

Application of Road Simulator Service Loads in Automotive Component Durability Assessment

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Abstract: This paper presents automotive component durability assessment based on road load data acquired using spindle coupled full vehicle road simulator test system. In this study, service loads in terms of response-time history signal was obtained from accredited test track using road load data acquisition. Replication of test track loads to the road simulator was achieved using iterative deconvolution where a portion of Belgian block service load data was selected as desired response signal. Linear estimate of the frequency response function model of the desired response and random simulator actuator signal was obtained using parametric model estimation. This system model is then mathematically inverted and convolved with the desired response time histories to provide simulator drive signal required to produce the response. Durability test in terms of fatigue analysis was later conducted by observing specimen response obtained on the simulator due to the developed drive signal. It is found that the divergences between fatigue life of desired and achieved loads are all within 50%. This study shows that by applying the iterative deconvolution method fatigue sensitive contents of the road load signals can be well produced by the road simulator.

Keywords: Durability assessment, road simulator, iterative deconvolution, frequency response function, parametric model estimation.

1. INTRODUCTION

In the past, durability was determined through prototype field testing. Results from the field test would then be used by the engineer for future improvement. This approach in determining durability is inappropriate due to the increasing pressures of shortened development cycles and the desire to save costs. Accurate replication of field test into laboratory testing can accelerate the design process due to the known advantages of time savings, the opportunity to observe the specimen and the overall controlled environment of a laboratory setting leading to repeatable results.

Road simulators were conceived in the late 1960s and this technology has promoted the controlled testing of specific vehicle structures without interruptions such as weather, driver fatigue, or mechanical failure of components unrelated to the structure of interest [1]. A trend towards utilizing the road simulator in the durability validation process also provides the test lab and the vehicle designer a direct method of comparing results, without introducing the errors, uncertainties and other limitations associated with comparing to proving ground data [2]. Introduction of minicomputers and lower cost array processor technology in the mid-seventies accelerate the development of an iterative deconvolution technique to converge toward accurate recreation of measured service responses in the laboratory [3].

The main task performed during durability analysis is the fatigue life assessment of components, such as engine parts, suspension parts, and body structures [4]. In general, fatigue life assessment of the component could be obtained using four different methodologies: the nominal stress-life (S-N) approach, the local strain-life (ϵ -N) approach, the fatigue crack growth approach or the two-stage approach which consist a combination of the third approach with either the first or the second approach. The nominal stress-life approach mainly deals with linear elastic stresses and strains, and hence it is applicable to components experiencing high cycle fatigue such as suspension systems and crankshaft where loading cycles to failure exceeds 10^5 . The local strain-life approach instead has been developed to model the elastic-plastic deformation of material. This approach is typically valid for low cycle fatigue with loading cycle ranges from 10^3 to 10^5 [5].

In terms of automotive component, the strain-life approach is a more generally applicable method than stress-life and is used widely where engineers are trying to design components to a finite life [6]. However, this approach suffers from serious limitation when applied to practical production components due to an inadequate algorithm when dealing with real surface conditions and multiaxial stress states [5]. The problem of multiaxiality is considered vital for lightweight design of automotive components which experience multiaxial stress states as a result of combined loading. In this case, the local stress or strain approaches in conjunction

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with the FEA results were found to provide more accurate life predictions, as compared with the commonly used nominal S–N approach [7].

This paper will focus on McPherson strut steering knuckle which is mainly used in the steering system of the front-wheel drive vehicles. This McPherson strut steering knuckle system consist of a strut mount at the top, ball joint at the bottom, and a steering arm on the side as illustrated in (Fig. (1)). The wheel spindle fits through a hole in the centre. Since it is connected to the steering parts and strut assembly from one side and the wheel hub assembly from the other, the component has complex restraint and constraint conditions and tolerates a combination of loads [8]. In this study, fatigue life of the steering knuckle system will be predicted using stress-life method in conjunction with the Finite Element Analysis (FEA) results.



Fig. (1). Steering knuckle system.

2. METHODOLOGY

2.1. Proving Ground Data Acquisition

Description of the operating environment is a vital component in the durability analysis. The goal is to develop an accurate representation of the loads, deflections, strains, noise, vibration etc. that would likely be experienced during the total operating life of the component [9]. The method proposed herein is to conduct a laboratory test that mirrors the processes used in the proving ground testing. Initially, road load data is collected with a physical prototype using the road load data acquisition (RLDA). The RLDA activity was established using a vehicle equipped with electronic data acquisition system (EDAQ). Fig. (2) illustrated the EDAQ in the form of instrumented suspension system which consists of accelerometers and force transducers which capable of sensing inclination, vibration and shock experiences by the vehicle's components as it progresses along the path of proving ground.

In this study, the instrumented vehicle was driven over 1.44 kilometers of the British Millbrook accredited proving ground in order to measure the response-time history. Due to the severe suspension input received, the vehicle was driven

with a constant speed of 50 km/h. The Belgian road is commonly used for testing vehicle durability since it has 100 times the severity in comparison with general roads [10]. Several passes of each proving ground road surface were collected to ensure a statistically valid and representative sample of data.



Fig. (2). Instrumented suspension system.

The responses are simultaneously recorded as a time history on the EDAQ. Data was collected directly in digital format using a sample and hold circuit prior to the analogue-to-digital (A/D) converter. The data acquisition sample rate was 512 points per second. Low-pass analogue filter were applied to the data prior to digitizing to prevent aliasing where the output of this step is a set of digitized time history records containing the "desired response" of the laboratory test system.

2.2. Data Editing and Analysis

The data collected from the proving ground was analyzed to identify the most significant and required inputs for the specimen under consideration. Non damaging portions were removed and remaining sections of the files were then smoothed on either side of the deletion region to remove any discontinuity prior to joining them to a new history. The edited time history was then band pass filtered from 1 Hz to 50 Hz. The rationale for this selection is that the road simulator test system is an inertially reacted system where it is difficult to achieve low frequency control without large actuator displacements. The upper frequency is chosen based on the experience that little road-induced damage is induced for frequencies above 50 Hz.

2.3. Critical Stress Location

In this study, critical stress location of the steering knuckle was identified by developing Finite Element (FE) model based on MSC / FatigueTM. The inputs to the process are an FE model of the component, a set of cyclic material properties and a set of representative load time histories. The FE model consists generally of 8-noded HEX elements with a minimum number of wedge elements and the steering knuckle material is spherical graphite cast iron FCD500, a high abrasion resistance material with low temperature shock property [11]. The material properties and the fatigue life characteristic of FCD500 are shown in Table 1. The S-N curve of the material obtained using yield strength and fatigue strength is shown in Fig. (3).

Table 1. Mechanical Properties of FCD500

Material Name	FCD500
Yield strength	360 MPa
Ultimate tensile strength	520 MPa
Elastic modulus	170 GPa
Stress range intercept	6880 MPa
Fatigue transition life	2e7 cycles
First fatigue strength exponent	-0.1781
Second fatigue strength exponent	0
R-ratio of specimen test	-1

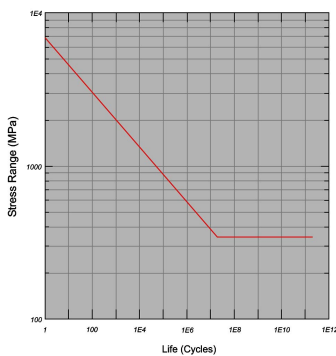


Fig. (3). S-N diagram of FCD500.

A set of 12 load cases was identified which in linear combination were considered able to illustrate the desired Belgian pave proving ground loading condition. In this case, four load directions which are the knuckle ball-joint longitudinal, knuckle ball-joint lateral, knuckle ball-joint vertical and knuckle steering were applied at the strut mount, the lower suspension ball-joint, and the steering rod mount. The load for the knuckle ball-joint in lateral load direction is shown in Fig. (4). The critical stress locations are presented in terms of FE contour plot as shown in Fig. (5).

In this study, mechanical and structural behaviors of components subjected to the desired load patterns were observed using micro measurement strain gauges. Strain gauges are strategically positioned at critical stress location of the steering knuckle to directly reflect the input loads experienced by the component as shown in Fig. (6). Quarter bridge circuits as well as shunt calibration were applied in

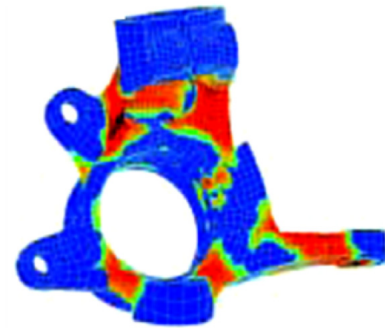


Fig. (5). Critical stress locations of steering knuckle.

order to convert electrical units measured by the strain gauge into the stress-time data. FE model is validated by comparing strain values measured by the strain gauges in physical component and values predicted by the FEA.



Fig. (6). Strain gauge bonded at critical stress location.

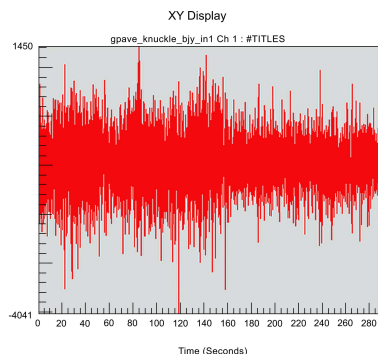


Fig. (4). Load-time histories for the knuckle ball-joint in lateral load direction.

2.4. Proving Ground Load Data Replication

The acquired time history from the proving ground data acquisition is utilized in the system and component level fatigue durability test using spindle coupled full vehicle road simulator. In this study the MTS 320 multi-axial spindle coupled road simulator shown in Fig. (7) is used for the laboratory testing. This system allows the excitation of each of the six degree of freedom which is translation in x, y, z and rotation around these axes with the simulation range of up to 50 Hz.



Fig. (7). Multi-axial spindle coupled road simulator.

In this spindle coupled full vehicle road simulator test system the drive signals are represented by the actuator displacements. In this study, a set of random time-history drive signals were developed to excite the specimen in the test system and the specimen response were measured through the same instrumentation as used to measure the proving ground data. In this case, the specimen which is a steering knuckle component was instrumented with low frequency sensing accelerometers to measure its response to service loading, where the service loading is characterized by the drive signal.

In this case, the response channels are steering knuckle in four load directions (ball-joint vertical, ball-joint lateral, ball-joint longitudinal and steering). Using fast Fourier transform and parametric model estimation, linear estimate of the frequency response function (FRF) which is the linear input-output relationship between drive and response was computed as illustrated in Fig. (8). This input-output system model is then mathematically inverted to become an output-input model in preparation for the initial drive file development.

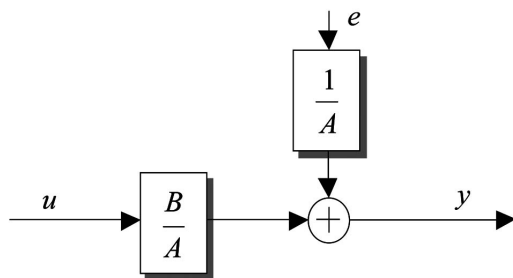


Fig. (8). Linear input-output relationships between drive (u) response (y) and drive error (e).

In this study, a portion of Belgian block proving ground load data as shown in Fig. (9) was selected as the desired response time history of the road simulator test system. This desired response time history data is then convolved with the

inverted system model to provide an estimate of the system drive signal required to produce the response. In terms of safety considerations, this drive estimate was scaled by half and applied to the test system. The resulting response of the specimen due to the drive estimate is then measured.

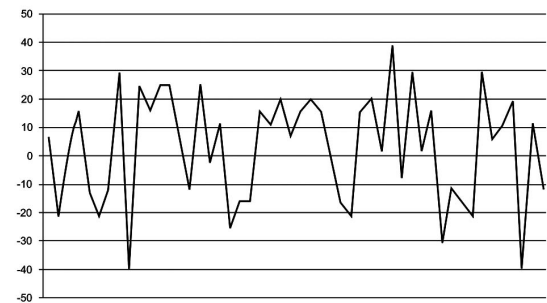


Fig. (9). Portion of Belgian block proving ground service load.

2.5. Iterative Deconvolution

Iterative algorithms are playing an increasing prominent role in a variety of applications where it is necessary to solve large systems of linear equations, often with side constraints on the unknowns, or to optimize functions of many variables [12]. In the case of the road simulator system, the inverse frequency response function (FRF) which represents relationship between input (actuator displacement) and output (response of the specimen) was developed to approximate the real proving ground test system [13]. The inverse FRF is applied to the tracking error, and the result is added to the test input. This off-line refinement process iterates until sufficient tracking accuracy is obtained [14].

For a linear system model, output of the system can be predicted if both input and the FRF are known. In this study, the front corner module proving ground load signals were the desired measurements that are to be produced. In this case, the road load simulator actuator drive signal can be predicted if the FRF is inverted and the desired road load data (output) is identified. In this application, both test system and the front corner module specimen have non-linearity but the inverse FRF was developed as a linear model. In order to compensate these differences, an iterative process was used to achieve actuator displacement that create very nearly the same response in the road simulator test system as was measured in the proving ground.

In this iterative process, the desired specimen response (from proving ground load history) is subtracted from the response achieve on the simulator test system due to the drive signal and the response error signal calculated. The response error signal is then convolved with the inverse FRF model and a linear estimate of the drive error signal results. This drive error is then added to the previous drive signal to generate a better estimate of the drive signal required to produce the desired response. The modified drive signal is then used to run to simulator test system and the new response recorded. A new response error is calculated as described above and the processes are repeated until the response error is reduced to a desired value where the achieved response on the test system has converged onto the desired proving ground load response. This iteration process is shown in Fig. (10) and the result of iteration with regards to desired re-

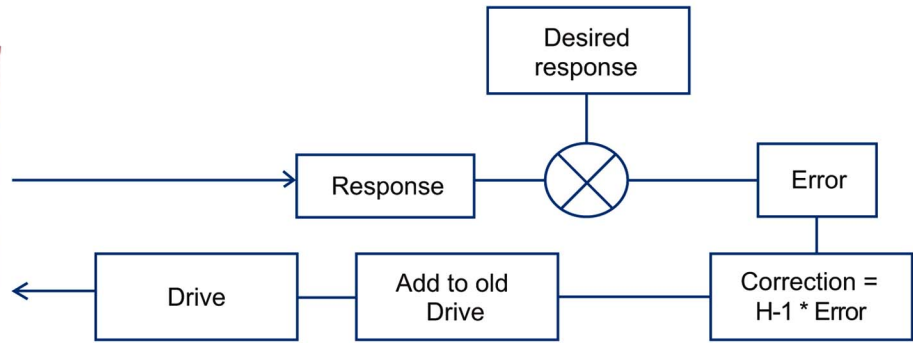


Fig. (10). Development of drive files by iterative deconvolution.

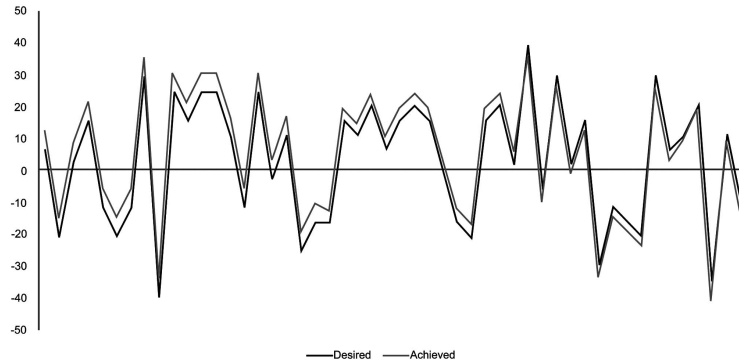


Fig. (11). Desired versus achieved knuckle ball joint load in vertical direction after 16 iterations.

response is shown in Fig. (11). The procedure is repeated for all recorded proving ground service load and drive signals are produced for each service load response. The final sets of drive signals files for each response signal file are then combined into a durability test schedule.

2.6. Durability Test and Finite Element Life Assessment

A durability test is consisted of selected proving ground road surfaces for each of which drive files have been created to reproduce the proving ground measured loading. The drive files are nested together in a series considered to be representative of customer usage. Fatigue software the nCode Glyphworks™ is applied to predict the service life of the components by combining the information from loads obtained from the road simulator and material properties of the component by fatigue damage accumulation theory.

In this study, fatigue life prediction for multiple loading conditions by Finite Element Analysis (FEA) was performed using MSC/Fatigue™ Multiaxial. The component is constrained at the wheel centre and 12 load cases are applied as shown in Fig. (12) which is 3 forces each at the lower ball joint, the steering arm and the strut mount, and 3 moments at the strut mount. Four replicated proving ground load time histories (longitudinal, lateral, vertical and steering forces) were applied to 1 of the 4 load application points on the model.

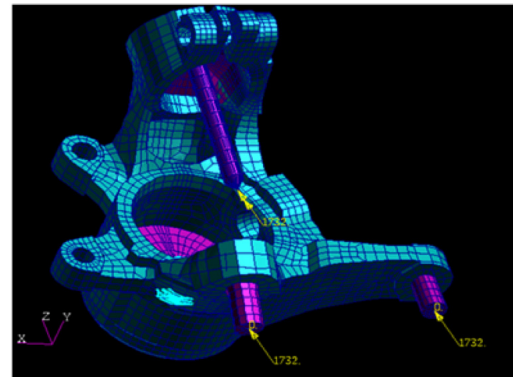


Fig. (12). Forces and moments applied to the knuckle.

relevant similarity of desired knuckle ball joint load signals and the load signals after 16 iterations of the road simulator. In the case of spectrum loading, life estimates of components can be determined by employing Palmgren-Miner rule along with rainflow cycle counting procedure [15]. Segmentation of the load-time data was done by implementing a rainflow cycle extraction algorithm in order to segment the load-time histories into maximum and minimum amplitude as well number of occurrences for certain amplitude ranges. The Goodman mean stress correction was applied in this stress-life analysis.

3. RESULTS AND DISCUSSION

3.1. Fatigue Analysis

In the case of component for a passenger car where the fatigue life is relatively long and the range of plastic deformation is relatively small, the stress-life (S-N) method is applied in the knuckle fatigue life prediction [10]. In this study, fatigue analysis was performed to evaluate the fatigue

Table 2 shows the lives of the steering knuckle for the different load directions. Fatigue contour plot for steering knuckle under the application of correlated proving ground loading inputs is shown in Fig. (13). Fatigue life results obtained using FEA as well as obtained from the durability analysis shows that greatest damage or shortest life appears to be at the vertical load direction of the steering knuckle (ball-joint connected to the end of the lower control arm).

Table 2. Number of Cycles and Fatigue Lives Comparison Between Desired and Achieved Load

	Fatigue Life obtain by FEA (x 10 ⁴ Cycle Repetition)	Fatigue Life of Desired Loads (x 10 ⁴ Cycle Repetition)	Ratio Between Desired and FEA	Fatigue Life of Replicated Loads (x 10 ⁴ Cycle Repetition)	Ratio Between Desired and Replicated
Knuckle ball-vertical	0.907	1.246	0.728	1.148	0.921
Knuckle steering	8.815	13.021	0.677	9.284	0.713
Knuckle ball-joint lateral	1.093	1.850	0.591	2.279	0.812
Knuckle ball-joint longitudinal	1.475	1.853	0.796	1.280	0.691

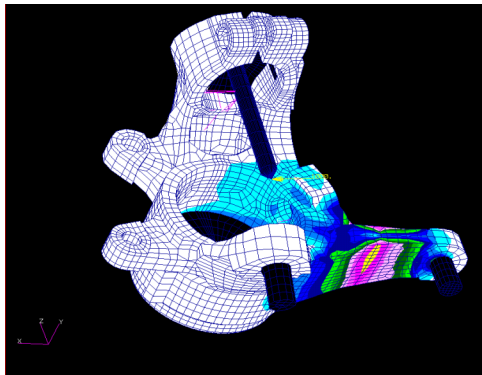


Fig. (13). Fatigue contour plots for steering knuckle.

It is also found that the lives of achieved load signals from road simulator are close to the ones of desired load signals obtained on the proving ground. In the case of stress-life analysis, the divergences between fatigue life obtained by FEA as well as those obtained by durability analysis using desired and achieved loads are all within 50%. This shows that fatigue sensitive contents of the road load signals can be well produced by the road simulator.

4. CONCLUSION

In this study, replications of service loads are demonstrated for steering knuckle. Road Load Data Acquisition activity acquire proving ground load pattern as input for the laboratory road simulator durability assessment. The critical stress location of the steering knuckle was identified by developing Finite Element (FE) model and the strain gauges were strategically positioned at critical stress location to directly reflect the input loads experienced by the component. Response of components towards load patterns are expressed in terms of irregular stress-time signals and the stress-life (S-N) method is used to calculate the fatigue life of the component. Results of the fatigue life obtained by Finite Element Analysis (FEA) and physical durability analysis based on actual and laboratory replicated loads were compared.

The fatigue analysis indicates that the differences of fatigue lives calculated for the proving ground measured signals and the achieved signals on the road simulator as well as results from the FEA were all within 50%. The study has demonstrated the use of iterative deconvolution method in order to reproduce fatigue sensitive contents of the road load

signals on the road simulator. Accurate replication of field test into laboratory testing can accelerate the design process due to the known advantages of time savings, the opportunity to observe the specimen and the overall controlled environment of a laboratory setting.

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REFERENCES

- [1] N. C. Hay and D. E. Roberts, "Iterative control in automotive testing", *Journal of System and Control Engineering*, vol. 221, pp. 223-228, 2006.
- [2] K. J. Dittmann, F. J. Albright and C. Leser, "Validation of virtual prototypes via a virtual test laboratory", In: 1st *European MSC. ADAMS User Conference*, London, England, 13-14 November, 2002.
- [3] B.W. Cryer, P.E. Nawrocki and R.A. Lund, "A road simulation system for heavy duty vehicles", In: *SAE Automotive Engineering Congress and Exposition*, February 1976.
- [4] Bignonnet, "Automotive industry and fatigue design", In: *The Seventh International Fatigue Congress*, 1999, pp. 2627-2634.
- [5] J. Devlukia, H. Bargmann and I. Rustenberg, "Fatigue assessment of an automotive suspension component using deterministic and probabilistic approaches", *European Structural Integrity Society*, vol. 22, pp. 1-16, 1997.
- [6] N. W. M. Bishop and F. Sherratt, *Finite Element Based Fatigue Calculations*. NAFEMS Ltd., October 2000.
- [7] M. Zoroufi and A. Fatemi, "Experimental durability assessment and life prediction of vehicle suspension components: a case study of steering knuckles", *Journal of Automobile Engineering*, vol. 220, pp. 1565-1579, 2006.
- [8] R. L. Jhala, K. D. Kothari and S. S. Khandare, "Component fatigue behaviors and life predictions of a steering knuckle using finite element analysis", In: *International MultiConference of Engineers and Computer Scientists*, March 2009.
- [9] E. A. A. E. Mohamed, M. A. Yusuff, D. A. Wahab, "Application of rainflow cycle counting in the reliability prediction of automotive front corner module system", In: *IEEE 16th International Conference on Industrial Engineering & Engineering Management*, vol. 1, 2009.
- [10] K. J. Jun, T. W. Park, S. H. Lee, S. P. Jung and J. W. Yoon, "Prediction of fatigue life and estimation of its reliability on the parts of an air suspension system", *International Journal Automotive Technology*, vol. 9, no. 6, pp. 741-747, 2008.
- [11] J. D. Kim and J. K. Ji, "Effect of super rapid quenching on fatigue fracture behavior of spherical graphite cast iron FCD500", *Journal of Materials Processing Technology*, vol. 176, no. (1-3), pp. 19-23, 2006.

- [12] C.L. Bryne, *Applied Iterative Method*, A.K. Peters Publisher: UK 2007.
- [13] S. G. Joo, S. You and C. Leser, "Virtual testing with a virtual spindle coupled road simulator and remote parameter control", In: *MSC Software Virtual Product Development Conference*, 13-15 October, 2003.
- [14] D. T. Westwick., K. George., M. Verhaegen, "Nonlinear identification of automobile vibration dynamics", In: *7th Mediterranean Conference on Control and Automation*, 28-30 June, 1999.
- [15] R. Ledesma and R. Carmine., "Establishment of customer correlated accelerated durability test cycle for a heavy duty trucks", In: *LMS User Conference Europe*, 22-23 March, 2006, Munich.

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