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TECHNICAL ARTICLE—PEER-REVIEWED

Effects of Axial and Multiaxial Variable Amplitude Loading Conditions on the Fatigue Life Assessment of Automotive Steering Knuckle

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Abstract In this paper, the author has attempted to investigate the effects of different loading conditions including axial and multiaxial variable amplitude loading (VAL) on the fatigue life assessment of automotive components under various maneuvers. To this end, a case study was conducted on the cast iron steering knuckle of a passenger car. In fact, the various VAL histories are entered on the three joints of knuckle, namely steering linkage, lower control arm, and MacPherson strut. However, previous studies have shown that this high super-critical component fails through the steering linkage. Moreover, the rotation of the steering linkage is the most destructive load. Hence, in this research, different loading cases such as axial (destructive load as means 1 channel), multiaxial (only relates to loading on the joint of knuckle and steering linkage means 3 channels), and full multiaxial (including all loading time histories means 9 channels) were considered. Afterward, finite element analysis was performed for each case, and fatigue life of the component was predicted under different conditions. Next, fatigue life of the component was evaluated using the time histories of stress tensor in the root of steering linkage which is extracted by transient dynamic analysis and applying probabilistic approach based on the Liu–Zenner equivalent stress criterion. Eventually, the responses from both techniques were compared in different cases. The results reveal that life predicted using two methods are slightly different. But, the results of probabilistic approach are more accurate than the results of FEM in comparison with experimental data for the axial state. Also, one of the major achievements of this study is that for the components with complex geometry and under multi-input loading like the steering knuckle, it is essential to perform fatigue analysis by considering all real conditions and cannot be only focused to the destructive loading.

Keywords Fatigue analysis · Axial and multiaxial variable amplitude loading · Steering knuckle · Finite element method · Equivalent stress criterion · Probabilistic approach

Introduction

Steering knuckle is one of the most super-critical components of various types of vehicles (passenger car, racing, and trucks), because it is the main interface between the two suspension and steering systems. This component has three main connections: One is the joint of steering linkage that provides automotive handling. The second is the joint of MacPherson strut; its main task being to damp the forces coming into the body and mechanical parts due to road excitation such as different pumps. And the last is the joint of lower control arm which connects to the chassis from the other side. The location of the knuckle connections to the other components of the suspension and steering systems is shown in Fig. 1. Moreover, the braking system is also installed on this component. On the other side, through the wheel hub, tires and rims are connected to this component by a number of screws (depends on the type of the car but typically 4, 5, and 6 screws). Also, it is attached to the axle shaft. Hence, steering knuckle is known as a major

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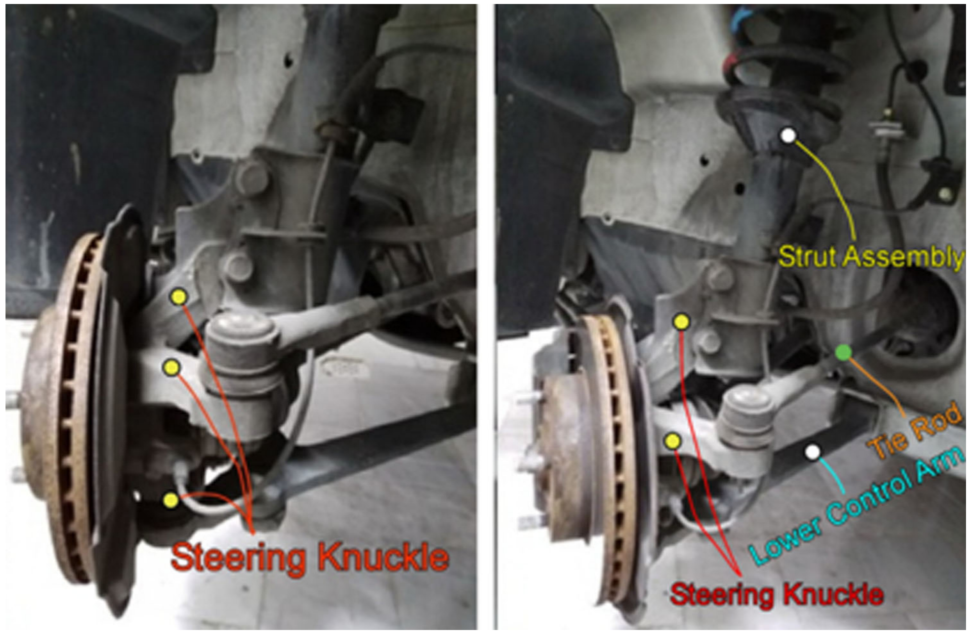

Fig. 1 Location of the knuckle connections to the other components of the suspension and steering systems [3]

highway in the suspension system. The failure of the knuckle can result in a lot of damage to the automobile and sometimes lead to horrific accidents with fatalities. In general, the geometric shape of this component is designed and manufactured based on the type of vehicle and the position of the other components of the suspension and steering systems. In other words, it does not have a specific shape and differs from car to car. Moreover, depending on the auto parts manufacturer, the steering knuckle is made of different materials including cast iron, aluminum alloy, and forged steel [1, 2].

In recent decades, many studies have been done to design, develop, and optimize the automotive steering knuckle considering static behavior such as maximum Von Mises stress, total and directional deformation, and even impact resistance. Fatigue analysis has been also performed to obtain the fatigue life of the component under different conditions, since the light metals in comparison with forged steel have been used to reduce weight, fuel consumption, and emission and increase acceleration. The static and fatigue strength of the components are also reduced and more attention must be paid to the phenomenon of fatigue and sudden failure of the component without any prior alarms and warnings. Nevertheless, previous researches have not responded to the industry needs and still face design problems from the fatigue point of view.

Dhamale and Bhingare have performed failure analysis of a suspension system ball joint [4]. They have optimized the design of the ball joint, which resulted in life cycle increasing. Chen et al. [5] have improved the fatigue strength of the steering knuckle of an electric vehicle. To achieve this purpose, topology optimization method (TOM) has been used to modify the design of steering knuckle. Then, fatigue life of optimized design has been calculated and compared to the fatigue life of initial design under road impact conditions (ISO 8608 road classes A-D). Moreover, design optimization of automotive component has been conducted through numerical study and using additive manufacturing [6]. Shuaib et al. [7] have optimized the geometry of the steering knuckle to improve its performance. To this end, 3D scanning has been used to precisely model the component, and then, the new design of steering knuckle based on the FE results has been manufactured utilizing 3D printing.

Niu et al. [8] have investigated the structure of a car steering knuckle using FEM (ANSYS software) at uneven road surface conditions. They found that the adjacent shoulder of steering knuckle will be damaged earlier than other parts. Azrulhisham et al. [9] have studied the influence of road simulator service loads on the durability assessment of automotive steering knuckle. Also, the effect of different road roughness on the automotive components has been studied [10]. Triantafyllidis et al. [11] have experimentally performed failure analysis of a vehicle's ductile iron steering knuckle which was broken by a car accident. They reported that the ductile cast iron is the best material for fatigue strength compared to other types of cast iron. However, this material is the second priority, and the best material is the forged steel to manufacture steering knuckle.

Several studies have been conducted to predict fatigue life of this highly critical component of the automotive using common finite element codes in which the loading is considered as sinusoidal function and applies the S–N method to solve the problem [12]. Kamal et al. [13] have evaluated life cycle of knuckle using multi-body simulation (MBS) technique. The actual road profile of road bumps has been used in the MBS, and the load time history has been extracted to use in the stress analysis. Then, the strain–life method has been employed to assess the fatigue life of the component. The results showed that the knuckle can pass 371 times through the road bumps at speed of 40 km/h. In this regard, different multiaxial fatigue criteria have been presented which have good ability to predict fatigue life of automotive components with complex geometry under various loading conditions [14–20].

Zoroufi and Fatemi [21] have experimentally studied the durability and life cycle of various manufacturing processes of steering knuckle considering different materials including forged steel, cast aluminum, and cast iron. The published results indicated that the cyclic yield strength of cast iron and cast aluminum is about 75% and 54% of forged steel, respectively. Moreover, the long-life fatigue strengths of cast iron and cast aluminum are about 72% and 35% of the forged steel, respectively. In other words, from fatigue point of view, they showed that the aluminum casting material is more suitable than cast iron for making an automotive steering knuckle. Also, a comparative study has been conducted to evaluate the fatigue life of automotive steering knuckles made of forged steel and cast iron [22], and between cast aluminum and forged steel [23].

Sonsino and Franz have assessed multiaxial fatigue life of cast aluminum steering knuckle under different loading conditions including constant amplitude loading (CAL) and variable amplitude loading (VAL) [24]. The main findings of this research revealed that the fatigue life of the component increases under non-proportional normal and shear stresses in contrast to ductile steels where life is reduced. Reza Kashyzadeh et al. [3] have evaluated multiaxial fatigue life of the cast iron steering knuckle using various high-cycle fatigue criteria and compared with the results of full-scale fatigue test under multi-input variable non-proportional loadings. They proved that static failure criteria ignoring the mean stress (e.g., von Mises, Carpinteri–Spagnoli, Findley, McDiarmid, and Dang Van) cannot accurately predict the fatigue life of the component with complex geometry under multi-input non-proportional loading. Moreover, they reported that in this case study the most accurate criteria are energy-based Shariyat and Liu–Zenner. Next, they have investigated the effect of different values of wheel angles including Toe and Camber on the life cycle of cast iron steering knuckle [25]. The results showed that the life cycle of the component reduces by decreasing the value of Camber angle. And the fatigue life of component will be improved 12% by using Camber angle of $+2$ instead of $+1$. For the first time, a probabilistic approach was used to assess fatigue life of automotive component by Reza Kashyzadeh [26]. He has proposed a new algorithm which used the Fourier series to obtain the probability distribution function (PDF). Also, two influence parameters of order of Fourier curve fitting and stress counting ranges have been updated to get the most accurate response compared to the laboratory results. The most important advantage of this method over the other methods is the speed of performance while also having good accuracy.

Recently, the effect of porosity of the cast aluminum alloys on the fatigue life of steering knuckle has been studied [27]. They proved that by using the newly presented model which takes into account porosity in the casting material, they can detect the scattering process of fatigue test results well. And artificial neural network (ANN) technique has been used to predict the fatigue damage on a rear axle-mounting bracket as a chassis component made of steel S420MC [28]. The structural of ANN has been formed based on the results of fatigue tests at different temperatures including room, 35 and 45 °C. The results of this research showed that the presented approach is not suitable for fatigue damage estimations at temperature above 45 °C. In other words, this approach (ANN) cannot work properly outside the trained range.

In the present research, a comparative study was conducted on the fatigue life assessment of cast iron steering knuckle considering various types of input including axial and multiaxial VAL. The main achievement of this research is to determine the evaluation process of the fatigue performance of the automotive components in the shortest possible time and to simplify loading conditions. To this end, two fast techniques including FEM and probabilistic approach based on Liu–Zenner criterion were employed. Finally, in order to the validation of the responses of both methods was also compared with the experimental results.

Methodology

The front left side steering knuckle of a four cylindrical passenger car was studied which is made of cast iron named ASTM A536-Grade 65-45-12. The monotonic and cyclic characteristics of ductile cast iron were considered in accordance with the previous paper [26]. The load histories were applied based on the results of full vehicle multi-body simulation (FVMBS) through passing an equivalent road including different road roughness (ISO-8606) and various maneuvers (e.g., straight, braking, acceleration, and cornering) [25]. Three different loading cases, namely axial (destructive load as means 1 channel), multiaxial (only relates to loading on the joint of knuckle and steering

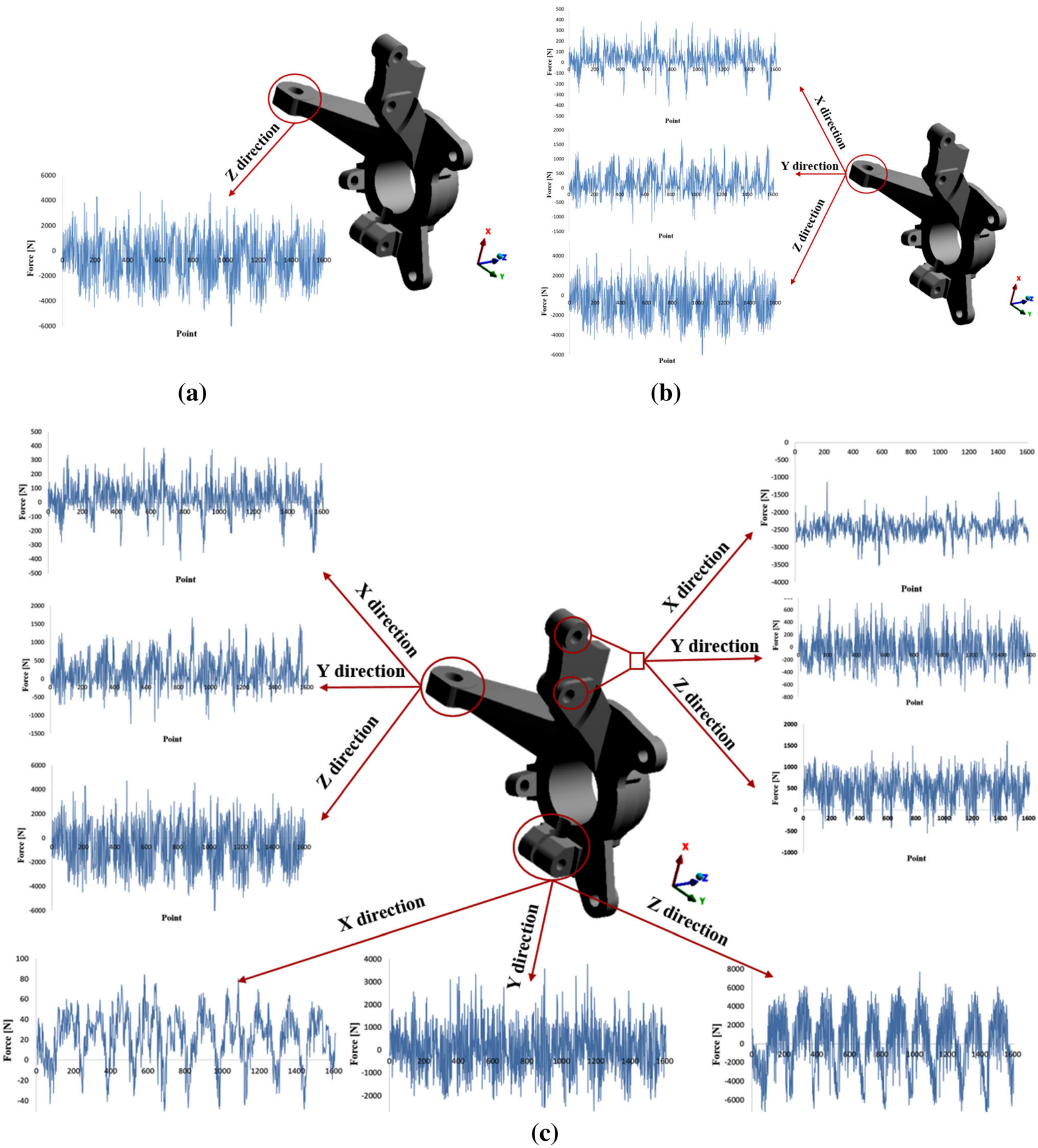

Fig. 2 Different loading cases used in this research including (**a**) axial loading as 1 channel, (**b**) multiaxial loading as 3 channels, and (**c**) full multiaxial loading as 9 channels

linkage means 3 channels), and full multiaxial (including all loading time histories means 9 channels), are shown in Fig. 2. Moreover, in all future analyses, the wheel hub is fixed at all degrees of freedom (DOF). As shown in Fig. 2c, in fact, three load histories are applied on each joint. Since this component is constrained through the center part (wheel hub), it can be stated that each arm is independently affected by its articular forces. On the other hand, the behavior of each arm can be assumed as an independent cantilever beam. Therefore, it is acceptable to reduce the number of loading channels from nine to three by knowing the location of failure (joint of knuckle and steering

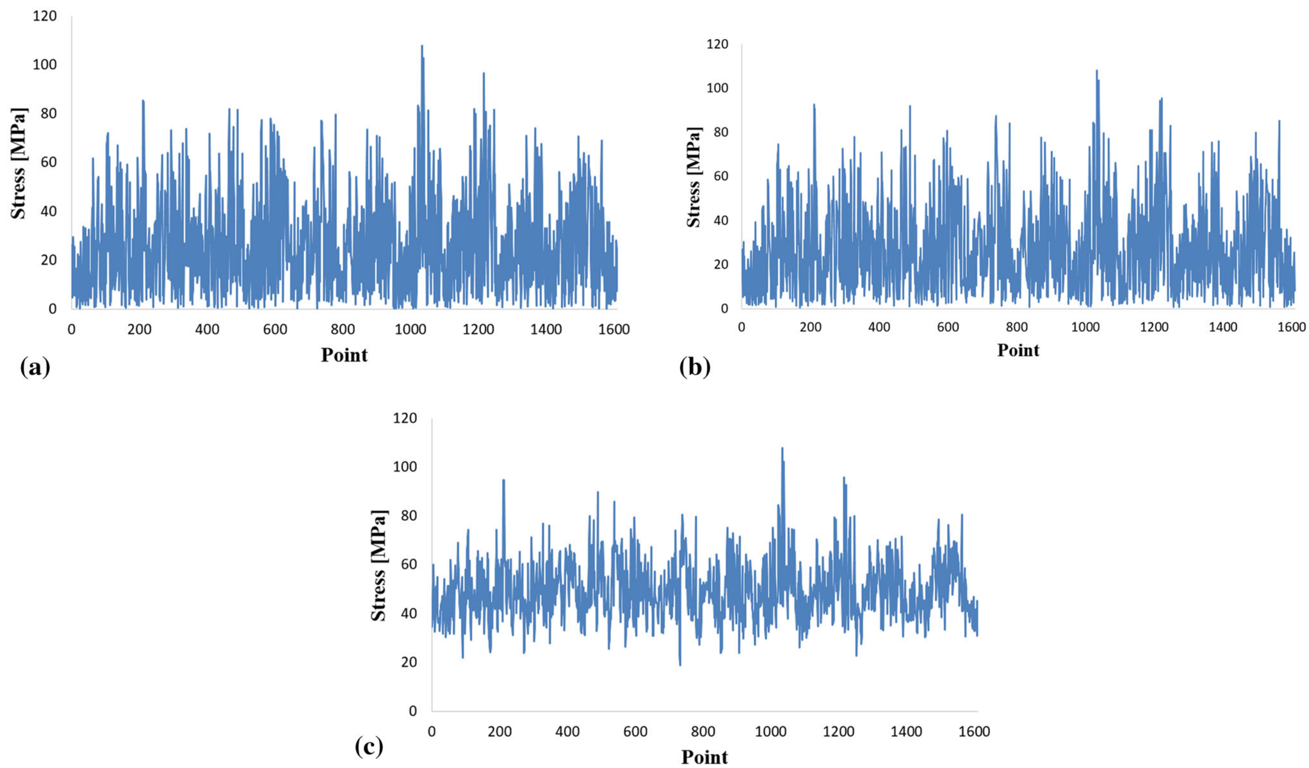

Fig. 3 Time histories of von Mises equivalent stress in the critical element for various cases: (**a**) axial loading as 1 channel, (**b**) multiaxial loading as 3 channels, and (**c**) full multiaxial loading as 9 channels

Table 1 Details of events counting for three loading conditions including 1-channel, 3-channel, and 9-channel

	Counting the occurrence			Percentage of occurrence		
	Number of inputs			Number of inputs		
Stress level (MPa)	1	3	9	1	3	9
0–10	360	348	0	22.37	21.63	0
10–20	366	346	1	22.75	21.5	0.06
20–30	289	287	31	17.96	17.84	1.93
30–40	222	231	311	13.8	14.36	19.33
40–50	154	164	589	9.57	10.19	36.61
50–60	113	112	396	7.02	6.96	24.61
60–70	53	57	209	3.29	3.54	12.99
70–80	33	37	53	2.05	2.3	3.29
80–90	15	18	9	0.93	1.12	0.56
90–100	2	7	8	0.12	0.44	0.5
100–110	2	2	2	0.12	0.12	0.12
Total	1609	1609	1609	100	100	100

linkage). Also, the range of force variations in one direction (*Z*) is more noticeable than the other two directions (*X* and *Y*). Hence, the influence of single channel loading on the fatigue lifetime of the component compared to three and nine channels was studied in order to simplify the simulation and reduce the computational cost and existence of some laboratory limitations (most research centers have axial fatigue testing facilities).

The CAD smooth geometric model of steering knuckle was provided using coordinate measuring machine (CMM) data [29]. Altair Hypermesh finite element analysis computer code (quad second-order pyramid elements) was used to create a finite element mesh of the knuckle. The convergence study was performed to opt an acceptable element size. Accordingly, the final FEM of the component contains 76,942 elements.

Finite Element Analysis

Stress analysis was performed under unit loads in each loading case by using FE software. Afterward, axial and multiaxial fatigue analyses in the time domain were carried out by coupling stress analyses and defining load histories in NCODE DESIGN LIFE software. The time histories of von Mises equivalent stress in the critical element for different loading cases were extracted as demonstrated in Fig. 3. And contours of lifetime associated with different loading cases are illustrated in Fig. 4.

It is clearly obvious that the time histories of equivalent stress in the critical element have positive mean stress in all cases (Fig. 3). But, the value of the mean stress in the 9-

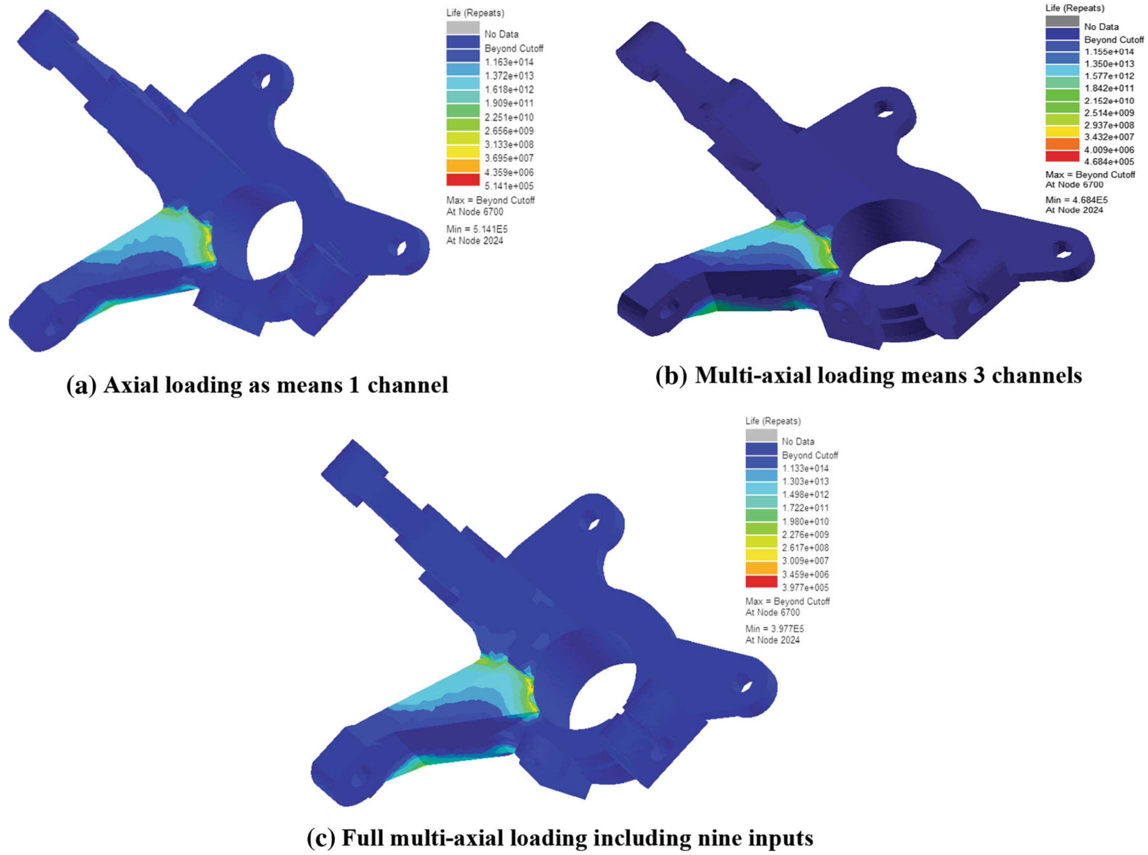

Fig. 4 Fatigue life contour of steering knuckle under various loading conditions: (**a**) axial loading as 1 channel, (**b**) multiaxial loading as 3 channels, and (**c**) full multiaxial loading as 9 channels

Table 2 Fatigue life predicted for different loading conditions using two different techniques, in terms of number of repetition of the given blocks of equivalent stress–time history

Type of loading	Number of inputs	Finite element simulation	Probabilistic approach
Axial	1	514,100	439,880
Multiaxial	3	468,400	425,090
Full multiaxial	9	397,700	365,573

channel loading case (full multiaxial loading) is much higher than in the other two cases (1-channel and 3-channel loading conditions). Therefore, the fatigue damage caused to the component under full multiaxial loading is expected to be greater than that of the other loading conditions.

The fatigue assessment results indicated that the life cycle of the steering knuckle caused by uniaxial loading is greater than that related to various multiaxial loading conditions (3-channel and 9-channel). Thus, it is inferred that it is important to perform the analysis under multiaxial loadings considering the working conditions of this component in reality. However, most studies have been conducted by employing axial loading because of some limitations, e.g., complicated geometry, solving time, and laboratory facilities, etc. The innovation of the present research is to determine the predicted lifetime differences for this automotive super-critical component under various loading conditions and to present a decreasing coefficient for real lifetime estimation in relation to the predicted axial fatigue lifetime.

Table 3 Comparison of fatigue life prediction by utilizing different techniques and experiment results, in terms of number of repetition of the given blocks of equivalent stress–time history

Finite element simulation	Probabilistic approach	Experimental results
514,100	439,880	423,758
21.32	3.80	Error (%)

Probabilistic Approach Based on Liu–Zenner Equivalent Stress Criterion

Firstly, the transient dynamic analysis was performed and time histories of the stress tensor components were obtained in the critical element for all loading cases (axial, multiaxial, and full multiaxial loading conditions). Next, the new fatigue life estimation algorithm presented by the author in the

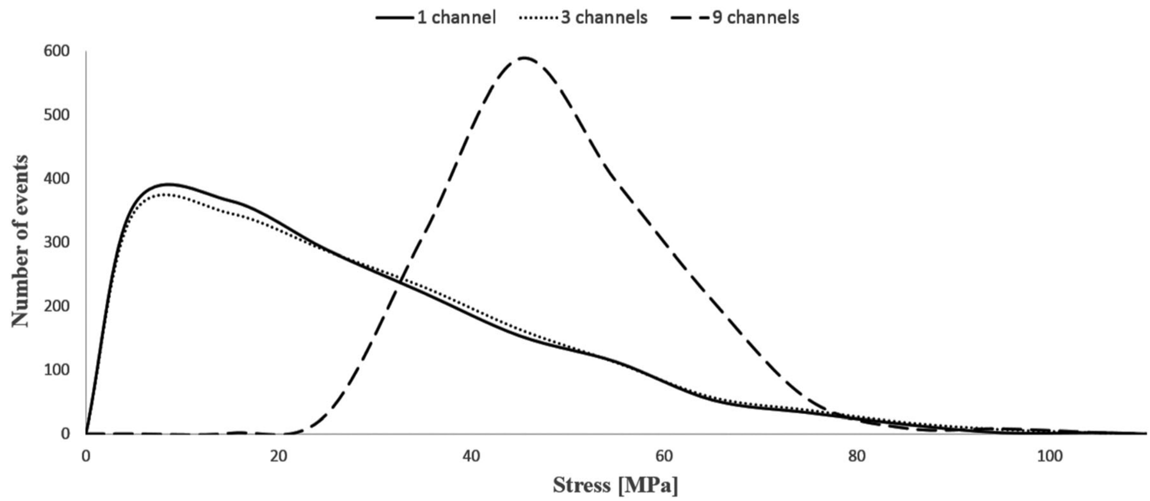

Fig. 5 Probability distribution of equivalent stress for various loading conditions

previous research [26] was used to predict the life cycle of the component. To this end, the steps are as follows:

1. Equivalent stress history was calculated using the time histories of the stress tensor components and employing Liu–Zenner criterion.
2. Stress leveling and counting the occurrences were performed on the Liu–Zenner equivalent stress history.
3. Probability distribution function was estimated utilizing Fourier curve fitting method.
4. Different influence parameters of curve fitting including Fourier order and stress counting range were updated to achieve the appropriate function form compared to the target function form.
5. Life cycle of the knuckle was predicted based on the mathematical expectation of fatigue damage.

In the present research, the values of 10 and 7 were considered for stress counting range and Fourier order, respectively (where is classified as S10-P12-O7). Therefore, the stress leveling and counting the occurrence for all cases of equivalent stress histories are presented in Table 1. The probability of stress distribution for different loading conditions is illustrated in Fig. 5. It is clear that the pattern of equivalent stress history for multiaxial loading including nine fully inputs is quite different from the pattern of equivalent stress histories for axial loading and multiaxial loading including 3-channel. The most events are related to a high level of stress for loading including all inputs. In contrast in the other loading conditions, most events are associated with a low level of stress. It is completely obvious that the probability distribution stress for different load conditions including one and three inputs is lognormal distribution type, whereas for the full loading of nine inputs it is normal.

Results and Discussion

The fatigue life of the automotive steering knuckle was estimated by utilizing two different methods for three loading conditions (uniaxial load including only 1-channel input, multiaxial loading including 3-channel input, and full multiaxial loading including nine inputs), and the obtained results are compared in Table 2.

As presented in Table 2, the obtained results vary for different loading conditions. Therefore, using destructive loading alone in one axis is not sufficient to calculate fatigue life, and multiaxial fatigue with a full nine inputs should be thoroughly employed. To verify the accuracy of the methods used in this research, the results of different methods (FEM and probabilistic approach) for axial loading were compared with the full-scale fatigue test result under variable amplitude loading (Table 3).

It is found that the results of fatigue lifetime prediction by utilizing probabilistic approach are closer to reality (error of 3.8%). One of the most important reasons for this disagreement is that the FE analysis uses the von Mises equivalent stress and this criterion is not accurate for multi-inputs non-proportional loading [3]. However, to increase the accuracy of the FEM, the von Mises equivalent stress was obtained on 18 planes separated by 10° angle increments; then the fatigue lifetime was calculated on all planes. Eventually, the lowest life on those 18 planes was considered as the fatigue life of the component. But, the Liu–Zenner equivalent stress criterion used in the probabilistic approach is one of the most accurate criteria for high-cycle multiaxial fatigue considering non-proportional loading.

Conclusion

In the present research, a comprehensive comparison was performed between results of different fast techniques of the fatigue life prediction including finite element analysis and probabilistic approach. The case study was conducted on the automotive super-critical component called the steering knuckle. The following practical conclusions may be drawn from the comparison of the predicted results with experimental data:

1. Results obtained from both methods were indicated that the life cycle of the knuckle under multiaxial fatigue loading is less than the life cycle of the component under axial fatigue loading. Hence, it is necessary to carry out multiaxial fatigue analyses considering the real working conditions of the component.
2. According to the findings of the present research, the decreasing coefficient of 0.831 and 0.773 should be used to estimate the multiaxial fatigue life of the knuckle from the predicted axial fatigue results using the probabilistic approach and FE method, respectively.
3. The results reveal that life predicted using two methods are slightly different. But, the results of probabilistic approach are more accurate than the results of FEM in comparison with experimental data for the axial state. Also, the knuckle lifetime prediction error under axial loading condition is 3.80% and 21.32% for using probabilistic approach and FE method, respectively.
4. It is found that the FE analysis uses the von Mises equivalent stress and this criterion is not accurate for multi-inputs non-proportional loading. Therefore, it is recommended to use other equivalent stress criteria such as Liu–Zenner for fatigue life assessment of the component with complex geometry and under complicated loading conditions.

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References

1. V. Sivananth, S. Vijayarangan, Fatigue life analysis and optimization of a passenger car steering knuckle under operating conditions. Int. J. Autom. Mech. Eng. **11**, 2417–2429 (2015)
2. S. Vijayarangan, N. Rajamanickam, V. Sivananth, Evaluation of metal matrix composite to replace spheroidal graphite iron for a critical component, steering knuckle. Mater. Des. **43**, 532–541 (2013)
3. K. Reza Kashyzadeh, G.H. Farrahi, M. Shariyat, M.T. Ahmadian, Experimental accuracy assessment of various high-cycle fatigue criteria for a critical component with a complicated geometry and multi-input random non-proportional 3D stress components. Eng. Fail. Anal. **90**, 534–553 (2018)
4. S.K. Dhamale, N.H. Bhingare, Analyze the failure of a suspension system ball joint. Res. J. Eng. Technol. **10**(2), 94–98 (2019)
5. Y.C. Chen, H.H. Huang, C.W. Weng, Failure analysis of a redesign knuckle using topology optimization. Mech. Sci. **10**, 465–473 (2019)
6. M.A.B. Marzuki, M.F.M. Azmi, R.L. Jaswadi, Design optimization of automotive component through numerical investigation for additive manufacturing. J. Built Environ. Technol. Eng. **6**, 19–26 (2019)
7. M. Shuaib, A. Haleem, L. Kumar, Rohan, D. Sharma, Design and analysis of steering knuckle joint, in *Advances in Engineering Design. Lecture Notes in Mechanical Engineering*, ed. by A. Prasad, S. Gupta, R. Tyagi (Springer, Singapore, 2019)
8. X. Niu, G. Wang, W. Li, Finite element analysis of the car steering knuckle based on ANSYS. Appl. Mech. Mater. **740**, 108–111 (2015)
9. E. Azrulhisham, Y.M. Asri, A.W. Dzuraidah, N.M. Nik Abdullah, C.H. Che Hassan, A. Shahrom, Application of road simulator service loads in automotive component durability assessment. Open Ind. Manuf. Eng. J. **4**, 1–7 (2011)
10. K. Reza Kashyzadeh, M.J. Ostad-Ahmad-Ghorabi, A. Arghavan, Investigating the effect of road roughness on automotive component. Eng. Fail. Anal. **41**, 96–107 (2014)
11. G.K. Triantafyllidis, A. Antonopoulos, A. Spiliotis, S. Fedonos, D. Repanis, Fracture characteristics of fatigue failure of a vehicle’s ductile iron steering knuckle. J. Fail. Anal. Prev. **9**, 323–328 (2009)
12. V. Sivananth, S. Vijayarangan, R. Aswathaman, Fatigue and impact analysis of automotive steering knuckle under operating load cases. In *Altair Technology Conference*, India (2015)
13. M. Kamal, M.M. Rahman, A.G.A. Rahman, Fatigue life evaluation of suspension knuckle using multibody simulation technique. J. Mech. Eng. Sci. **3**, 291–300 (2012)
14. A. Carpinteri, A. Spagnoli, S. Vantadori, A review of multiaxial fatigue criteria for random variable amplitude loads. Fatigue Fract. Eng. Mater. Struct. **40**(7), 1007–1036 (2017)
15. M. Shariyat, A fatigue model developed by modification of Gough’s theory, for random non-proportional loading conditions and three-dimensional stress fields. Int. J. Fatigue **30**(7), 1248–1258 (2008)
16. A. Fatemi, N. Shamsaei, Multiaxial fatigue: an overview and some approximation models for life estimation. Int. J. Fatigue **33**, 948–958 (2011)
17. M. Shariyat, Three energy-based multiaxial HCF criteria for fatigue life determination in components under random non-proportional stress fields. Fatigue Fract. Eng. Mater. Struct. **32**, 785–808 (2009)
18. J. Marzbanrad, A. Yadollahi, Fatigue life of an anti-roll bar of a passenger car. Int. J. Mech. Aerosp. Eng. **6**, 274–280 (2012)
19. M. Shariyat, Two new multiaxial HCF criteria based on virtual stress amplitude and virtual mean stress concepts, for complicated geometries and random non-proportional loading conditions. Trans. ASME J. Eng. Mater. Technol. **131**, 1–13 (2009)
20. M. Shariyat, New multiaxial HCF criteria based on instantaneous fatigue damage tracing in components with complicated geometries and random non-proportional loading conditions. Int. J. Damage Mech. **19**, 659–690 (2010)
21. M. Zoroufi, A. Fatemi, Durability comparison and life predictions of competing manufacturing processes: an experimental study of steering knuckle. In *25th Forging Industry Technical Conference* (2004)

22. A. Fatemi, M. Zoroufi, *Fatigue Performance Evaluation of Forged Versus Competing Manufacturing Process Technologies: A Comparative Analytical and Experimental Study* (American Iron and Steel Institute, Toledo, 2004)
23. M. Zoroufi, A. Fatemi, Experimental durability assessment and life prediction of vehicle suspension components: a case study of steering knuckles. Proc. Inst. Mech. Eng. D J. Autom. Eng. **220**(11), 1565–1579 (2006)
24. C.M. Sonsino, R. Franz, Multiaxial fatigue assessment for automotive safety components of cast aluminum EN AC-42000 T6 (G-AlSi7Mg0.3T6) under constant and variable amplitude loading. Int. J. Fatigue **100**, 489–501 (2017)
25. K. Reza Kashyzadeh, G.H. Farrahi, M. Shariyat, M.T. Ahmadian, The role of wheel alignment over the fatigue damage accumulation in automotive vehicle steering knuckle. J. Stress Anal. **3**(1), 21–33 (2018)
26. K. Reza Kashyzadeh, A new algorithm for fatigue life assessment of automotive safety components based on the probabilistic approach: the case of the steering knuckle. Eng. Sci. Technol. Int J. (2019). https://doi.org/10.1016/j.jestch.2019.05.011
27. R. Hidalgo, J.A. Esnaola, I. Llavori, M. Larranaga, I. Hurtado, N. Herrero-Dorca, Fatigue life estimation of cast aluminum alloys considering the effect of porosity on initiation and propagation phases. Int. J. Fatigue **125**, 468–478 (2019)
28. M. Jimenez-Martinez, M. Alfaro-Ponce, Fatigue damage effect approach by artificial neural network. Int. J. Fatigue **124**, 42–47 (2019)
29. K. RezaKashyzadeh, G.H. Farrahi, M. Shariyat, M.T. Ahmadian, Experimental and finite element studies on free vibration of automotive steering knuckle. Int. J. Eng. Trans. B Appl. **30**(11), 1776–1783 (2017)

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