

Durability/Reliability Analysis, Simulation, and Testing of a Thermal Regeneration Unit for Exhaust Emission Control Systems

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ABSTRACT

Durability and reliability performance is one of the most important concerns of a recently developed Thermal Regeneration Unit for Exhaust (T.R.U.E-Clean®) for exhaust emission control. Like other ground vehicle systems, the T.R.U.E-Clean® system experiences cyclic loadings due to road vibrations leading to fatigue failure over time. Creep and oxidation cause damage at high temperature conditions which further shortens the life of the system and makes fatigue life assessment even more complex. Great efforts have been made to develop the ability to accurately and quickly assess the durability/reliability of the system in the early development stage. However, reliable and validated simplified engineering methods with rigorous mathematical and physical bases are still urgently needed to accurately manage the margin of safety and decrease the cost, whereas iterative testing is expensive and time consuming. In this paper, the state-of-the-art of the current engineering technologies and practices for durability and reliability assessments is reviewed. These technologies include, but are not limited to: the traction stress analysis method, the master S-N curve based fatigue life assessment method, multi-axial cycle counting method, time domain and frequency domain based fatigue life assessment approaches, and the tolerance limit concept based design method. The complexity caused by multiple failure modes, nonlinear behavior at high temperature, damage initiation and growth are also addressed. Finally, a synthesized analysis module for durability and reliability analysis of the T.R.U.E-Clean® system developed for commercial vehicle exhaust applications is demonstrated with several case studies.

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INTRODUCTION

To meet the increasing demand on emission control, many advanced technologies have been developed over the years to reduce harmful air pollution from diesel engines before it is emitted into the air. Diesel particulate filters (DPF) have been successfully developed to reduce particulate matter (PM) emissions from on-road, off-road, and stationary diesel applications. A DPF cleans exhaust gas by forcing the gas to flow through wall-flow filter and the filter substrate traps the soot traveling through the exhaust system within its walls and stores them. As soot accumulates on the filter, backpressure increases, and usually, with the increased backpressure the exhaust temperatures are elevated to burn off the soot,

passively, depending on the hotness of the stream, which is related to the duty cycle [1]. Passive regeneration is typically catalytically driven, relying on adequate duty cycle temperatures to effectively control soot loads, and it is preferred since it does not consume additional fuel. However, in the real world, the necessary temperatures for some passive regeneration systems can never be achieved, and the ability of the engine and/or catalyst to elevate exhaust temperatures can be problematic, resulting in overloaded filters that have become clogged over time and regular cleaning is the only way to ensure a filter will maintain its effectiveness [1]. The active thermal regeneration strategy is often adapted to ensure even under low-temperature application duty cycles, sooth

load can be controlled by actively elevating temperatures to oxidize the soot [1]. For active regeneration an external source of heat is applied to raise its temperature to a sufficient level for the soot to be burned off [1,2,3,4,5,6,7,8,9,10,11,12]. This can be achieved by injecting fuel directly into the system and igniting it for certain time period [1].

T.R.U.E-Clean[®] is a recently developed new active thermal regeneration system (burner for short)[1, 2]. It operates with an airassist nozzle, leveraging the necessary secondary air not only for combustion, but also for fuel atomization. The burner is divided into primary and secondary combustion chambers [1]. The primary chamber is at the unit's inlet and isolated from the exhaust, reducing sensitivity to system flow rates for both ignition and flame retention. The initial combustion occurs in this zone, producing gas temperatures greater than 1000°C. The performance attributes of the burner have been thoroughly studied on the following aspects: operation coverage, scalability and packaging, pressure drop, flow and temperature uniformity, fuel demands and controls, transient response, secondary emissions, thermal cycling response, vibration response, and preliminary durability analyses etc. [1]. Implementation of the system on numerous vehicles has also been demonstrated, exemplifying the simplicity and scaling benefits with such a design [1]. Even though such high temperatures do not entirely transfer to the chamber materials, the durability and reliability are one of the major concerns in the product design because many potential failure modes such as oxidation and creep, which are not an issue at low temperature, are expected to show up and eventually the durability and reliability performance of the system deteriorate. Durability refers in general to the resistance of a component or a system to failure under one or several different damage mechanisms such as fatigue, wear, corrosion, creep, oxidation, etc. It defines the ability of that component or system to survive its operating environment for a targeted duration. Reliability is related to the consistency or repeatability of life cycles. In the increasingly competitive market environment, product designers and manufacturers are challenged to design, develop, and test new products within a short time period and with "zero defects" philosophy [13]. Therefore, both durability and reliability are vital parts of product designs, especially for high temperature components and systems.

A substantial knowledge has been accumulated over the years on traditional exhaust components and systems, which may consist of many components such as manifold, engine mount, hanger, bracket, flange, heat shield, muffler, flexible coupling, pipe, diesel oxidation catalyst (DOC), DPF, Selective Catalytic Reduction (SCR), and supporting mat. These components are connected with various joining methods, mostly by welds for permanent connection, to form a full exhaust system. Years of experience has shown that the prevailing failure modes in conventional exhaust systems are

cracked welds at joints between pipes and muffler/resonator/converter (360° welds), cracked hanger-to-pipe welds (line welds), and broken hanger rods [14]. However, for the burner with such high temperature, many failure modes such as creep, fatigue, oxidation or their combinations appear in a failure process. Unfortunately, the durability and reliability performance of materials at such high temperatures are essentially unknown. Actually, very few researches have been conducted on the fundamental behaviors of materials at such extreme conditions. Furthermore, preliminary results have shown that the failure locations are not limited to welds anymore, and base materials are also becoming vulnerable to failure at elevated temperature. A reliable and validated analytical method to predict durability life is urgently needed to predict the performance of the burner system, while iterative testing is expensive and time consuming. Therefore, some very basic and challenging theoretical, numerical, and experimental researches have to be conducted to fully understand the potential durability and reliability issues. Furthermore, knowledge and know-how-based product design strategy must be adopted, otherwise, costs could significantly increase with the traditional "trial-and-error" approach and the quality of the products could be compromised.

In this paper, a general plan for durability and reliability studies of the burner is presented. Potential techniques for overcoming some critical technical barriers are described in detail. Some preliminary results are demonstrated with several case studies.

THE PLAN FOR DURABILITY AND RELIABILITY ASSESSMENTS

For the durability and reliability assessment of the burner system, a complete plan including strategy, timeline, and roadmap must be carefully worked out in advance and should be updated and adjusted regularly with more recent observations and improved understanding. The overall plan for durability and reliability assessment of the burner as well as other exhaust systems is plotted in Fig.1. The plan generally consists of three parts: theoretical analysis, virtual simulation, and testing. Determination of potential service loads is the first step of the plan. For a burner, the major loading typically comes from thermal cycling during the regeneration process. Additionally, vibration caused by mechanical loading superimposed on the thermal loading should also be considered. In order to successfully analyze the durability and reliability performance of the burner system, analytical, virtual simulation, and testing should work in synergy. It is essential that analytical and numerical simulation techniques are employed at the earliest possible design stage, so that design errors and drawbacks can be identified as early as possible because physical tests are usually expensive and timeconsuming. Advanced analysis and simulation tools can provide quick, efficient, and often times reliable information on concept generation, mechanism

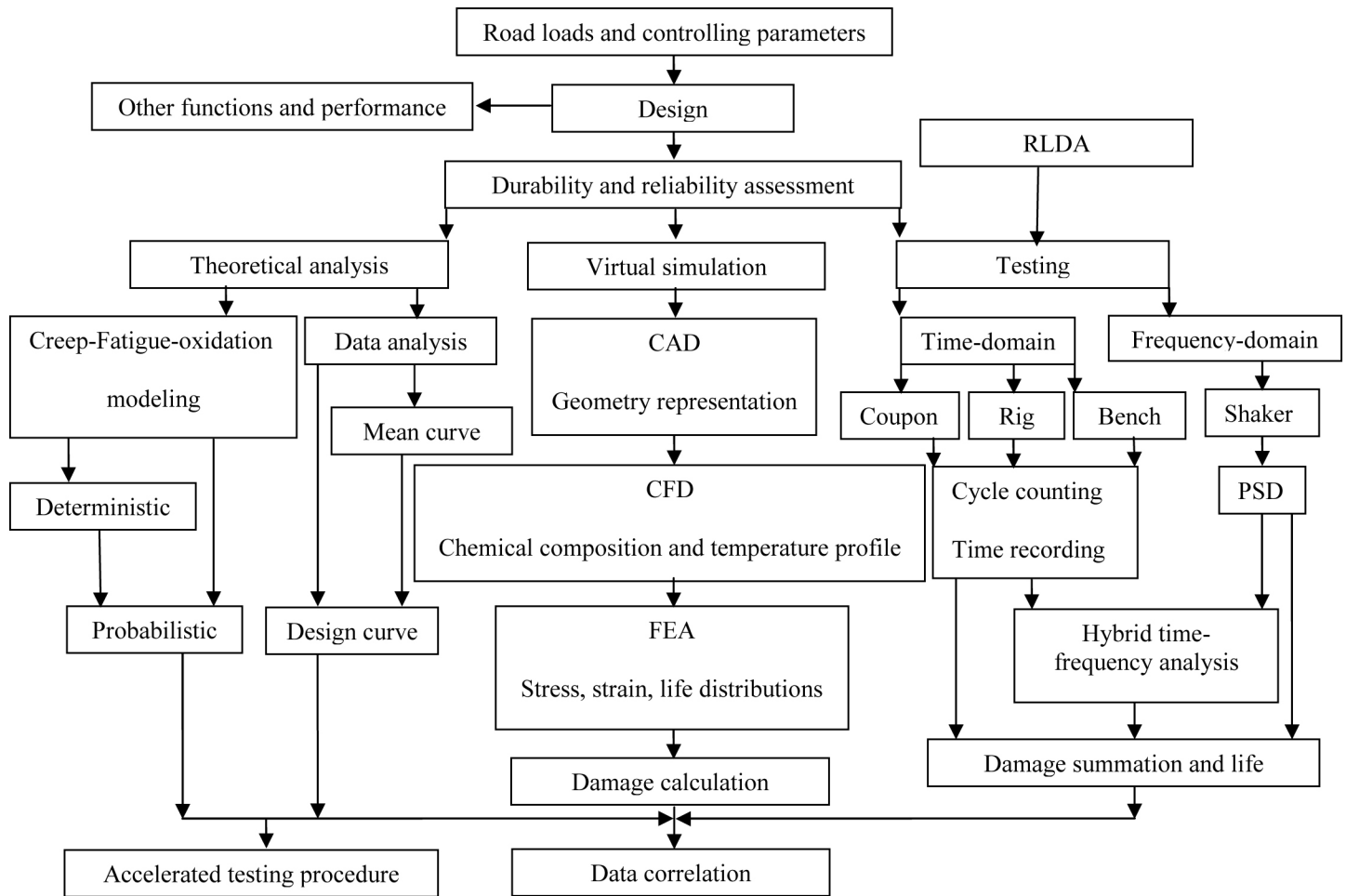


Fig.1. The module of durability and reliability analysis procedure for exhaust systems

identification, and problem isolation. Key elements in making reliable analysis and simulation, apart from the use of adequate models, are the accuracy of inputs, such as controlling parameters, boundary conditions, and basic material properties. The first two are determined by the task and applications, and the basic material properties can be found in open literature, reports, and previous designs. Simulation also allows detailed sensitivity analyses to be conducted until an acceptable durability is obtained. These analysis loops give an insight to the predominant influencing factors and the distribution of durability lives. In parallel to analysis and virtual simulations, tests are conducted in the field or laboratory at several stages to provide basic data from the beginning of the project to final validation. Due to the inherent scatter in durability life and all of the possible sources of inaccuracy and variability, physical testing represents the final validation of the design. Testing itself is often time consuming, and at this stage several accelerated testing techniques may be applied in order to speed up and optimize the design process. Usually, many iterations of designs, planned or unplanned, may be needed in a complete

product development cycle to meet the durability and reliability requirements.

Theoretical analysis is an essential part of an engineering design process. For any given problem, the relationship between the controlling parameters, such as stress and temperature, and durability life must be identified with a theoretical approach, and subsequently, exact or approximate solutions, if they exist, must be pursued first with analytical approaches before the numerical simulation and testing are started. Theoretical analysis provides physical insight into numerical and test results and it is an indispensable part in a whole product design process. As more numerical methods and commercial software with a wide variety of functions and complexities are available, engineers now rely heavily on computer simulation technologies. However, physical insight is the “soul” of all and is more important than the numerical and testing data generated. Without strong analytical skills, numerical and testing may be ended up with “garbage in, garbage-out” (GIGU) situation. For the burner and other exhausts designs, the most important concepts in analysis are several basic laws, including the mass, energy, species conservation laws, and several concepts such as equilibrium,

uncertainty, and dimensionless. Perturbation method is also useful to find approximate solutions to complex problems when an exact solution does not exist.

Computational aided design (CAD), computational fluid dynamics (CFD), and finite element analysis (FEA) are the most widely used virtual approaches in burner and other exhaust systems design. CAD is a necessary tool for a product design, and it provides the basic geometrical information for later development. CFD can generate temperature fields as well as the information about chemical composition, flow characteristics, which can provide the initial input for subsequent FEA and durability analysis. CFD has many advantages over experimental methods. For example, for a burner system, it is impossible to directly measure the whole field temperature distribution on the burner surfaces, instead, CFD can provide a complete picture of the information about the flow, temperature, and chemical composition, such as oxygen content. However, calibration must be conducted for CFD to give a meaningful result. FEA is utilized to calculate mechanical information such as stress (e.g von Mises stress and principal stress), strain, and energy density, which can be directly related to durability life with proper established theories. Static weight, modal analysis, transient and random analyses are also often conducted. Transient analysis is performed in the time domain for short discrete events. Random vibration analysis concerns the frequency domain, with loads being specified in terms of power spectral density (PSD) functions.

Test allows verification and correlation of product design. The correlations between test and virtual simulation/analytical analysis are critical to ensure high confidence in the results and design. Test results implicitly include all complex factors that may not be possible to correctly account for in analysis and simulation. The real service load data is most important, and knowing the loads that a burner is experiencing in real world conditions is not a trivial task. Care should be taken when evaluating or measuring these loads so that they are representative of the in-service usage. Physical tests can be divided into several categories such as prototype tests, basic coupon tests, and intermediate tests. Physical prototype tests consist of proving ground, rig, shaker, and bench tests. The purpose of road load data acquisition (RLDA) testing is to capture the mechanical and thermal histories of loading events which result from engine operating conditions as well as from road roughness. Different test methods have advantages and drawbacks. Based on difficulty, predictability, and cost, a combination of these testing types can lead to an optimal design. These tests are mature and being widely used in the durability testing of exhaust components and systems. Basic coupon testing is important for failure modes identification, material database build-up for FEA analysis, and material selection. The measurement of static properties of materials is the basis, and transient thermal-mechanical information such as in-phase and out-of-phase may be also helpful. Pure-fatigue, purecreep, oxidation, and combined creep-fatigue-oxidation

should also be considered in coupon tests. Many high temperature testing methods can be used to do coupon tests and induction heating is one of the most promising approaches in not only steady material behavior testing but also transient in-phase and out-of-phase thermal-fatigue testing. The oxidation effect can be compared with results conducted in an air environment and an inert gas or vacuum environment. One such heating and testing system is shown in Fig.2. Testing of real components and systems is time-consuming and expensive, while the coupon test results have to be combined with FEA to predict the durability of products with complex geometry and boundary conditions. Sometimes, an intermediate testing procedure can provide useful information at a reduced cost, while at the same time providing useful predictions. One such example is the tubular specimen test, shown in Fig.3, used for the thermal-fatigue durability analysis of exhaust manifolds. V-shape and tubular-shape specimen testing has been intensively studied and used in exhaust system design [15]. It is also being considered in the burner design process for materials screening and selection. Since the burner is subjected to complex high temperature thermal-mechanical loading, fatigue, creep, oxidation or their combination are to be expected. Therefore, it is necessary to use metallurgical examination techniques to examine all possible failure modes of the products. For all of these test types, pilot testing should be conducted before any formal testing is conducted in order to reduce testing risks.

Since durability testing is the most time-consuming part of a product design, accelerated testing should be considered whenever possible. A successful accelerated durability test, such as the rig test, should satisfy many criteria. The following two are the most important:

1. If possible, the test should replicate the same failure mechanisms and their relative proportion should match that observed in real loading environments. However, this is sometimes very difficult to achieve for durability life degradation with multiple failure mechanisms and therefore, the damage equivalency principle is often employed to relax this limitation.

2. Accelerated testing should not incur unrealistically high loads that might alter the failure mechanisms and introduce severe nonlinearity.

It should be noted that burner design is a complex task because of many limiting factors are involved in the design process. Therefore, iteration of designs is often unavoidable because of many unanticipated issues coming out. Therefore, risk analysis and risk mitigation management should be part of the test plan and should be thoroughly conducted before the execution of any physical tests. Additionally, test plans must be reviewed regularly and the overall goal and tasks must be adjusted as necessary as updated information become available. In addition to technical difficulties and the availabilities of facilities, budget and timing are additional constraints on any test plan. In cases of limited budget and