

Road Spectrum Based Fatigue Life Assessment of a Helical Suspension Spring

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Abstract—This paper presents an integrated analytical and numerical framework for the fatigue-life assessment of a helical compression spring under road-induced random excitation. A suspension spring was analytically designed to achieve a target stiffness of 20 N/mm for a sprung corner mass of 367 kg using SAE 5160 carbon steel. A three-dimensional finite element model was developed and verified in ANSYS through static structural and modal analyses. Synthetic road profiles for Highway (ISO Class B), Urban (ISO Class C) and Rural (ISO Class D) conditions were generated in MATLAB using the ISO 8608 power spectral density classification and applied to a two-degree-of-freedom quarter-car model at 80 km/h. The dynamic spring displacement was converted into a shear stress history using the spring geometry and Wahl correction factor. Fatigue life was independently predicted using a time-domain Rainflow–Miner approach and a frequency-domain Dirlik spectral approach. The two methods agreed to within 1% for Urban, 10% for Rural and 34% for Highway conditions. The spring displacement response PSD from ANSYS random vibration analysis was compared against the MATLAB quarter-car PSD across 20 frequency points, with errors of 0.36%, 3.05% and 5.50% at the dominant resonance frequency, confirming strong dynamic consistency between the two models.

Index Terms—Helical suspension spring, SAE 5160 steel, ISO 8608 road profile, quarter-car model, power spectral density, Rainflow cycle counting, Palmgren–Miner rule, Dirlik method, random vibration fatigue, finite element analysis

I. INTRODUCTION

Suspension components in road vehicles operate under continuously varying load conditions driven by road

surface irregularities, speed and payload variations. The coil spring is the primary energy-storage and load-transfer element within this system, absorbing cyclic impact loading generated at the wheel and regulating how that load reaches the chassis [6]. This loading is inherently repetitive — a spring does not fail under a single overload in normal service, but after an accumulated number of stress cycles individually well within the material's static strength limit. Fatigue is therefore the governing failure mode, and strength-based design criteria alone are insufficient for predicting spring service life [9].

Road-induced excitation is not deterministic. It is more accurately treated as a stationary random process characterised through its power spectral density (PSD) rather than a single constant-amplitude stress cycle [19]. This drives the use of two parallel fatigue-analysis approaches: a time-domain method based on Rainflow counting with Miner's rule, and a frequency-domain method using the Dirlik spectral distribution applied to the stress PSD.

Most published work on suspension spring fatigue relies on experimentally measured strain or displacement signals from instrumented vehicles [10, 11, 12, 20, 21, 22]. While realistic, this requires physical road access and instrumentation not available at the design stage. The present study addresses this by constructing a fully synthetic pipeline: ISO 8608 road profiles generated computationally are applied to an analytical quarter-car model to produce the spring stress response, and both Rainflow–Miner and Dirlik fatigue predictions are made from the same input and compared across three road severity levels. ANSYS random vibration analysis is additionally used to

verify the dynamic response of the finite element spring model against the quarter-car predictions.

II. SPRING DESIGN AND MATERIAL SELECTION

A. Design Parameters

The spring was designed to meet a target stiffness of 20 N/mm for a sprung corner mass of 367 kg. The shear stress in the spring wire is given by the Wahl-corrected expression:

$$\tau_{max} = Kw \times \frac{8FD}{\pi d^3}$$

where Kw is the Wahl correction factor:

$$Kw = \frac{4C - 1}{4C - 4} + \frac{0.615}{C}$$

and C = Dm/d is the spring index. Spring stiffness relates to geometry through:

$$k = \frac{Gd^4}{8D^3N}$$

These relationships were used together to determine the spring geometry. The resulting design parameters are given in Table I.

Table I. Final Analytical Design Parameters

Parameter	Value	Unit
Wire diameter, d	12.6	mm
Mean coil diameter, Dm	130	mm
Number of active coils, Na	6	—
Free length, Lf	315	mm
Spring index, C	10.32	—

B. Material Properties

SAE 5160 carbon steel was selected for its high fatigue resistance and good hardenability, widely used in automotive suspension springs. The properties used are summarised in Table II.

Table II. Mechanical and Fatigue Properties of SAE 5160 Steel

Property	Symbol	Value	Unit
Young's modulus	E	207	GPa
Poisson's ratio	ν	0.27	—
Ultimate tensile strength	Sut	1584	MPa
Fatigue strength coefficient	σ'_f	2063	MPa

Fatigue strength exponent	b	−0.08	—
Fatigue ductility coefficient	ϵ'_f	9.56	—
Fatigue ductility exponent	c	−1.05	—

III. FINITE ELEMENT MODEL

A. 3D Geometry and Mesh

The spring geometry was constructed in ANSYS using a sweep-based CAD procedure. A five-turn main helical coil was built from a 12.6 mm diameter wire swept along a 275 mm Y-axis path, with two tapered half-turn pigtail ends added using a diameter reduction factor of 0.75. The model was meshed using ANSYS fine mesh settings with a 10 mm element size, producing 83,588 nodes and 16,863 elements.

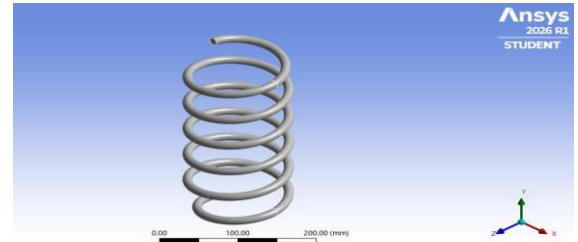


Figure 1. 3D CAD model of the helical coil spring in ANSYS, showing the completed five-turn helical geometry with tapered pigtail ends.

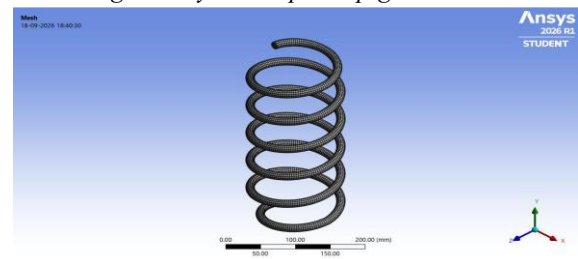


Figure 2. Finite element mesh of the helical coil spring.

B. Boundary Conditions

The lower end of the spring was fully constrained and the design load was applied at the upper end, replicating the compression loading condition in vehicle suspension service.

C. Static Structural Results

The finite element stiffness of 20.01 N/mm agreed with the analytical target of 20.00 N/mm, a difference of approximately 0.05%. The equivalent von Mises stress peaked on the inner surface of the active coils,

consistent with the Wahl-corrected analytical prediction.

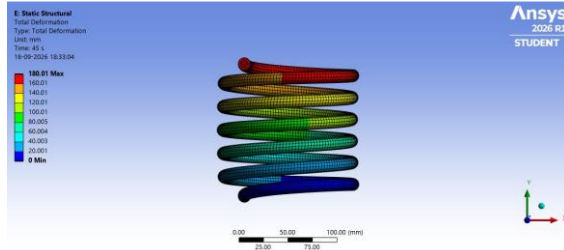


Figure 3. Total deformation contour of the helical spring under static loading showing axial compression behaviour.

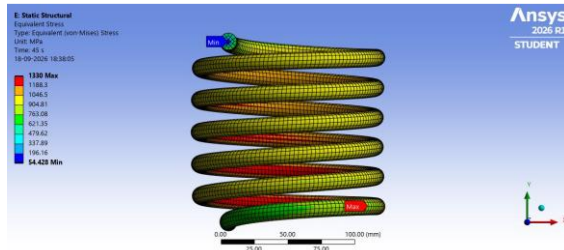


Figure 4. Equivalent von Mises stress distribution from static structural analysis, with peak stress on the inner coil surface.

Table III. Comparison of Analytical and Finite Element Spring Stiffness

Method	Applied Load (N)	Deflection (mm)	Stiffness (N/mm)
Analytical	3602.27	180.11	20.00
Finite Element (ANSYS)	3602.27	180.01	20.01

D. Modal Analysis Results

Modal analysis extracted the natural frequencies of the constrained spring. The lower modes correspond to lateral bending deformation and fall within the frequency range of road excitation energy. Selected mode shapes are shown in Figures 5 and 6.

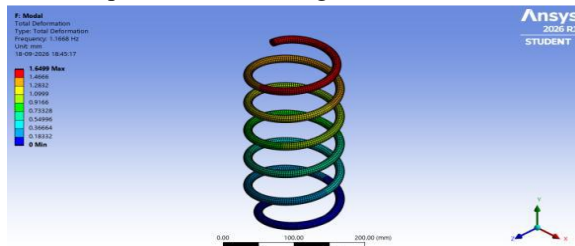


Figure 5. Mode 1 shape of the helical coil spring from ANSYS modal analysis.

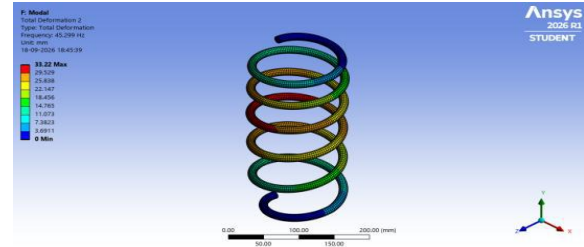


Figure 6. Mode 2 shape of the helical coil spring from ANSYS modal analysis.

IV. ROAD EXCITATION AND QUARTER-CAR MODEL

A. ISO 8608 Road Profile Generation

The road surface was represented using the ISO 8608 power spectral density:

$$G_q(n_i) = G_q(n_0) \left(\frac{n_i}{n_0} \right)^{-w}$$

where $n_0 = 0.1$ cycles/m is the reference spatial frequency and $w = 2$ is the waviness exponent. Road profiles were generated using the spectral representation method:

$$q(x) = \sum_{i=1}^N \sqrt{2G_q(n_i) \Delta n} \cos(2\pi n_i x + \phi_i)$$

where ϕ_i are random phase angles drawn uniformly from $[0, 2\pi)$. Profiles were generated over a 1000 m road length and converted to time-domain excitation at 80 km/h. The statistical properties of the generated profiles are given in Table IV.

Table IV. Statistical Properties of the Generated Road Profiles

Road Condition	ISO Class	RMS Height (mm)	Max (mm)	Min (mm)
Highway	B	11.88	35.64	-31.86
Urban	C	23.75	71.46	-63.73
Rural	D	47.50	142.92	-127.44

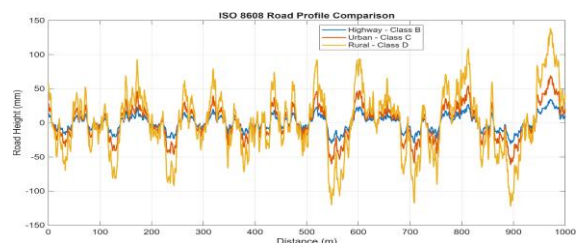


Figure 7. Generated road elevation profiles for the Highway, Urban and Rural conditions over the 1 km simulation length.

B. Quarter-Car Model

A two-degree-of-freedom quarter-car model was used with the equations of motion:

$$\begin{aligned} M_s \ddot{z}_s + C_s(\dot{z}_s - \dot{z}_u) + K_s(z_s - z_u) &= 0 \\ M_u \ddot{z}_u + C_s(\dot{z}_u - \dot{z}_s) + K_s(z_u - z_s) + K_t(z_u - q) &= 0 \end{aligned}$$

The model parameters are given in Table V.

Table V. Quarter-Car Model Parameters

Parameter	Symbol	Value	Unit
Sprung mass	M_s	367	kg
Unsprung mass	M_u	54.32	kg
Suspension stiffness	K_s	20,000	N/m
Tyre stiffness	K_t	200,000	N/m
Damping ratio	ζ_s	0.30	—

The relative spring displacement $\delta_s(t) = z_s(t) - z_u(t)$ was obtained for each road condition. Spring displacement statistics are shown in Table VI.

Table VI. Suspension Spring Displacement Statistics

Road Condition	RMS (mm)	Max (mm)	Min (mm)
Highway	6.55	20.71	-24.52
Urban	10.19	39.07	-34.85
Rural	15.41	52.85	-65.50

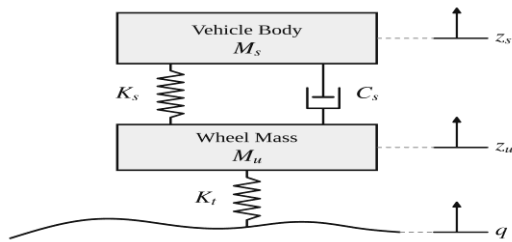


Figure 8. Quarter-car model response showing sprung mass displacement, unsprung mass displacement and relative suspension displacement for the three road conditions.

C. Spring Stress Calculation

The dynamic shear stress was calculated as:

$$\tau(t) = \frac{K_w 8 K_s \delta_s(t) D_m}{\pi d^3}$$

With $C = 10.317$ and $K_w = 1.140$, the resulting stress statistics are given in Table VII.

Table VII. Spring Shear Stress Statistics

Road Condition	RMS (MPa)	Max (MPa)	Min (MPa)
Highway	24.70	78.16	-92.54
Urban	38.45	147.44	-131.49
Rural	58.15	199.45	-247.17

The stress PSD was estimated using the Welch method with $NFFT = 4096$ and $Noverlap = 2048$.

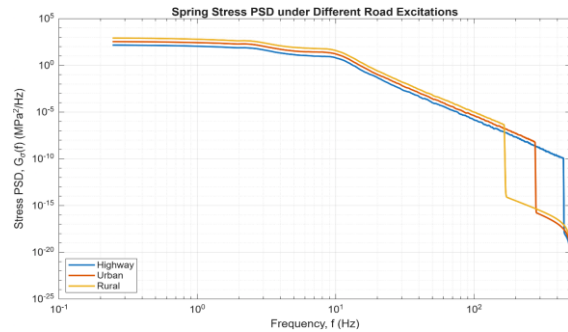


Figure 9. Combined spring stress PSD for Highway, Urban and Rural conditions estimated using the Welch method.

V. FATIGUE ANALYSIS

A. Time-Domain: Rainflow–Miner Method

The Rainflow counting method was applied following ASTM E1049. For each cycle i , stress amplitude and mean stress are:

$$\begin{aligned} \Delta\sigma_i &= \sigma_{\max,i} - \sigma_{\min,i}, & \sigma_{a,i} &= \frac{\Delta\sigma_i}{2} \\ \sigma_{m,i} &= \frac{\sigma_{\max,i} + \sigma_{\min,i}}{2} \end{aligned}$$

Fatigue life of SAE 5160 steel was represented using the Basquin relationship:

$$\sigma_a = \sigma'_f (2N_f)^b$$

where $\sigma'_f = 2063$ MPa and $b = -0.08$. Cumulative damage was calculated using the Palmgren–Miner rule:

$$D = \sum_{i=1}^k \frac{n_i}{N_i}$$

Failure is predicted when $D = 1$. Fatigue life was expressed as road distance:

$$L_f = \frac{L_{\text{seg}}}{D_{\text{seg}}} = \frac{1}{D_{\text{seg}}} \text{ km}$$

Cycle count results are shown in Table VIII.

Table VIII. Rainflow Cycle Count Summary

Road Condition	Total Cycles	Max Amplitude (MPa)
Highway	433	85.35
Urban	692	139.47
Rural	1141	223.31

B. Frequency-Domain: Dirlik Method

The Dirlik method uses spectral moments of the stress PSD:

$$m_n = \int_0^\infty f^n G_\sigma(f) df$$

The probability density of stress ranges is:

$$p(S) = \frac{1}{2\sqrt{m_0}} \left[\frac{D_1}{Q} e^{-Z/Q} + \frac{D_2 Z}{R^2} e^{-Z^2/(2R^2)} + D_3 Z e^{-Z^2/2} \right]$$

where $Z = S/(2\sqrt{m_0})$ and D_1, D_2, D_3, Q, R are Dirlik coefficients derived from the spectral moments. The fatigue damage rate is:

$$\dot{D} = \nu_0 \int_0^\infty \frac{p(S)}{N(S)} dS$$

The spectral parameters are summarised in Table IX.

Table IX. Spectral Parameters of the Spring Stress PSD

Parameter	Highway	Urban	Rural
m0	612.74	1449.58	3344.43
m1	1368.16	3333.21	7763.29
m2	6426.36	16201.31	37934.76
m4	577715.8	1453125	3402499
RMS Stress (MPa)	24.75	38.07	57.83
Mean Frequency (Hz)	3.24	3.34	3.37
Peak Frequency (Hz)	9.48	9.47	9.47
Irregularity factor γ	0.342	0.353	0.356

The Dirlik coefficients are given in Table X.

Table X. Dirlik Coefficients for the Three Road Conditions

Parameter	Highway	Urban	Rural
D1	0.2128	0.2102	0.2106
D2	0.5603	0.5575	0.5549
D3	0.2269	0.2323	0.2345

Q	0.2660	0.2627	0.2633
R	0.1238	0.1373	0.1383

VI. RESULTS AND DISCUSSION

A. Fatigue Life Comparison

The predicted fatigue lives from both methods are given in Table XI.

Table XI. Comparison of Rainflow–Miner and Dirlik Fatigue Life Predictions

Road Condition	Rainflow–Miner (km)	Dirlik (km)	Difference (%)
Highway	9.16×10^{16}	6.02×10^{16}	~34
Urban	1.68×10^{14}	1.69×10^{14}	~1
Rural	4.92×10^{11}	5.41×10^{11}	~10

The two methods agree to within 1% for Urban, 10% for Rural and 34% for Highway. The larger discrepancy on the Highway road is attributed to the lower stress amplitudes there, where fatigue damage is concentrated in a small number of higher-amplitude cycles and the Dirlik approximation to the tail of the cycle distribution is more sensitive. Expressing damage per kilometre relative to the Highway condition, the damage ratios are approximately $1 \times$ for Highway, $545 \times$ for Urban and $186,000 \times$ for Rural, illustrating the strong sensitivity of fatigue damage to road severity. Despite this, predicted fatigue lives across all conditions are extremely large, reflecting the high fatigue resistance of SAE 5160 steel at the stress amplitude levels generated under normal road excitation.

B. ANSYS Random Vibration Response Comparison

The ANSYS random vibration analysis was performed using the finite element spring model and the unsprung mass PSD as excitation input. The sprung-mass displacement response PSD was extracted and compared with the MATLAB Welch PSD estimate. The error was calculated as:

$$\text{Error (\%)} = \frac{|\text{PSD}_{\text{ANSYS}} - \text{PSD}_{\text{MATLAB}}|}{\text{PSD}_{\text{MATLAB}}} \times 100$$

The point-by-point comparison for each road condition is summarised below at five representative

frequencies spanning the dominant low-frequency peak, the mid-range, and the high-frequency tail of the response.

Table XII. Selected MATLAB–ANSYS
Displacement PSD Comparison — Highway
(mm²/Hz)

Freq (Hz)	MATLAB	ANSYS	Err (%)
0.2441	217.095	216.320	0.36
2.9297	0.1785	0.1743	2.35
9.7656	2.745×10^{-3}	2.727×10^{-3}	0.65
19.5312	5.182×10^{-6}	5.126×10^{-6}	1.07
39.0625	1.507×10^{-8}	1.299×10^{-8}	13.76

Table XIII. Selected MATLAB–ANSYS
Displacement PSD Comparison — Urban (mm²/Hz)

Freq (Hz)	MATLAB	ANSYS	Err (%)
0.2441	1038.676	1070.400	3.05
2.9297	0.6165	0.5985	2.92
9.7656	8.083×10^{-3}	7.920×10^{-3}	2.02
19.5312	9.931×10^{-6}	9.768×10^{-6}	1.64
39.0625	2.968×10^{-8}	2.560×10^{-8}	13.74

Table XIV. Selected MATLAB–ANSYS
Displacement PSD Comparison — Rural (mm²/Hz)

Freq (Hz)	MATLAB	ANSYS	Err (%)
0.2441	3803.682	4012.780	5.50
2.9297	1.1756	1.1377	3.22
9.7656	1.762×10^{-2}	1.740×10^{-2}	1.26
19.5312	3.158×10^{-5}	3.119×10^{-5}	1.22
39.0625	8.033×10^{-8}	6.918×10^{-8}	13.88

At the dominant resonance frequency of 0.2441 Hz — which carries the largest share of response energy — errors are 0.36%, 3.05% and 5.50% for Highway, Urban and Rural respectively. In the range 2.93 Hz to 29.30 Hz, errors are generally between 1% and 4%. Larger deviations of 14–27% appear only at 39–49 Hz, where the PSD magnitude is several orders of magnitude below the dominant peak and the contribution to fatigue damage is negligible. The dominant resonance frequency was consistently located at 9.47–9.48 Hz in both models across all road conditions.

The close agreement in the displacement PSD between the two models also provides indirect support for the Dirlik fatigue life predictions. Since the Dirlik method operates on the stress PSD — derived from the same

displacement response through the spring stiffness and geometry — a good match in displacement PSD implies that the spectral moments and Dirlik parameters computed from the MATLAB stress signal are consistent with what a finite element random vibration analysis would produce.

VII. CONCLUSION

The following conclusions are drawn from this study:

1. The helical compression spring designed for a target stiffness of 20 N/mm using SAE 5160 steel was reproduced in ANSYS with a finite element stiffness of 20.01 N/mm, a deviation of only 0.05%, confirming the accuracy of the finite element model.
2. Synthetic ISO 8608 road profiles for Highway, Urban and Rural conditions correctly reproduced the intended road severity hierarchy, with RMS heights of 11.88, 23.75 and 47.50 mm. Applied to the quarter-car model, these produced spring RMS stresses of 24.70, 38.45 and 58.15 MPa, dominated by the primary suspension resonance at 3.2–3.4 Hz.
3. The Rainflow–Miner and Dirlik fatigue-life predictions agreed to within 1% for Urban, 10% for Rural and 34% for Highway conditions, with both methods predicting extremely large spring fatigue lives across all conditions, confirming the suitability of SAE 5160 steel for this application under normal road service loading.
4. The ANSYS random vibration displacement PSD agreed closely with the MATLAB quarter-car PSD across all three road conditions, with errors below 5.5% at the dominant resonance frequency and within 1–4% in the fatigue-relevant frequency range, confirming the dynamic consistency of the two modelling approaches.
5. The Dirlik spectral method is demonstrated as a reliable frequency-domain alternative to full time-domain Rainflow analysis for road-induced suspension spring fatigue, within a fully synthetic pipeline requiring no physical road measurements.

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