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Research paper

Structural reliability simulation for the latching mechanism in MEMS-based Safety and Arming device

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ABSTRACT

Based on the deterministic performance analysis of latching mechanism in MEMS (micro-electro-mechanical system)-based Safety and Arming device (S&A device), probabilistic algorithms and Kriging approximation method coupling with finite element simulation are used to quantify the effect of input uncertainties on the response metrics of the mechanism. It firstly uses performance function to represent the failure of the latching mechanism mathematically, and then constructs the corresponding reliability model according to structural reliability theory. In order to relieve the burden of further reliability and sensitivity calculations, Kriging interpolation technique is adopted to approximate the performance function and hence simplify the reliability model. Samples of input variables and the corresponding response, which all together serve as the inputs of Kriging approximation, are gotten through finite element simulations based on the design of experiments. An efficient CAE software integration method is proposed to facilitate the repetitive FE-based calculations of those samples. Finally, FORM (First Order Second Moment Method) is utilized to get the reliability index and its sensitivities with respect to the input random variables and their parameters, which can not only be employed for reliability assessment of the latching mechanism, but also can help to identify key factors for additional structural improvements.

1. Introduction

MEMS-based Safety and Arming device (S&A device) has been the emerging subject of research for its applications in small-caliber munition fuzes. It can not only reduce the cost and volume of the conventional S&A, but also increase system safety and reliability to some extent. The design of MEMS S&A aims to incorporate the functions of a conventional mechanical S&A in a single inertially-driven S&A chip, which can control the components of a specially-designed explosive micro-firetrain and can integrate directly with the fuze circuit [1,2]. However, present designs of MEMS S&A devices cannot achieve the high reliability demanded for the small-caliber munition fuzes commonly with peak acceleration up to 60,000 G's and a muzzle spin rate of 1250 rps. Due to expensive laboratory and field experiments, pre-fabrication numerical simulations of MEMS S&A are usually used for its performance assessments, or potential failures predictions [3–5].

One of the most common-used simulation techniques is the Finite Element Method (FEM), which has many commercially available software packages, such as ABAQUS (ABAQUS, Inc.), HyperWorks (Altair, Inc.). Unfortunately, deterministic finite element models in those software packages fail to account for the potential impact of performance variability caused by the uncertainty in design variables. Especially, it commonly contains inherent variability in geometries, material properties because of the uncertainty in the micromachining and etching processes used for MEMS manufacturing [6]. Tolerances on shapes of MEMS device can be relatively high, usually 1%∼10%, owing to their small dimensions [6,7]. The material properties of the MEMS device can also exhibit large variation, generally 1%∼15% according to [7,8]. Those variations in dimensions and material properties can have a significant impact on the mechanical behavior of the MEMS device.

Naturally, it would be of more significance for engineering applications of MEMS S&A that if further reliability evaluation can be taken based on the performance simulations. In the reliability evaluation, it aims to quantify the MEMS S&A reliability and identify the most significant design variables, which serve to judge whether the given design will meet specified performance or reliability criteria, and provide valuable information for design improvement and optimization.

In this paper, we focus on reliability assessment of the latching mechanism that is the weakest part in MEMS S&A according

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to prior designing experience. Reliability simulation method based on reliability theory and FEM will be used for the assessment as it is done in [4–6]. However, there are two essential problems that deserve extra attention while dealing with real-scale issues of engineering interest. The first one is how to efficiently automate the integration of the FEM programs or tools in the reliability analysis procedures. The other one is how to decrease the number of times of nested deterministic FE simulation during the reliability assessment.

This paper attempts to develop an efficient reliability simulation method for the latching mechanism in MEMS-based S&A device based on FEM. Approximation techniques are applied to reduce the computation burdens caused by repetitive performance function evaluations in reliability analysis, where efficient integration method for CAE programs is also proposed. It then uses FORM (First Order Second Moment Method) [9,10] to get the reliability index and its sensitivities with respect to the random variables and their parameters. All the results can not only be employed for reliability assessment of the latching mechanism, but also can help to guide the further structural improvements.

Furthermore, the simulation method presented in this paper can also be applied to reliability assessment of other MEMS structures (such as comb structures in MEMS accelerator and gyroscope, micro spring in MEMS actuators) during the design stage. Especially, the structural reliability modeling method can be used to describe the failure mode and its mechanism of the MEMS in functional level (the other three levels are design level, technology level, an integration level discussed in [11]) mathematically. The FE software integration method can partly help to solve the problems in MEMS in design level, where FE simulations are commonly adopted for performance prediction. The simulation workflow method can not only facilitate the reliability modeling process, but also help to define simulation problem graphically and efficiently. Before quantitative reliability analysis of MEMS structures, more attention should be paid to the understanding of potential failure modes or failure mechanisms of the structures. Reviews about studies of MEMS failure mechanism can be found in [8,12,13]. Other aspects of MEMS reliability such as packaging, fabrication and approaches for reliability enhancement are broadly discussed in [11].

2. Description of the problem

The MEMS-based S&A device of interest in this paper is shown in Fig. 1.

The MEMS S&A device consists of two MEMS springs, the first safety lock, arming slider, the second safety lock, and latching mechanism as shown in Fig. 2. All the components of the device interact on a planar substrate in response to the centrifugal load once the small-caliber munition has been initiated. The ultimate function of the device is to move en electric detonator, a critical element of firetrain, in-line with detonating tube. The chip dimension of the device is Φ14mm × 1.5 mm, which is suitable for the application of a variety of small-caliber fuzes.

Prior to intended launch of small-caliber munition, the first safety lock and the second one will keep the arming slider within explosive isolation position. Once launch occurs, MEMS S&A device will suffer great recoil load and the peak acceleration can be 60,000 G's. When the spin rate of MEMS S&A reaches 30000r/min that is lower than the maximum 75000r/min, it will remove the first safety lock, the first constraint of arming slider, because of the centrifugal load induced by high spin rate.

After the small-caliber munition has arrived at a certain specified distance from the muzzle, the second safety lock will be pulled down by an electric thruster with designed command, hence making the arming slider free to move towards the latching mechanism. After the latching mechanism has taken into effect and then the arming slider has been locked firmly, the fuze is ready for ignition.

A finite element model to simulate the latching mechanism is constructed by HyperMesh (Altair, Inc.), where an equivalent velocity is applied to the counterweight block of arming slider. Deterministic dynamic simulation shows that the maximum von-Mises stress is 1.1078 GPa (as shown in Fig. 3). The yield strength of the mechanism, which is made of beryllium bronze, is 1.2 GPa according to material experiments based on [14]. The mechanism will survive during the operation of MEMS S&A if uncertainties in geometry, material properties and loads are not taken into account. However, inherent scatter exists in those factors commonly and the latching mechanism may fail to fulfill its specified function. It is necessary to quantify how much the maximum stress characterizing the latching mechanism behavior is affected by the randomness of inputs. If the mechanism cannot survive or conforms to the specified requirements, it should take some measures to improve its reliability according to the sensitivities results.

3. Reliability simulation method

3.1. Reliability modeling

According to structural reliability theory [15], a performance function representing the failure of the latching mechanism can be defined as

$$g(\mathbf{x}) = s - y(\mathbf{x}) \tag{1}$$

where s represents the strength or resistance of the structure. $y(\mathbf{x})$ is called load effect or applied stress and here is the maximum stress of the latching mechanism calculated through FEM, which is a complex function of a set of input variables. $\mathbf{x}$ is a vector of random variables:

$$\mathbf{x} = (s, w, r, r_0, B, H, E)^T \tag{2}$$

where w is the peak spin rate of the MEMS S&A device. r_0 and r are the initial and ultimate eccentric distances of the arming slider respectively as shown in Fig. 2. B and H are the width and thickness of the latching mechanism respectively as shown in Fig. 3. E is the Young's modulus of beryllium bronze.

The latching mechanism if safe (desired performance) if $g(\mathbf{x}) > 0$ and not safe (undesired performance) while $g(\mathbf{x}) < 0$. Eq .(1) is also called as limit state function, corresponding to the boundary between desired and undesired performance while $g(\mathbf{x})=0$. The reliability of the latching mechanism is equal to the probability that the undesired performance will not occur, which can be expressed in terms of Eq. (1) as

$$R = P(g(\mathbf{x}) \geq 0) \tag{3}$$

where $P(*)$ is probability of the event $*$. The probability of failure is $P_f = 1\text{-}R$.

As $y(\mathbf{x})$ is the maximum stress predicted by FE analysis, $y(\mathbf{x})$ is an implicit function with respect to $\mathbf{x}$ and therefore makes the performance function $g(\mathbf{x})$ implicit mathematically. Reliability analysis based on Eq. (3) with Monte Carlo or FORM may have high computational cost due to the great number of deterministic finite element simulation trials. Kriging approximation model [16,17] of $y(\mathbf{x})$ will be constructed to replace the true input-output relationship hence making $g(\mathbf{x})$ explicit and easy for further reliability and sensitivity calculation.

3.2. Approximation of performation function

According to Kriging approximation theory [16], the true relationship of the output $y(\mathbf{x})$ and the input $\mathbf{x}$ can be assumed to be