

FAILURE ANALYSIS AND FINITE ELEMENT-BASED STRUCTURAL OPTIMIZATION OF ENGINE VALVE SPRINGS

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Abstract –This paper studies the fracture failure mechanism and structural redesign of engine intake and exhaust valve springs from a manufacturer. Fractography and metallographic tests on fracture surfaces identify the core failure cause. Poor heat dissipation induces temperature-driven metal phase transformation in springs. This transformation creates intense thermal stress concentration, leading to crack growth and final fracture due to insufficient structural bearing capacity. A geometry-optimized variable-diameter valve spring is proposed to solve this problem. Finite element (FE) static simulation results meet static strength requirements: the optimized intake valve spring has a safety factor of 1.47, and the exhaust valve spring has a safety factor of 1.24 under maximum service loads. Modal analysis confirms the first-order natural frequencies of the redesigned intake and exhaust valve springs are 125.71 Hz and 110.09 Hz, respectively. Both values are far higher than the valve reciprocating operating frequency of 16 Hz, so resonance damage is completely avoided. Fatigue performance is assessed using the Palmgren-Miner linear cumulative damage criterion. The optimized springs possess theoretical infinite fatigue life, satisfying the specification of GB/T 19055-2024 *Reliability Test Methods for Motor Vehicle Engines*. The proposed structural optimization method effectively suppresses spring fracture caused by thermal stress concentration and heat-induced phase transformation.

Keywords: Engine Valve Spring; Finite Element Analysis; Static Strength Verification; Modal Analysis; Structural Optimization; Fatigue Life.

1. Introduction

The valve train constitutes a core assembly of internal combustion engines. By providing restoring forces during cyclic compression and rebound, valve springs enable accurate valve repositioning and airtight sealing of combustion chambers, thereby exerting a decisive influence on cylinder thermal efficiency and operational stability. With increasingly stringent environmental regulations, modern engines are developing toward high power density, low energy consumption and lightweight design. Cylindrical helical springs have drawbacks such as fixed stiffness and low material utilization, making them difficult to meet the performance requirements under complex working conditions.

The development of finite element simulation technology provides an efficient means for the precise design and performance optimization of valve springs, which can complete strength verification and dynamic characteristic analysis

before installation, significantly reducing research and development costs and cycles.

At present, scholars have conducted extensive research on the performance optimization of valve springs. In terms of process design, Qin et al. [1] adopted the high-frequency induction hardening process to improve the hardness of valve springs, effectively avoiding the cracking problem. Yu [2] conducted an in-depth study on the thermal stress of valve springs during operation and improved their performance through reasonable design of hot pressing processes. Meanwhile, numerous studies have shown that adding an appropriate amount of trace elements to spring materials has a significant effect on enhancing the fracture resistance of valve springs [3, 4]. In terms of structural design, Wang et al. [5] adjusted the geometric parameters of valve springs and compared the mechanical responses of optimized and original designs through finite element simulations, finding that reasonable design of valve spring parameters is of great significance for ensuring their normal operation. Li et al. [6]

successfully achieved parameter matching of valve springs by reselecting the structure of fractured ones. Modifying the design parameters of different types of springs is also an important approach to improve the performance of related products [7, 8]. In recent years, with the improvement of assembly and manufacturing processes and precision, combined spring structure design [9-12] and variable-stiffness springs have been well applied in the field of engine valve springs [13-15]. Zhang [16] conducted a systematic research and analysis on the variable-stiffness nonlinearity and new materials of valve springs, and proposed a relatively comprehensive design method.

The theoretical and numerical research on spring thermo-structural coupling has formed a mature system. Numerous authoritative studies focus on automobile suspension coil springs and alloy leaf springs, establishing standardized thermo-mechanical coupled FE methods to quantify thermal residual stress and high-temperature fatigue crack propagation [17-19]. These literatures fully reveal the coupling law of thermal and cyclic mechanical loads on spring damage. However, few studies target thermally induced failure of engine exhaust valve springs, which endure persistent high-temperature radiation from combustion chambers. Most valve spring optimization works merely adjust wire diameter and average coil diameter under room-temperature conditions, ignoring the inner-outer coil thermal gradient and heat-triggered phase transformation that cause fracture [20,21]. Although variable-stiffness and combined dual springs are widely used for dynamic stiffness matching, systematic variable-diameter single spring designs for thermal stress homogenization are rarely reported in valve train research [22].

The finite element method is an important optimization design approach for valve spring development. A large number of finite element research cases have shown that using the finite element method to conduct static and dynamic analysis of valve springs is an important way to ensure their static strength and impact strength [23]. Based on the actual parameters of valve springs of a certain vehicle model, this study verifies their static strength and dynamic characteristics through finite element analysis, conducts force analysis and structural optimization, proposes a variable-diameter optimization scheme, and achieves improvements in lightweight and multi-condition adaptability, aiming to obtain better mechanical properties of the valve spring.

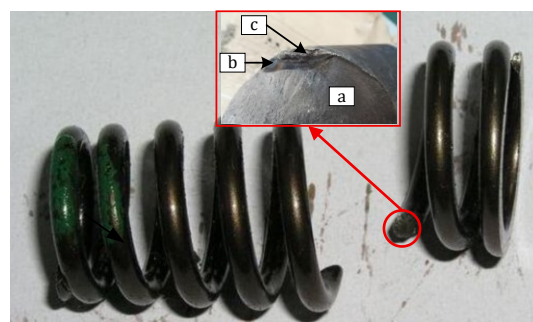
This customized optimization solution targeting exhaust thermal cracking failure can shorten the prototype iteration cycle by approximately 30%, eliminate batch outer-coil fracture defects, and reduce engine after-sales maintenance costs caused by valve spring failure, presenting clear promotion value for high-power-density internal combustion

engine valve train design. Static, modal and fatigue FE analyses are standard mechanical verification methods. This study combines metallographic fracture tests and variable-diameter optimization. The method solves high-temperature cracking of exhaust valve springs. It builds a full closed-loop engineering verification process.

2. Sample Introduction and Finite Element Modeling

2.1 Sample Introduction

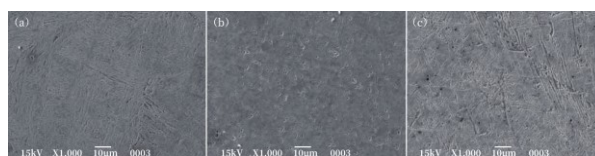
A fractured exhaust valve spring sample provided by the enterprise is selected as the research object, and the macroscopic fracture morphology of the exhaust valve spring is analyzed, as shown in Figure 1.



(a) Matrix Structure; (b) Crack initiation zone; (c) Abnormal Fracture Area

Figure 1: Macroscopic fracture morphology of 55SiCr exhaust valve spring

It can be seen from Figure 1 that the fracture position of the exhaust valve spring is located at the outer coil, and three distinct fracture regions are observed on the fracture surface. Scanning Electron Microscope (SEM) morphology analysis was conducted on the fracture surfaces of the three regions, and the results are shown in Figure 2.



(a) matrix structure; (b) crack initiation zone; (c) abnormal fracture area

Figure 2: The SEM morphology of 55SiCr spring fracture

It can be seen from Figure 2 that the microstructural characterization via scanning electron microscopy (SEM) reveals that the spring substrate consists of tempered martensite. However, the microstructures at the crack initiation zone and abnormal fracture zone differ markedly from the intact substrate matrix. Grains within the crack initiation zone are refined, whereas severe grain coarsening is observed across the abnormal fracture surface. This indicates an excessively high surface cooling rate in the fracture source region. Such coarsening is most likely attributed to the reheating

of the microstructure to a temperature close to the austenitization temperature, which is induced by the overhigh temperature of the exhaust valve. In the meantime, the inadequate heat dissipation of the spring leads to coarse grains in the abnormal fracture region. It is analyzed that an excessively large temperature difference between the inner and outer coils of the spring material causes the cracking of the outer coil. Fatigue failure of the material is thus ruled out as the cause of the spring fracture.

To further enhance the mechanical properties of the spring, modifying its structural dimensions is an effective measure to reduce the temperature difference between the inner and outer coils. In addition, performing finite element simulation on the structurally modified spring under the existing working condition parameters is the most efficient method to ensure the operational reliability of the spring.

2.2 Three-Dimensional Modeling of Springs

Taking the intake and exhaust valve springs as the research objects, three-dimensional models were established using SolidWorks. The original and improved parameters of the valve spring are shown in Table 1 below:

Table 1. Structural Parameters of Valve Springs

No.	Parameter Name	Original/Improved Intake Valve Spring	Original/Improved Exhaust Valve Spring
1	Wire Diameter (mm)	1.8/2	2.5/2.8
2	Mean Diameter (mm)	26/30	26/30
3	Outer Diameter (mm)	30/32	30.8/32.8
4	Inner Diameter (mm)	26/28	26.2/27.2
5	Compressed Length (mm)	32.8/25.2	38.22/29.4
6	Total Number of Coils	6	7
7	Free Length (mm)	42	49
8	Maximum Working Load (N)	160	220
9	Preload (N)	260	360

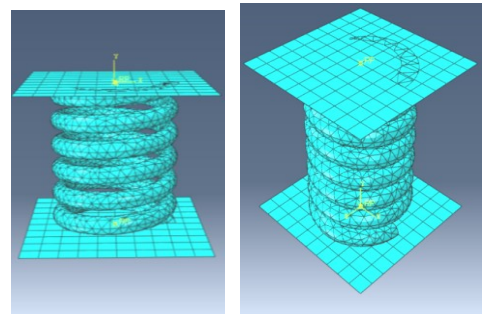
Increasing the size of the valve spring appropriately helps improve its structural strength,

and the relevant research approaches can be found in Literature [5].

2.3 Element Discretization and Material Definition

The valve spring is a type of cylindrical helical spring, made of 55CrSi alloy steel and processed through a series of manufacturing processes including quenching, tempering, surface treatment, nitriding, shot peening and stress annealing. The intake valve spring is preloaded to a maximum working load stroke of 7.6 mm, with a preload length of 32.8 mm and an elastic force of 160 N, and a maximum load length of 25.2 mm and an elastic force of 260N; the exhaust valve spring has a stroke of 8.82mm, a preload length of 38.22 mm and an elastic force of 220 N, and a maximum load length of 29.4 mm and an elastic force of 360 N.

The valve spring geometries were discretized using unstructured tetrahedral meshes, and the resultant meshed finite element models are presented in Figure 3.



(a) Intake valve spring (b) Exhaust valve spring
Figure 3: Discretized mesh models of valve springs

In the meshed model, tetrahedral elements were adopted for free meshing. The intake valve spring was divided into 7989 elements, and the exhaust valve spring into 9534 elements.

Material parameters of the valve spring were defined. The spring material (55CrSi) is presented in Table 2 below:

Table 2. Chemical Composition and Mechanical Properties of the 55CrSi Material

No.	Name	Parameters
1	Standard Name	GB4362
2	Grade	55CrSi
3	Diameter (mm)	1.6-8.0
4	Shear Modulus (GPa)	79
5	Elastic Modulus (GPa)	206
6	Yield Strength (MPa)	1814
7	Reduction of Area (%)	≥40
8	Poisson's Ratio	0.3
9	Tensile Strength (MPa)	1960
10	Density (g/cm ³)	7.73

2.4 Application of Constraints and Definition of Loads

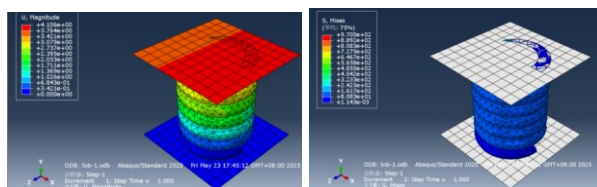
Static stress analysis is an important part of finite element analysis, which is used to evaluate the stress distribution, deformation, and overall performance of structures under static loads. Its main purpose is to ensure that valve springs meet design requirements while possessing sufficient strength, toughness, and fatigue resistance.

As a critical component inside automobile engines, the performance of valve springs directly affects the operational quality and working reliability of the engine. In static stress analysis, primary attention is focused on the stress contours and displacement contours of valve springs under preload and maximum working load conditions. Based on the structural parameters in Table 1, massless rigid reference planes were created at both spring ends to facilitate uniform force loading. Variable compressive loads were applied to extract the stress and displacement distribution characteristics of the spring structure.

3. Static Analysis of Valve Springs

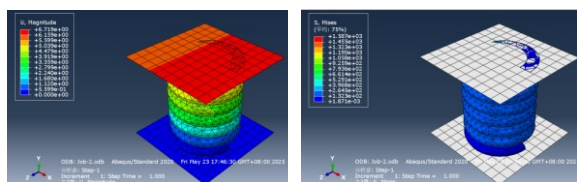
3.1 Static Analysis of Exhaust Valve Springs

Stress contours and displacement contours of the exhaust valve spring under preload and maximum working load conditions are presented in Figures 4 and 5, respectively.



(a) Displacement contour (b) Stress contour

Figure 4: Displacement distribution contour (a) and stress contour (b) under preload



(a) Displacement contour (b) Stress contour

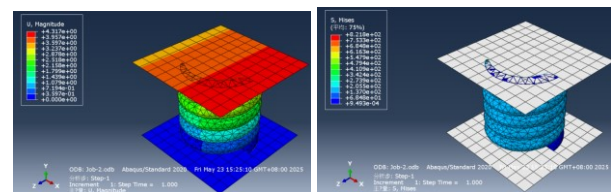
Figure 5: Displacement contour (a) and stress contour (b) under maximum working load

Analysis of the deformation and stress distribution contours of the exhaust valve spring shows that under preloading conditions, the von Mises maximum equivalent stress of the exhaust valve spring reaches 970 MPa, with the peak stress rising to 1587 MPa at the maximum working load. The maximum stress is lower than the material ultimate strength (1960 MPa). The corresponding

safety factor equals 1.24. The static strength satisfies design specifications. Observation of the deformation characteristics under preload indicates that the maximum structural deformation reaches 4.106 mm, which is significantly smaller than the allowable deformation limit specified in the design specification. When subjected to the maximum load, the spring deformation of 6.709 mm is also less than the design deformation margin. All deformation values stay within the safety threshold. No structural failure occurs under working loads. The optimized spring provides elastic force as designed.

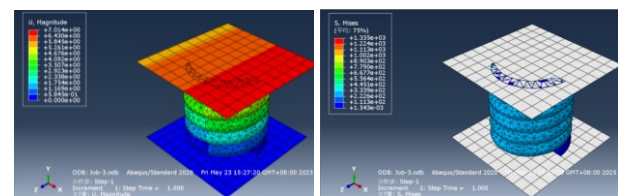
3.2 Static Analysis of the Intake Valve Spring

Through the analysis of the intake valve spring under preload and maximum working load conditions, the stress and displacement contours of the intake valve are shown in Figures 6 and 7 below.



(a) Displacement contour (b) Stress contour

Figure 6: Displacement contour (a) and stress contour (b) under preload



(a) Displacement contour (b) Stress contour

Figure 7: Displacement contour (a) and stress contour (b) under maximum working load

Analysis of the deformation and stress distribution contours of the intake valve spring shows that the maximum stress borne by the spring in the initial preload state is 821.8 MPa, and the stress peak increases to 1335 MPa under the maximum working load condition. This value is significantly lower than the material's ultimate strength of 1960 MPa, and the calculated safety factor is 1.47, which fully confirms that the static strength of the spring meets the service requirements. Observation of the deformation characteristics under preload indicates that the measured maximum deformation is 4.317 mm, which is much lower than the allowable design deformation range. When subjected to the maximum load, the spring deformation of 7.014 mm is also less than the design deformation margin. These data demonstrate that the deformation of the spring during operation is always within the safe range,

which will not cause structural failure. Meanwhile, proved that the intake valve spring can provide elastic restoring force complying with design standards when the predetermined deformation is achieved.

4. Modal Analysis of Valve Springs

On the premise of meeting the requirements of static analysis, modal analysis of valve springs needs to be conducted to ensure that they do not suffer resonance damage, thereby enhancing the credibility of the valve springs meeting the design requirements [24].

4.1 Modal Analysis of Intake Valve Springs

The first ten order mode shapes of the intake valve spring under preload obtained from modal analysis are shown in Figure 8 below:

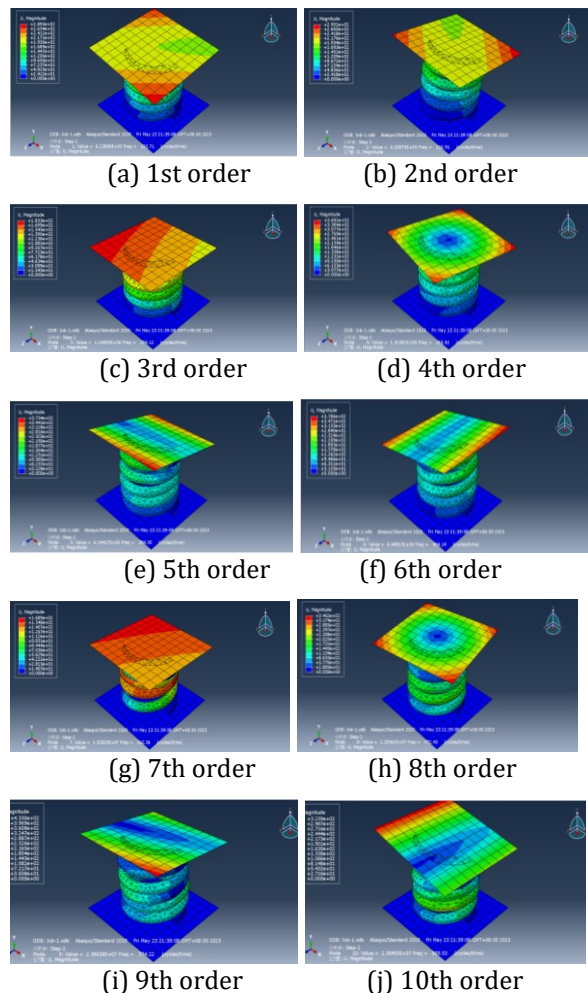


Figure 8: First ten order mode shapes of the intake valve spring

Based on the analysis results, the natural frequencies of each order mode shape of the intake valve spring are presented in Table 3 below:

Table 3. Natural Frequencies of Each Order Mode Shape for Intake Valve Spring Modal Analysis Under Preload

Order	Frequency (Hz)	Order	Frequency (Hz)
1	125.71	6	404.14
2	126.91	7	510.36
3	174.12	8	572.43
4	195.82	9	774.22
5	394.50	10	809.03

Analysis of Table 3 shows that the 3rd order vibration corresponds to the axial movement of the spring, the 1st, 2nd, and 5th order vibrations are the lateral movement of the spring, and the other six orders of vibrations are the coupled deformation of axial movement, lateral movement, and torsion of the spring. It can be seen from the frequency results in Table 3 that the frequency of the 1st order is 125.71 Hz, which is higher than the operating frequency of the valve spring ($960/60=16$ Hz). The comparison between the natural frequency and the actual operating frequency indicates that no resonance will occur during the operation of the intake/exhaust valve spring.

4.2 Modal Analysis of Exhaust Valve Springs

For the modal analysis of the exhaust valve spring, only the preload needs to be adjusted to 220 N. The first ten order mode shapes of the exhaust valve spring obtained from modal analysis under preload are shown in Figure 9 below:

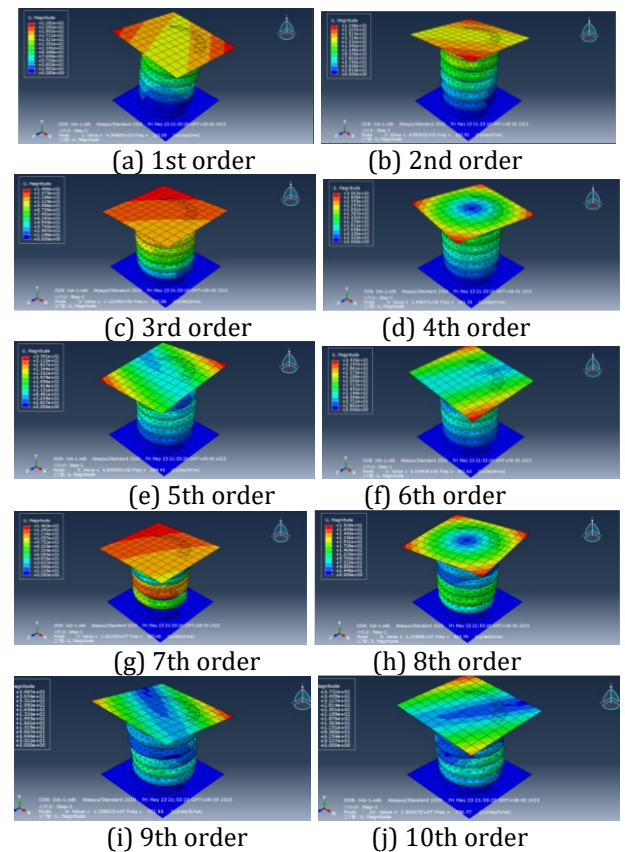


Figure 9: First ten order mode shapes of the exhaust valve spring

Based on the analysis results, the natural frequencies of each order mode shape are presented in Table 4 below:

Table 4. Natural Frequencies of Each Order Mode Shape for Exhaust Valve Spring Modal Analysis Under Preload

Order	Frequency (Hz)	Order	Frequency (Hz)
1	110.09	6	391.63
2	110.95	7	503.66
3	170.86	8	563.79
4	191.55	9	772.95
5	384.45	10	796.77

Analysis of the results shows that the 2nd, 3rd, and 7th order vibrations correspond to the axial movement of the spring, the 1st, 5th, and 6th order vibrations are the lateral movement of the spring, and the other four orders of vibrations are the coupled deformation of the spring's axial movement, lateral movement, and torsion. From the frequency results in Table 4, the frequency of the 1st order is 110.09 Hz, which is much higher than the operating frequency of the valve spring ($960/60=16$ Hz), indicating that no resonance will occur.

The performance variations between the original and optimized valve springs are presented in Table 5.

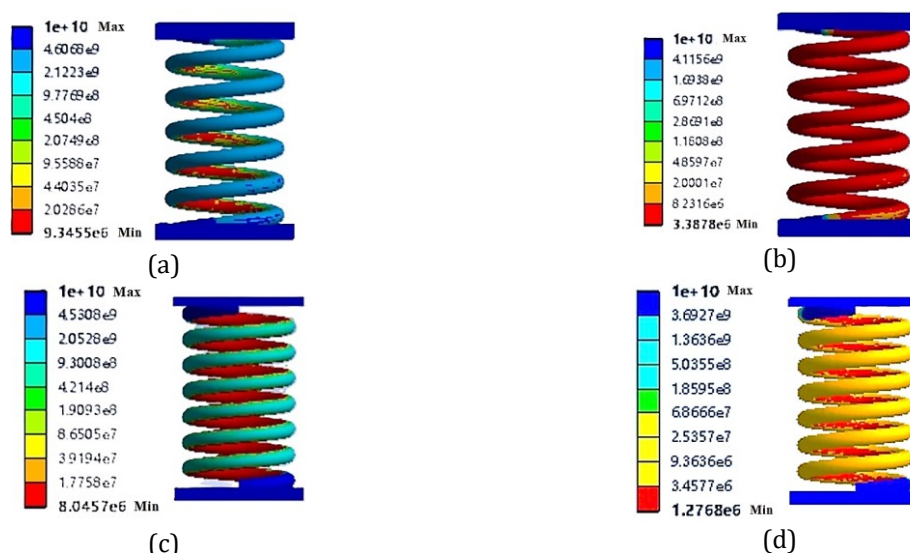
Table 5. Comparison of Key Mechanical Performance of Valve Springs Before and After Optimization

Performance Index	Working Condition	Spring Type	Intake Valve Spring	Exhaust Valve Spring	Variation Amplitude	Variation Percentage	Safety Factor Criterion
Maximum Mises Stress / MPa	Preload	Original	821.8	970	-	-	Material yield strength: 1960 MPa
		Optimized	1150	910.1	Intake: +328.2 Exhaust: -59.9	Intake: +39.93% Exhaust: -6.18%	All values below yield limit
	Maximum Working Load	Original	1335	1587	-	-	Material yield strength: 1960 MPa
		Optimized	1869	1489	Intake: +534.0 Exhaust: -98.0	Intake: +40.00% Exhaust: -6.17%	All values below yield limit
Maximum Axial Deformation / mm	Preload	Original	4.317	4.106	-	-	Within allowable design compression stroke
		Optimized	3.569	3.061	Intake: -0.748 Exhaust: -1.045	Intake: -17.33% Exhaust: -25.45%	Improved stiffness under identical load
	Maximum Working Load	Original	7.014	6.709	-	-	Within allowable design compression stroke
		Optimized	5.8	5.42	Intake: -1.214 Exhaust: -1.289	Intake: -17.31% Exhaust: -19.21%	Sufficient deformation margin
1st-order Natural Frequency / Hz	Preloaded Modal State	Original	125.71	110.09	-	-	Engine excitation frequency: 16 Hz
		Optimized	138.6	121.5	Intake: +12.89 Exhaust: +11.41	Intake: +10.25% Exhaust: +10.36%	Effectively avoid resonance range

5. Fatigue Life Analysis of Valve Spring

Cracking may be induced due to insufficient fatigue life. To further ensure that the designed valve springs have adequate fatigue service life, the stress

cycle distribution of the springs was imported into Ncode software for fatigue life analysis. The fatigue life of the valve springs is calculated in accordance with the Palmgren-Miner criterion. The calculation results are presented in the figure 10 below.



(a) Contour of fatigue life of intake valve spring under preload; (b) Contour of fatigue life of intake valve spring under maximum load
(c) Contour of fatigue life of exhaust valve spring under preload; (d) Contour of fatigue life of exhaust valve spring under maximum load

Figure 10: Fatigue life contours of the valve springs

From the fatigue life analysis results, it is found that the theoretical fatigue life of both exhaust and intake valve springs reaches reasonable cycles under the maximum working load. This value far exceeds the cyclic service life requirement of 5×10^5 to 1×10^6 cycles for valve springs stipulated in the national standard. Thus, an infinite service life is achieved in theory, with an ample safety margin.

Furthermore, the fatigue life analysis contours reveal that the inner coil is identified as the critical stress weak zone of the spring during cyclic service. The analytical results are highly consistent with the test results specified in National Standard GB/T 19055-2024, which verifies the rationality of the above analytical results. Meanwhile, combined with the test samples provided by the enterprise, the outer coil fracture failure caused by the unreasonable structural design of the original valve springs is effectively resolved through the structural optimization in this study.

6 Conclusions

Based on the structural parameters of the failed valve spring provided by the enterprise, its failure mechanism was analyzed, and a new spring model was established. The finite element method was adopted to conduct analytical verification on the newly designed valve spring model. The main research conclusions are presented as follows:

(1) Original fracture morphology and metallographic tests identify a special failure mechanism of exhaust valve spring insufficient heat dissipation leads to cross-section temperature difference, metal phase transformation and grain coarsening, further triggering thermal stress cracking. Targeted variable-diameter structural dimensional optimization is proposed to reduce the radial thermal gradient between inner and outer

coils, effectively suppress thermal stress concentration, improve overall structural bearing capacity, and fundamentally solve the outer-coil fracture failure of the original spring.

(2) Static structural analysis demonstrated that under preload and maximum working load conditions, the maximum stress of the intake valve spring reached 821.8 MPa with a safety factor of 1.47, and that of the exhaust valve spring reached 1587 MPa with a safety factor of 1.24. The deformation values of both springs were within the design allowable range. Modal analysis verified that the first-order natural frequencies of the intake and exhaust valve springs (125.71 Hz and 110.09 Hz, respectively) were far higher than the operating frequency of 16 Hz. No resonance risk was identified, which validated the operational reliability of the newly designed valve springs.

(3) Fatigue life analysis was carried out for the valve springs in accordance with the Palmgren-Miner criterion. The analytical results revealed that the valve springs achieved a theoretical infinite service life, which complied with the test requirements specified in National Standard GB/T 19055-2024 *Reliability Test Methods for Motor Vehicle Engines*. Meanwhile, the calculation results indicated that the critical stress region of the optimized valve springs was located at the inner coil, which avoided the risk of outer coil fracture to a certain extent and effectively solved the practical engineering problem proposed by the enterprise.

The mechanical simulation does not couple the high-temperature degradation of material mechanical properties and thermal stress induced by exhaust heat, which may overestimate the safety factors of the optimized valve springs. The thermo-mechanical coupling performance parameters of the valve spring will be continuously calibrated, and

further experiments will be carried out to investigate failure induced by uneven heat dissipation.

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