 Fabrication of the proposed piston retractor

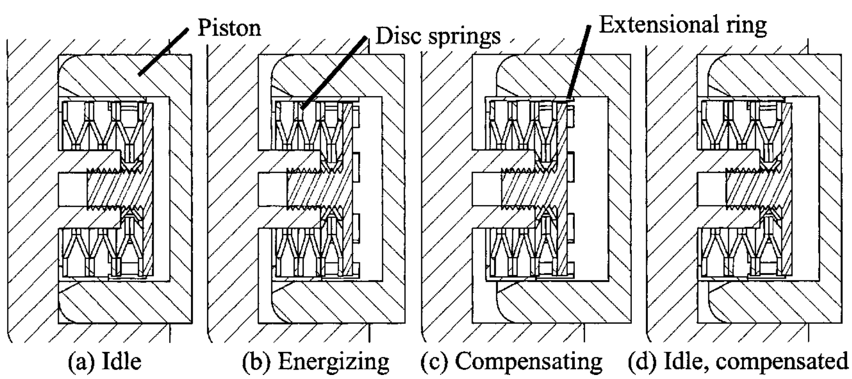

Fig. 5 Operations of the proposed piston retractor

between the extensional ring and the inner wall of the piston drags the extensional ring outwards when the piston is activated. Hence the disc springs are compressed and deformation energy stored in the disc springs grows larger. If the pad wear is small, the piston stroke is small and thus the disc spring compression is small. If the expansion force of the disc springs f_d is smaller than the friction force f_r, slip does not occur between the ring and piston and the ring locates at its current position on the inner wall of the piston. When the fluid pressure is removed, the piston is retracted by the ring, which is pulled by the expansion force f_d, according to its current position on the inner wall of the piston. The piston goes back to the initial position shown in Fig. 5a.

If the pad wear is large enough to cause the spring force f_d to become larger than the friction force f_r, slip between the ring and piston occurs. Figure 5c shows that the extensional ring slips on the inner wall of the piston for a certain distance and stops at a new position where the new expansion force f_d equals the friction force f_r. This procedure achieves the automatic adjustment function of the proposed retractor. After the fluid pressure is removed, the piston is retracted by the ring, which is pulled by the expansion force f_d according to the new position on the piston wall. The piston returns to a new initial position and is ready for the next brake operation. A constant clearance between the pad and disc is kept using the proposed retractor with an automatic adjustment function, since each idle stroke adapts to each pad wear amount. The clearance is larger than a regular design with only ring seals to retract the piston and is smaller than a commercial product without the automatic adjustment mechanism under the assumptions defined in section 2.1. Section 3 describes the experimental values of these products compared with the proposed design.

3 EXPERIMENTS

3.1 Prototyping

The prototyped extensional ring is made of steel with a tolerance of ± 0.05 mm. Figure 6 depicts the prototype.

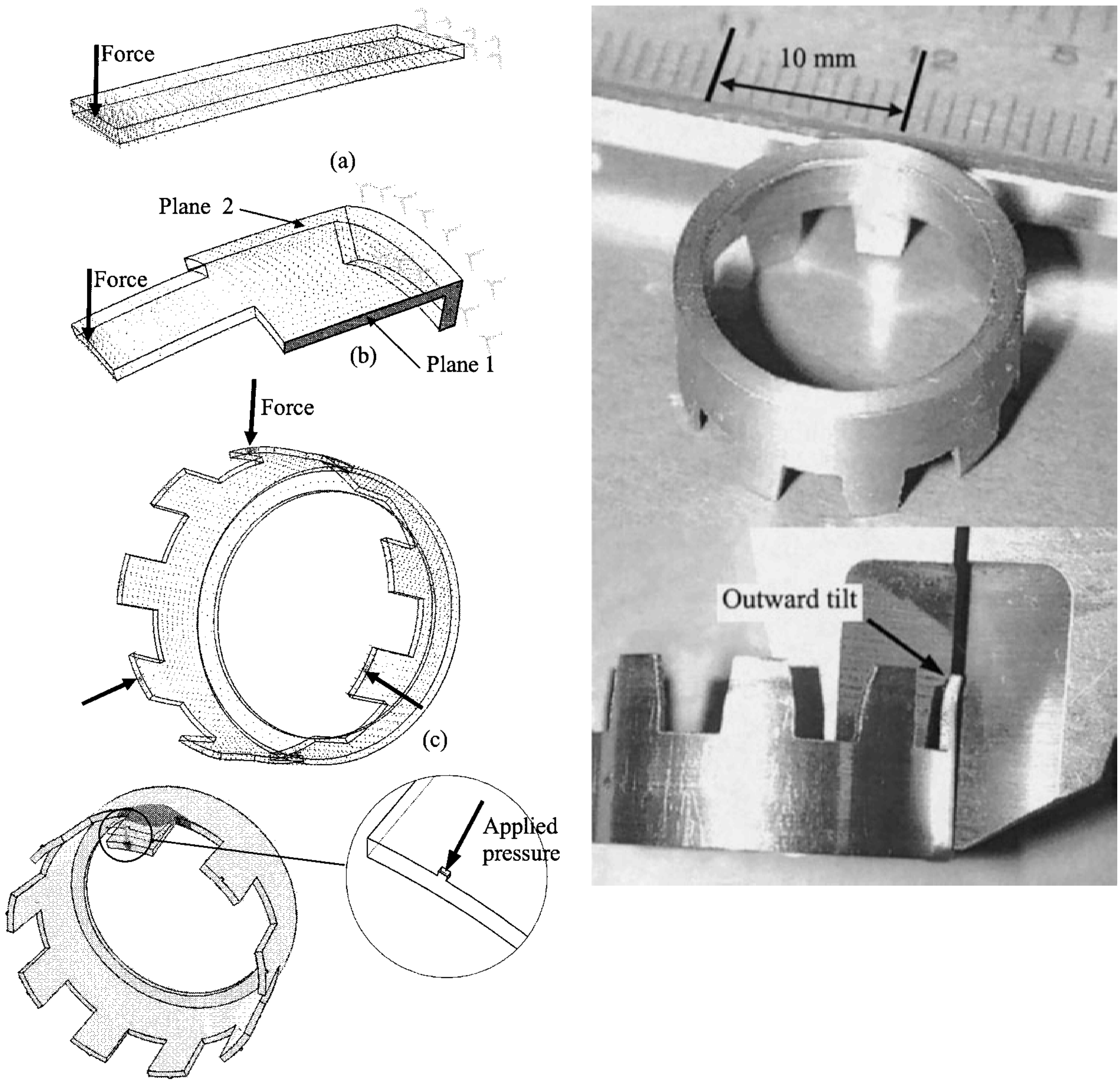

Fig. 6 The prototyped extensional ring

The tongue tip tilts outwards to produce the extension force when it is placed inside the piston and compressed by the piston inner wall. The tongue thickness is 0.3 mm. All of the tilt heights are made and measured to be the same.

3.2 Configuration

The goal of this experiment is to demonstrate the effectiveness of the piston retraction and the automatic adjustment function of the proposed design. Therefore, a clearance for each pair of forward and idle strokes during each braking operation is measured and recorded. The test rig is equipped with a laser distance recorder to measure the distances through which the piston travels in both the forward and backward directions. Figure 7 shows the caliper and instruments on the test rig [**12**].

A pneumatic cylinder pulls the brake lever in different ways, producing different piston strokes. The laser distance recorder is fixed on to the caliper body and is utilized to measure the pairs of forward and idle strokes, which can be used to derive the clearances. The curve of clearances is determined as the piston retraction performance of a hydraulic disc brake system in this study.

3.3 Test results

The performances of the proposed design in different numbers of tilts are derived and compared to those of a commercial hydraulic disc brake system with only the ring seal as the retractor and to those of a specialized hydraulic disc brake system equipped with a piston retractor but without the automatic adjustment function. Fifty data points of clearances are obtained by the laser distance recorder for each of the four designs. Figure 8 presents experimental results of these designs. Curves of the data points are defined as follows:

Design 1: a brake caliper utilizing only the ring seal as the retractor.
Design 2: a caliper with the proposed retractor having three tilts.
Design 3: a caliper with the proposed retractor having six tilts.
Design 4: a caliper equipped with a piston retractor but without the automatic adjustment function.

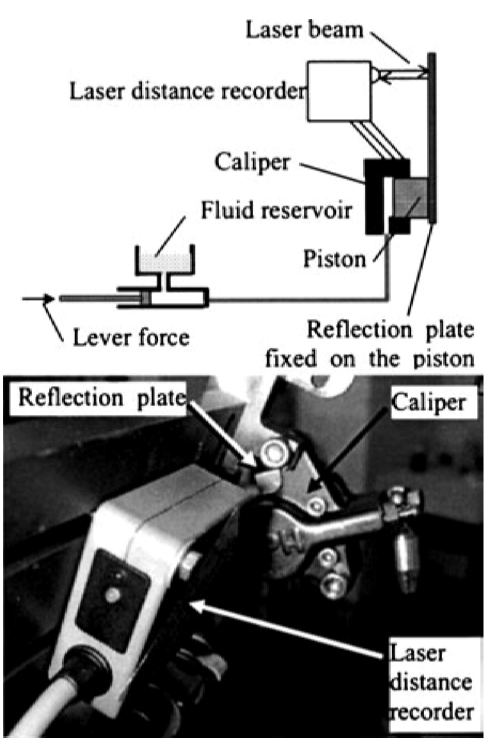

Fig. 7 Schema and photograph of the caliper and instruments

The horizontal axis represents the amount of wear on the pad during each braking operation and the vertical axis indicates the clearance between the pad and disc after each braking operation. The values of wear and clearance are derived from the forward and idle strokes defined in section 2.1 and shown in Fig. 2.

The clearances of design 1 are smaller than 0.3 mm and have a greater possibility of inducing the aforementioned problems than larger clearances of other objects. The curve of design 4 shows that the clearance increases as the wear grows without any adjustment being made. The piston stays at the predefined position, which is increasingly far from the disc after each braking operation, regardless of the amount of pad wear. Experienced manual adjustments for this product are necessary in order to maintain proper clearance within a safe range.

The performances of the proposed retractor of designs 2 and 3 are between the two previous designs. The curve of design 2 is above design 1, revealing a superior retraction performance where a larger clearance is maintained, thus reducing the possibility of inducing noise. The automatic adjustment function is activated after the wear reaches 0.4 mm and the average clearance after this point is kept to the value of 0.45 mm.

Design 3 keeps the average clearance at 1.09 mm after the wear reaches 1.2 mm, which is 0.64 mm larger than design 2. The clearance is too far from the disc surface and may produce safety problems mentioned in section 1. This result indicates that the total extension force between the extensional ring and piston is too large, causing an excessive friction force between the ring and piston. Therefore the ring does not slide on the inner wall of the piston.

The clearance of design 3 approximately doubles that of design 2, which confirms the fact that if the total extension force by the tongues is doubled, the clearance between the pad and disc is doubled. Theoretically, the extension force produced by the tongue tilts can be influenced by:

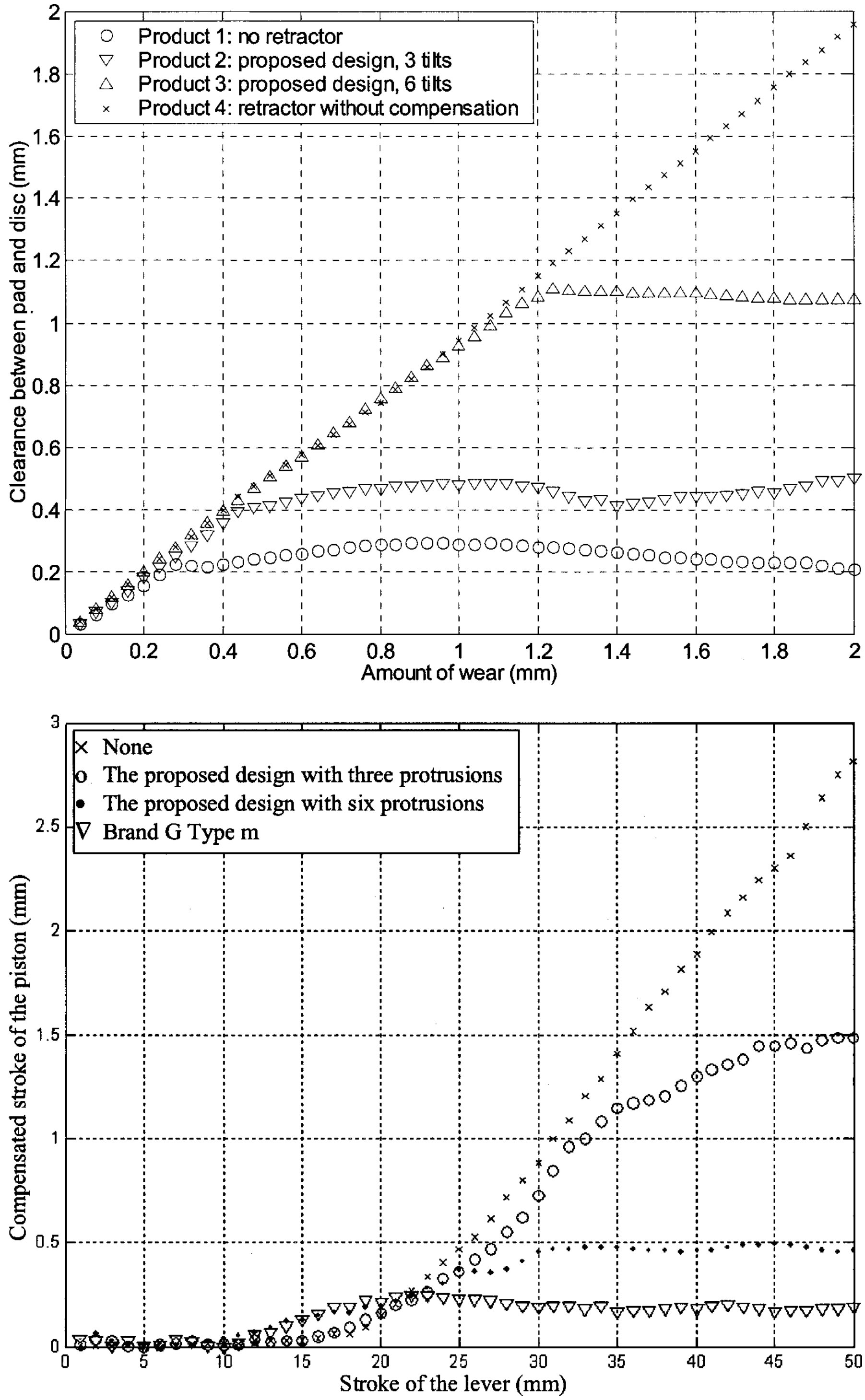

Fig. 8 Experimental results of the four calipers

1. The tongue thickness. Treat the tongue as a cantilever spring. The thickness increment will enlarge its strength. For an identical deformation at the tongue tip, the extension force is larger if the tongue is thicker.
2. The number of tongue tilts.
3. The height of the tongue tilt. The deformation energy increases as the deformation of the cantilever spring increases. If the height is larger, the deformation is larger when it is compressed inside the piston, producing a larger extension force.

The friction force between the ring and piston changes as the extension force varies. Hence it is reasonable to assume that there are at least three design variables that can be used by designers or manufacturers to alter the self-adjusting clearance produced by the proposed piston retractor, namely the tongue thickness, tilt number and the tilt height.

4 CONCLUSION

An innovative piston retractor with an automatic adjustment function is proposed in this study. This design improves the piston retraction performance of current hydraulic disc brake systems for bicycles. Prototype experiments are made under the assumptions that the fluid dynamics and temperature effect are not considered. According to the proposed design, three design variables, including the tongue thickness of the extensional ring, the number of tongue tilts and the heights of tilts, are adjustable, enabling manufacturers to define clearances for individual brake systems. Hence the clearances between the lining pads and disc rotor are definable in the design or manufacturing stages. Clearances kept by the proposed design are maintenance-free for riders, reducing the possibility of inducing friction problems when freely running. The proposed design provides consistent piston retraction performances and improves brake system safety.

ACKNOWLEDGEMENT

The authors would like to thank the National Science Council of the Republic of China for financially supporting this research under Contract NSC90-2622-E-194-008.

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