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Sensitivity Analysis for Safety Design Verification of General Aviation Reciprocating Aircraft Engine

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Abstract

This paper presents an application of global sensitivity analysis for system safety analysis of reciprocating aircraft engine. Compared with local sensitivity analysis results, global sensitivity analysis could provide more information on parameter interactions, which are significant in complex system safety analysis. First, a deterministic aviation reciprocating engine thermodynamics model is developed and parameters of interest are defined as random variables. Then, samples are generated by Monte Carlo method for the parameters used in engine model on the basis of definition of factor distribution. Eventually, results from engine model are generated and importance indices are calculated. Based on the analysis results, design is improved to satisfy the airworthiness requirements. The results reveal that by using global sensitivity analysis, the parameters could be ranked with respect to their importance, including first order indices and total sensitivity indices. By reducing the uncertainty of parameters and adjusting the range of inputs, safety criteria would be satisfied.

Keywords: sensitivity analysis; safety analysis; airworthiness; reciprocating aircraft engine; design verification

1. Introduction

General aviation is defined as all aviation other than military and scheduled commercial airlines. General aviation has become one of the world's most important and dynamic industries. It touches every aspect of our lives, our economy and our future. For example, general aviation contributes more than 150 billion to the United States economy annually and employs more than 1 265 000 people [1]. As to the engine type, single-engine piston-powered airplanes comprise most of the current general aviation aircraft. In the United States over 80% of the general aviation fleet are equipped with single piston engine and most of them are personal-use aircraft, thanks to their relatively low acquisition cost [2].

Aerospace Recommended Practice (ARP) was developed in the context of Federal Aviation Regulations (FAR) and Joint Airworthiness Requirements (JAR). System development process model was introduced by ARP 4754. In this model, safety assessment progress and system development process interact with each other [3]. This kind of development assurance establishes confidence that system development has been accomplished in a sufficiently disciplined manner to limit the likelihood of development errors that could impact aircraft safety. As to system safety analysis, ARP 4761 was developed as a document of standards for safety analysis [4]. System safety assessment (SSA) is an essential step in the process of system safety analysis according to ARP 4761. SSA verifies whether the safety requirements are met in the implemented design.

Sensitivity analysis is an essential tool in the process of SSA. Firstly, at design stage, there is unavoidable lack of detailed information about the system. Furthermore, detailed mathematical model of interaction between engine and its operation environment is not feasible at this stage. It is desired to identify the most

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important factors in order to get supplementary information. These information could be introduced by questioning the manufacturer on a limited number of elements or by enhancing some aspects of the rather simple analysis model used in the SSA phase [5]. And secondly, if the safety requirements were not met, design should be changed until it satisfies the requirements. Hence, it is typically useful to figure out which factors are the most important. Then more effects could be focused on these important factors to improve the safety level. Probably it is these important factors that push the global behavior of the engine into a critical zone, while other parameters have almost no influence on its behavior. Finally, it is inevitable that uncertainties exist between the design model and the real engine. These uncertainties may arise from manufacture, operation environment, maintenance, etc. After the safety assessment, some special measures should be taken to ensure that the actual safety level of the most important factors is consistent with the safety level used in SSA, if necessary. Safety assessment should hence benefit from the large amount of on-going research devoted to developing sensitivity analysis within large industrial engineering and modeling [6-7].

Typically sensitivity analysis was performed using a one-factor-at-a time (OAT) approach [8], i.e., each factor is perturbed in turn while keeping all other factors fixed at their nominal values. When the purpose of sensitivity analysis is to assess the relative importance of input factors in the presence of factor uncertainty, this approach is only justified if the model is proven to be linear. This approach is naturally limited as it does not permit accounting for simultaneous variation of uncertain parameters and it is carried out with respect to a reference situation [5], although it is known that parameter interactions are generally important in system safety analysis.

Another sensitivity analysis method has been referred to as importance measures in the literature [9]. Quantitative measures of sensitivity were defined to measure the importance. The Fourier amplitude sensitivity test (FAST), the Sobol'I's method [10] , the measures of importance of Iman and Hora [9], and those of Ref. [11] all coincide with importance measures. Generally, the system output is generated by numerical method which is time-consuming when complex problems have to be solved. Meanwhile, Monte Carlo method is employed to obtain statistics of system output. In order to achieve more insight in the model behavior in an efficient way, Sobol'I's method is a choice [12-13].

The objective of this paper is therefore to propose a modus operandi for sensitivity analysis in SSA which takes into account the uncertainty of factors and the interactions between parameters by using importance measures. This paper also shows how to improve safety design level based on the results of sensitivity analysis, which is a critical step in system safety analysis.

2. Methods

The methodology developed in this paper is shown in Fig. 1. First, a deterministic engine thermodynamics model is needed that is called "nominal model" in this paper. This model should include parameters of interest and design outputs which can be compared with the defined safety criteria. Second, samples are generated by Monte Carlo method for the parameters used in engine model on the basis of factors distribution definition. Last but not least, data statistics function processes the results obtained from engine model and calculates the importance indices. If the SSA results meet the safety requirements, the design steps into the next stage. Otherwise, design should be improved until the requirements could be satisfied. The important indices provide helpful information for the design improvements.

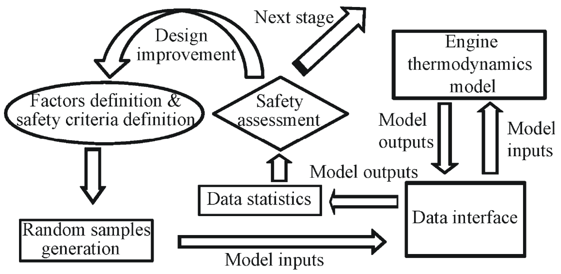

Fig. 1 Sensitivity analysis embedded in SSA.

2.1. Nominal model

A 50 kW two-stroke lightweight heavy-fuel reciprocating engine is considered in this paper and the numerical 1D thermodynamics model was developed. At this stage, thermodynamics parameters need to be confirmed to satisfy the power requirements but not to exceed the safety boundary. Obviously, high pressure and high temperature will contribute large power and high power-to-weight ratio that is desired in aero-engine. However, this may threaten structure integrity. Therefore, pressure and temperature in the cylinder should be calculated and verified.

The model consists of intake system, exhaust system, fuel injection control system and other function blocks. Intake pressure and temperature were treated as input factors. As it was a two-stroke engine, scavenging area was one of the important parameters. Other parameters would be discussed in the following sections. Combustion model imposed the combustion burn rate using a three-term Wiebe function. Classical Woschni correlation was adopted as the heat transfer model. When the simulation convergence satisfied the criteria, the maximum pressure would be extracted from the simulation results by a specific function block.

2.2. Variables of interest and safety criteria

In order to ensure structure integrity, the pressure