Comparison of probabilistic and deterministic optimizations using genetic algorithms

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Abstract This paper describes an application of genetic algorithms to deterministic and probabilistic (reliability-based) optimization of damping augmentation for a truss structure. The probabilistic formulation minimizes the probability of exceeding upper limits on the magnitude of the dynamic response of the structure due to uncertainties in the properties of the damping devices. The corresponding deterministic formulation maximizes a safety margin with respect to these limits. Because this work was done in the context of an experimental comparison of the reliabilities of the resulting designs, antioptimization was used to maximize the contrast between the probabilities of failure of the two designs. This contrast maximization was also performed with a genetic algorithm. The paper describes the genetic algorithm used for the optimization and antioptimization, and a number of modifications to the antioptimization formulation intended to reduce the computational expense to an acceptable level. Optimal designs are obtained for both formulations. The probabilistic design shows a very significant improvement in reliability.

1 Introduction

Structural design optimization is usually based on analytical models. Performance levels predicted by these models correspond to nominal values of geometric, loading and material properties. However, these properties are random in nature and generate scatter in the performance of the actual system. Design optimization problems typically involve a large number of performance requirements. Deterministic optimization tends to make several requirements critical in a deterministic sense (i.e. for the nominal system). Since the property variations are neglected, this may increase the number of possible failure modes, which in turn tends to increase the probability for the actual system to violate one or more of these requirements. Large safety factors are used to reduce this probability. Unfortunately, these safety factors are not systematically adjusted to discriminate between requirements with different magnitudes of scatter or different costs. As a result, deterministic optimization can lead to either unreliable or overdesigned systems (see e.g. Moses and Kinser 1967; Moses 1977).

Probabilistic optimization, on the one hand, attempts to use some knowledge about the statistics of the uncertainties in the system to predict – and minimize – the probability of violating the design requirements. This approach is gaining popularity and has been shown in numerical simulations to provide safer designs (e.g. Farim and Cohn 1978; Yang et al. 1990; Sepulveda 1994).

In this paper, we compare optimal designs obtained from deterministic and probabilistic formulations of the same design problem. Both optimizations are performed using genetic algorithms (GA). This comparison is performed as part of a program for experimental validation of probabilistic optimization that was the focus of a previous publication by Ponslet et al. (1994) and Ponslet (1994). In this context, it is important to have a large difference between the probabilities of failure of the two designs (because a small difference would be difficult to measure). To achieve this, we formulate a contrast maximization problem that finds a problem that maximizes the difference in probabilities of failure between the two designs. Some parameters of the deterministic and probabilistic optimization problems are used as the de-
design variables in this contrast maximization. This process can be seen as antioptimization (e.g. Haftka and Kao 1990; van Wamelen et al. 1993), in the sense that it makes the deterministic design look as bad as possible compared to the reliability-based design. The antioptimization is also solved using a genetic algorithm.

The design case used throughout this paper is that of a truss structure with damping augmentation where the main source of response uncertainty is the variability in the properties of the nominally identical damping devices. The uncertainties are quantified by measuring the properties of a large number of dampers.

In the rest of the paper, we first describe the truss and dampers used in this study. We then describe the design problem and the models and analysis techniques for estimating the vibration amplitude and probability of failure of a truss design. The alternative formulations of the deterministic and probabilistic optimization problem are presented next. We then describe in detail the genetic algorithm used in this study, followed by the formulation of the antioptimization problem. Finally, optimization results are presented and the deterministic and probabilistic optimal designs are compared.

2 System description

The structure is shown in Fig. 1. It is a short, beam-like truss assembled from aluminium members and nodes. The truss is about 1 meter long and weighs about 4.4 kg. The same truss was the subject of a previous experimental study of the scatter in natural frequencies due to uncertainties in the masses and stiffness of the members and in the masses of the nodes (Ponslet et al. 1993).

Figure 2 shows a plot of the magnitude of an experimental frequency response function (FRF) from excitation force to response acceleration for that truss. The first three modes are well separated. Their natural frequencies are about 100, 130 and 193 Hz. We also observe that the inherent damping in the second mode is much higher than in the other two modes. For that reason, only modes 1 and 3 are considered in this work.

This structure is equipped with tuned vibration absorbers to reduce the dynamic response of the first and third modes. The tuned dampers (Fig. 3) consist of symmetric cantilevered beams, attached by their middle point to a node of the structure and carrying adjustable tip masses. Their first bending mode is tuned to a natural frequency of the truss to obtain a tuned damper behaviour. Two slightly different versions of this damper design (we will refer to them as type 1 and type 3 are used to target the first and the third natural frequency of the structure. The reader is referred to the work of Ponslet et al. (1994) and Ponslet (1994) for a detailed description of these dampers.

Although the mass of the dampers is very small compared to the mass of the structure (about 10 grams, or 0.2% of the total mass of the truss), they provide significant damping to the truss. Figure 4 shows the frequency response function of a tip node acceleration, before and after adding one type-3 damper to the structure (the damper was tuned to the frequency of mode 3 and located at the node and in the direction that correspond to the largest amplitude of vibration in the third mode shape). The reduction in amplitude achieved in mode 3 is more than 25 dB.

Note that the tuned damper does not significantly affect the other modes of the truss because the natural frequencies of these other modes are far from the tuned frequency of the damper, preventing any significant exchange of energy between the truss and the damper. This implies that at least