Optimum Design of Return and Cushion Springs for Automatic Transmission Clutches

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Reprinted From: Transmission and Driveline Systems Symposium 2001
(SP-1598)
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ISSN 0148-7191
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Printed in USA
ABSTRACT

Clutches and brakes are important elements in automatic transmissions in terms of function, number of parts and design works involved. Among the many design options and variables involved in the clutch and brake design, selection of return and cushion spring types and their characteristics are important for positive disengagement and better shift quality. However, not much information is available on the advantages and disadvantages of various return and cushion spring types, such as Multiple Round Wire Coil Springs, Flat Wire Wave Coil Springs, Disk Springs and Wave Springs.

In this paper, the functions and design requirements of return and cushion springs are reviewed. In order to provide some design guidelines for engineers, sample designs of return and cushion springs have been made using round wire coil, flat wire wave coil, disk and wave springs. A comparison of the results in terms of space, weight, cost and transmission performance is also provided.

INTRODUCTION

In automatic transmissions, wet-multiple-disk clutches and brakes are used to transmit engine power to the planetary gear set members or to ground them. The clutches and brakes are activated by hydraulic pressure provided by the hydraulic control system.

When hydraulic pressure is released in order to disengage the clutch, the clutch piston must be returned to its off-position quickly to avoid drag between the friction disks and clutch plates during free rotation. Drag between the friction disks and clutch plates reduces transmission efficiency and can result in friction disk failure. The simple mechanical spring shown in figure 1 is the most effective means available to return the clutch piston.

Furthermore, cushion springs are often used to improve the shift quality of the transmission (Fig. 1). Even though the return spring has some cushioning effect, the cushion spring provides extra cushion and slightly increases the clutch engagement time. This may be particularly effective in improving shift quality in static shifts (N-D, N-R shifts) when uncontrolled hydraulic pressure is applied for various reasons.

FUNCTIONAL REQUIREMENTS OF RETURN SPRINGS

FORCE – As a minimum, the return spring force for clutches must be greater than the centrifugal force created by the transmission fluid inside of the clutch piston and retainer. Usually, check balls or hydraulically balanced pistons are used to reduce the centrifugal force, thereby lowering the required force of the return spring.

Friction between the piston seals and the retainer, and friction on the splines of friction disks, clutch plates and hubs must also be added to the required spring force.

On the other hand, if the return spring force is unnecessarily high, the hydraulic pressure applied to the clutch must be increased to obtain the required clutch
torque capacity, which will result in increased oil pump capacity. Needless to say, increased oil pump capacity reduces the transmission efficiency.

The return spring force for brakes is usually lower than the clutch return spring because there is no centrifugal force acting on the piston.

To minimize the spring force, the spring itself must have minimum load hysteresis and should be manufactured with small load tolerances. This must be accomplished without cost penalties.

TRAVEL - The return spring travel, from the installation height to the fully engaged height, includes the clearance between the friction disks and clutch plates and compression of the friction facings.

In general, the hydraulic pressure acting on the clutch pack is high enough to cause some elastic deformation on the clutch piston and retainer. This deformation also needs to be considered when determining the required spring travel. Lastly, wear on the friction facings must be added to the spring travel.

The total travel becomes the stroke used during spring durability testing. Since there always is tolerance on the installed spring height, the starting point of the durability test may be either the maximum installed height or the minimum installed height. The stress level and fatigue life usually vary depending on the initial installed height. Therefore, the installed height which yields the highest stress level is typically used for durability testing to insure the reliability of the transmission.

FUNCTIONAL REQUIREMENTS OF CUSHION SPRINGS

Unlike return springs, cushion springs are installed at their free height. Therefore, spring force at installed height is zero. Close control of the spring free height is important, otherwise the clearance between the friction disks and clutch plates may be reduced.

The determination of cushion spring stroke and force characteristics may be difficult for design engineers because there is no theoretical background to calculate them. Currently, the best way to determine the optimum performance characteristics of cushion springs is through testing each clutch and brake assembly.

TRENDS IN AUTOMATIC TRANSMISSIONS

Compact and light weight designs are increasingly important in current automatic transmissions along with higher torque capacity, higher efficiency and better shift quality.

Since clutches and brakes have important portions in automatic transmissions in terms of number of parts and space in the transmission's powertrain, every component in clutch and brake assembly needs to be optimized. Types of return spring and cushion spring affect the clutch and brake pack configuration and its size. Therefore, the best spring type must be selected to match the given functional and space requirements.

Multiple round wire coil springs, flat wire coil springs and slotted disk springs are used for return springs in modern automatic transmissions. Disk springs and the wavespring are used for cushion springs (Fig. 2).

RETURN SPRINGS

- Multiple Round Wire Coil Spring
- Flat Wire Wave Coil Spring
- Inner Slotted Disk Spring
- None Slotted Disk Spring
- Wave Spring

CUSHION SPRINGS

Fig. 2 Return and Cushion Springs
DESIGN COMPARISON – RETURN SPRINGS

In order to select the best spring type and characteristics for the return springs and the cushion springs it is necessary to understand the advantages and disadvantages of the various spring types.

To compare each type of spring and its characteristics, sample designs of return springs were made for the sample clutch and brake as shown in Fig. 3. Table 1 shows the assumed design requirements of the return springs.

To simplify the design effort, all radial dimensions of other parts in the clutch assembly are assumed fixed. The axial length may be adjusted freely within the given space for the spring. This goal is to design a spring that results in the minimum axial length and the lightest weight of the clutch and brake assemblies. By minimizing the length and weight of the clutch and brake assembly, packaging of the engine & transmission assembly and the fuel economy of the vehicle will be improved.

DESIGN RESULTS – RETURN SPRINGS

Fig. 4 and 5 provide a comparison of each spring type for the sample clutch and brake applications. To make an objective comparison between each spring design, the springs are designed for the same working stress level and expected life.

Depending upon the experience of the designer and manufacturer, the spring specifications shown in Fig. 4 (c) and 5 (c) may be different, but not significantly. These results are sufficient to give a general overview of each spring type.

MULTIPLE ROUND WIRE COIL SPRINGS - The round wire coil spring demonstrates linear spring characteristics and, therefore, can easily be designed to meet the force requirements at the given installed and full engaged height. The spring can be manufactured with a force tolerance well below ±10 %. The springs may also be designed to work at a low stress level, such that the fatigue life is not a problem in most cases.

However, it is important to have some distance between the Facing Wear Height (F.W.H.) and the solid height of the spring. Otherwise, stresses will be increased to an unacceptable level as the friction facing wears.

A carbon steel retainer plate approximately 1mm thick is required to hold each coil spring in its correct position. This retainer plate increases the total length of the spring assembly by its thickness. The opposite sides of the individual springs are guided by holes or fingers made on the clutch piston or the balance piston.

FLAT WIRE WAVE COIL SPRINGS - Flat wire wave springs also have linear characteristics but it may not always be easy to meet the exact force requirements at the given installed and engaged heights. A ±10 % force tolerance can be achieved and the working stress level is usually low enough to meet the fatigue requirements of a clutch or brake return spring.

In automatic transmission applications, usually one turned shim (no waves) is added on one or both sides of the spring to provide solid seats on the piston or retainer. However, these shims increase the length of the spring by an amount equal to their material thickness. It is also necessary to have a separate retainer for brake applications to fix the spring in the radial position and provide a contact area for the snap ring.

INNER SLOTTED DISK SPRINGS - Disk springs usually have non-linear characteristics as shown in Fig. 4 (b) and 5(b). However, by selecting the geometric parameters properly, the spring force requirements at given heights can be well met with negligible difference.

The working stress level can also be lowered to achieve more than 2 million load cycles, which usually far exceeds the expected life cycle requirements of the clutch or brake of the automatic transmission. With special heat treatment processes, disk springs can be manufactured with load tolerance under ±10 %, which is important for consistent shift quality of the transmission.

Unlike other springs, disk springs do not require an extra part to hold their position in clutch pack. The spring is normally guided by its outer diameter and the piston. Because of this and its inherent configuration, disk springs are ideal to support high load under the minimum axial space requirement.

However, in order to optimize the performance of the disk spring, the contact points on the piston or the snap ring must be properly configured. In any case, the contact point should not change as the piston operates. If this happens, the spring force jumps as the piston strokes as shown in Fig. 6. This will result in unpredictable shift quality but can be avoided with properly bent spring fingers (Fig. 6). In general, however, bent spring fingers demonstrate higher spring force hysteresis when compared with straight finger springs as shown in Fig. 7. Therefore, the contact point on the piston or snap ring should be angled or rounded to reduce hysteresis rather than bending the spring fingers.

Fig. 7 also shows the effect of the contact point configuration on the spring force hysteresis. In most cases, the round projection gives the minimum hysteresis. Therefore, a rounded contact point used with a straight finger spring design provides the best working condition for the disk spring.
Fig. 3 Sample Clutch and Brake for Spring Design Comparison

<table>
<thead>
<tr>
<th>Design Constraints</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Clutch</td>
</tr>
<tr>
<td>Function</td>
<td>Shifting Clutch (2 friction disks)</td>
</tr>
<tr>
<td>Space Requirement</td>
<td>Minimize the axial length of the clutch assembly (Piston OD:158.0 mm, Piston ID:108.0 mm)</td>
</tr>
<tr>
<td>Load at</td>
<td></td>
</tr>
<tr>
<td>Installed Height (I.H.)</td>
<td>880 N (-10% min.)</td>
</tr>
<tr>
<td>Engaged Height (E.H.)</td>
<td>1,020 N (+10% max.)</td>
</tr>
<tr>
<td>Travel</td>
<td></td>
</tr>
<tr>
<td>From I.H. to E.H.</td>
<td>0.8 mm</td>
</tr>
<tr>
<td>Facing Wear (FW)</td>
<td>0.8 mm</td>
</tr>
<tr>
<td>Total Travel</td>
<td>1.6 mm</td>
</tr>
</tbody>
</table>

Table 1 Design Constraints for the Clutch and Brake Return Springs (Fig. 3)
**Round Wire Coil Spring**

**Flat Wire Wave Coil Spring**

**Inner Slotted Disk Spring**

(a) Configuration

(b) Spring Characteristics

(c) Spring Assembly Specification

Fig. 4 Design Comparison of Sample Clutch Return Springs
Round Wire Coil Spring

47.5

Retainer (t=1.0)

Total Number of Springs = 30

Flat Wire Wave Coil Spring

48.8

Retainer (t=1.0)

Shim

Inner Slotted Disk Spring

35.4

Stopper (2 pieces)

(a) Configuration

Force (N)

K=94.7 N/mm

984

870

681

Travel (mm)

15.8 13.8 12.6

(I.H.) (E.H.) (F.W.H.)

(b) Spring Characteristics

K=95.1 N/mm

984

870

680

17.1 15.1 13.9

(I.H.) (E.H.) (F.W.H.)

K=97.0 N/mm

872

678

4.0 2.0 0.8

(I.H.) (E.H.) (F.W.H.)

Material | Music Wire
---|---
Wire Diameter | 1.1 mm
Outside Diameter | 10.0 mm
Total No. of Coils | 9.5
No. of Active Coils | 6.5
Free Height | 23.0 mm
Installation Height | 15.8 mm
Solid Height | 11.5 mm
Weight (Assy.) | 1.04 N
No. of Total Springs | 30
Retainer CTR Dia. | 148 mm

Material | High Carbon Spring Temper Steel
---|---
Wire Thickness | 1.46 mm
Wire Radial Wall | 9 mm
Outside Diameter | 157 mm
No. of Active Turns | 3
No. of Waves | 4.5
No. of Shims | 2
Free Height | 24.3 mm
Engaged Height | 17.1 mm
Solid Height | 8.3 mm
Weight (Assy.) | 2.85 N

Material | High Carbon Spring Temper Steel
---|---
Material Thickness | 1.55 mm
Outer Diameter | 168 mm
Slot Diameter | 153 mm
Inner Diameter | 140 mm
Inner Load Dia. | 140 mm
No. of Fingers | 10
Width of Fingers | 8 mm
Free Height | 5.6 mm
None Slotted Height | 3.8 mm
Weight (Assy.) | 0.51 N

(c) Spring Assembly Specification

Fig. 5 Design Comparison of Sample Brake Return Springs
**Fig. 6 Spring Contact Point Change – Spring Force Jump**

<table>
<thead>
<tr>
<th>Design of Contact Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>20°</td>
</tr>
<tr>
<td><img src="image1" alt="Diagram" /></td>
</tr>
<tr>
<td>155 N → 180 N</td>
</tr>
<tr>
<td>25% → 20%</td>
</tr>
<tr>
<td>80 N → 55 N</td>
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<tr>
<td>12% → 7%</td>
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<tr>
<td>10°</td>
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<tr>
<td><img src="image2" alt="Diagram" /></td>
</tr>
<tr>
<td>136 N → 141 N</td>
</tr>
<tr>
<td>22% → 15%</td>
</tr>
<tr>
<td>75 N → 50 N</td>
</tr>
<tr>
<td>11% → 7%</td>
</tr>
<tr>
<td>radius</td>
</tr>
<tr>
<td><img src="image3" alt="Diagram" /></td>
</tr>
<tr>
<td>105 N → 87 N</td>
</tr>
<tr>
<td>17% → 11%</td>
</tr>
<tr>
<td>51 N → 40 N</td>
</tr>
<tr>
<td>7% → 5%</td>
</tr>
</tbody>
</table>

**Fig. 7 Effect of Contact Point and Spring Finger Configuration on Hysteresis**
COMPARISON – RETURN SPRING TYPES

AXIAL LENGTH AND WEIGHT

The results shown in Fig. 4 and 5 indicate that a properly designed disk spring minimizes the axial length of the clutch and brake assembly. The disk spring usually requires more radial space than the coil spring or wave coil spring. In most cases, however, there is sufficient space on the piston wall, because the pistons always have clearance between the outer and inner diameter.

Because of its short axial length, implementing disk type return springs can also reduce the weight of the clutch and brake assembly. Compact clutch assemblies not only reduce the weight of clutch but also the weight of other parts in the transmission, such as the transmission case, shafts, etc. Typically, there are more than 5 clutches or brakes in a 4 speed automatic transmission and if disk type return springs are used throughout the transmission, the total weight saving and length reduction will be considerable. Fig. 8 and 9 show the estimated transmission weight savings and axial length reductions of the sample clutch and brake with disk type return springs (Fig. 3). Transmission weight is calculated based on an assumed transmission configuration.

COST

The multiple round wire coil spring and the flat wire wave coil spring require a carbon steel retainer plate to hold and maintain the radial position of the spring. The retainer increases the cost and assembly time associated with these spring types. On the other hand, disk springs are typically guided by the piston and do not require a retainer. This simplifies the assembly, part control and handling.

TRANSMISSION PERFORMANCE

Shift Quality - When the return spring is installed in the clutch assembly, there is always some tolerance on the installation height. In the case of springs with linear characteristics, the installation height tolerance combined with the spring force tolerance may result in considerable spring force variation between the engaged height (new facings) and full facing wear height as shown in Fig. 10. And this makes it difficult to maintain consistent shift quality from one transmission to the next unless a very rugged adaptive control system is employed.

On the other hand, disk spring can minimize such effects because they can be designed to have a flat load curve beyond the minimum engaged height (Fig. 10).

![Diagram](image)

Fig. 10 Effect of Installation Height Tolerance on Spring Force Tolerance

Efficiency – The oil pump capacity or line pressure may be reduced with disk springs that have a flat load curve beyond the engaged height especially with return springs with a high spring rate. This effect is more distinct in the clutches or brakes with many friction disks where the friction facing wear is considerable over time (Fig. 11).

Reduced line pressure or oil pump capacity improves the transmission efficiency and thus the fuel economy of the vehicle as shown in Fig. 12.
Fig. 8 Comparison of Sample Clutch Assembly Length and Transmission Weight

Fig. 9 Comparison of Sample Brake Assembly Length and Transmission Weight
DESIGN COMPARISON – CUSHION SPRINGS

In order to compare the various types of cushion springs (Fig. 2) and their characteristics, sample cushion spring designs were made for the sample brake (Fig. 3) using a disk type return spring.

Table 2 represents the assumed design requirements for the cushion springs.

Again, in order to simplify the design effort, all radial dimensions of other parts in the brake assembly are assumed fixed. The objective is to optimize the axial length of the spring (free height).
Disk Spring  Wave Spring (Splined)  Disk Spring (Piston Guided)

(a) Configuration

Force (N)  Force (N)  Force (N)
K=2685 N/mm  K=2696 N/mm  K=2714 N/mm

(b) Spring Characteristics

<table>
<thead>
<tr>
<th>Material</th>
<th>High Carbon Spring Temper Steel</th>
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<tr>
<td>Material Thickness</td>
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<tr>
<td>Outer Diameter</td>
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<tr>
<td>Inner Diameter</td>
<td>169.2 mm</td>
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<tr>
<td>Inner Load Dia.</td>
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<tr>
<td>Free Height</td>
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<td>Weight (Assy.)</td>
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<td>Inner Diameter</td>
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<tr>
<td>No. of Waves</td>
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<tr>
<td>Free Height</td>
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</tr>
<tr>
<td>Weight (Assy.)</td>
<td>0.44 N</td>
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</table>

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<tr>
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<th>High Carbon Spring Temper Steel</th>
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<tbody>
<tr>
<td>Material Thickness</td>
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<tr>
<td>Outer Diameter</td>
<td>175.0 mm</td>
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<tr>
<td>Inner Diameter</td>
<td>169.0 mm</td>
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<tr>
<td>No. of Waves</td>
<td>10</td>
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<tr>
<td>Free Height</td>
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<tr>
<td>Weight (Assy.)</td>
<td>0.29 N</td>
</tr>
</tbody>
</table>

(c) Spring Specification

Fig. 13  Design Comparison of Sample Brake Cushion Springs
DESIGN RESULTS – CUSHION SPRINGS

Fig. 13 shows various design arrangements for disk and wave type cushion springs for the sample brake. Again, depending on the experience of the design engineers and manufacturers, the results can be varied, but not considerably.

DISK SPRING - Disk springs without fingers are typically used in cushion spring applications. The spring rate from free height to working height is held almost constant. The stress level at the working height is usually low enough that fatigue life is not an issue in cushion spring applications.

The required force at the working height can be met with only slight variations. A $\pm 10\%$ force tolerance at the working height can be obtained with special manufacturing processes.

WAVE SPRING (SPLINED) - When axial length is limited, the outer splined wave spring as shown in the Fig. 13 (a) is a good option. In this case, the outer and inner diameter of the spring and clutch plate can be identical. Therefore, the thickness of the spring can be reduced considerably for a given load and stroke condition. In most cases, the stress level is low enough that fatigue life is not a problem. A $\pm 10\%$ force tolerance at the working height can be obtained with special manufacturing processes, however some cost penalties may be incurred.

It is usually difficult to obtain the desired spring force at the target working height with a wave spring. However, by varying the number of waves and material thickness, the desired load characteristics can be achieved with minor deviations.

WAVE SPRING (PISTON GUIDED) - If the piston is thick enough in both the radial and axial direction, the wave spring can be nested in the piston as shown in Fig. 13 (a). In this design, the stroke of the wave spring can be held precisely by controlling the difference in the piston height and spring free height.

In this case, the radial width of the spring is small therefore, the stress level at the working height is higher. However, the stress levels are usually low enough that the spring will have sufficient fatigue life for clutch or brake applications. Once again, a $\pm 10\%$ force tolerance at the working height can be obtained with special manufacturing processes but with some potential cost penalties.

COMPARISON – CUSHION SPRING TYPES

As shown in Fig. 13 the piston guided wave spring results in the shortest axial length of the brake assembly.

However, the weight and space savings are not as significant when compared with return springs. However, when the weight and size goals of the transmission is aggressive, these differences can not be neglected.

CONCLUSION

By evaluating sample spring designs in conditions similar to those found in actual clutch and brake applications, the authors determined that the size and weight of the clutch and brake assembly vary considerably depending on the spring type used. The type of return and cushion springs used can significantly influence the total weight and size of the transmission.

In the sample return spring designs evaluated in this paper, the use of Inner slotted disk spring resulted in the most compact and lightweight design of the clutch and brake assembly. Furthermore, the disk spring can maintain a flat load curve beyond the engaged height resulting in improved the shift quality and higher transmission efficiency.

The costs associated with each spring type can vary considerably depending on the spring manufactuer and the requirements of the application. Therefore, it is difficult to make an objective cost comparison between the various spring types.

Unlike other springs, disk springs do not require any additional parts to maintain their position in the clutch or brake assembly. This not only reduces the cost of the spring but also related components by simplifying the assembly process and reducing the number of parts involved.

For cushion springs, even though the differences may not be large, the wave spring minimizes axial length. If the size and weight goals for the transmission are aggressive, these small differences can not be neglected.

As a final example, the best and worst case scenarios are shown in Fig. 14. As one can see, proper selection of the return and cushion springs can provide a dramatic improvement in the design of the transmission.

REFERENCES

LENGTH: + 14.5 MM
TRANSMISSION WEIGHT: + 16.7 N

(a) **Coil Return Spring**
    + **Disk Cushion Spring**

(b) **Disk Return Spring**
    + **Wave Cushion Spring**

Fig. 14 Comparison of Maximum and Minimum Sample Brake Axial Length and Transmission Weight