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Topology optimization for minimizing the maximum dynamic response in the time domain using aggregation functional method

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ABSTRACT

This paper develops an efficient approach to solving dynamic response topology optimization problems in the time domain. The objective is to minimize the maximum response of the structure over the complete vibration phase. In order to alleviate the difficulties due to the max operator in the objective function, an aggregation functional is proposed and employed to transform the original problem formulation into one that is computational tractable. The main advantage of the proposed aggregation functional over the existing aggregation functions, such as KS function and the p-norm function is that, for the dynamic response problems in the time domain, the differentiate-then-discretize approach can now be used for adjoint sensitivity analysis, instead of the discretize-then-differentiate approach, which is tightly coupled with the numerical integration schemes of the primal analysis and is more cumbersome. In addition to the solution method, some issues of dynamic response topology optimization problems in the time domain are discussed. The reason why the maximum dynamic response may occur in the free vibration phase for transient load is uncovered. A strategy to reduce the maximum dynamic response over the complete vibration phase is proposed. Numerical examples demonstrate the effectiveness of the proposed method.

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1. Introduction

The widely used static topology optimization methods [1] provide engineers an efficient way to find optimal design of structures under loads that are static or vary slowly. However, when the loads change rapidly, their time-dependent characteristic and the inertia effect must be considered, therefore the dynamic response topology optimization methods should be employed. The dynamic response topology optimization problems have both been studied in the frequency domain and in the time domain. The former tries to improve the steady state response of a structure under harmonic loads [2–8], while the latter attempts to reduce the vibration of a structure under general loads [9–13]. This work will focus on the dynamic response topology optimization problems in the time domain.

Min et al. [9] first studied dynamic response topology optimization problems in the time domain, where the mean dynamic compliance of structures was minimized by using the homogenization design method. Turteltaub [14] proposed an algorithm to optimize a two-phase composite under dynamic loads and illustrated the effect of the dynamic loading. Jang et al. [11,15] proposed a topology optimization approach to minimizing the average or the peaks of the strain energy in the time domain based on the equivalent static loads method. Stolpe [16] suggested a modified method for calculating the equivalent static loads, but it requires, at every outer iteration, the computation of the gradients of the displacement vectors at every time-step which can be computational and storage demanding. Mello et al. [17] applied a topology optimization approach to reduce the response time of electrothermomechanical MEMS. Zhang and Kang [18] studied dynamic topology optimization of piezoelectric structures with active control for reducing transient response, where the vibration level over a specified time interval is minimized. Yan et al. [13] presented an optimal topology design of damped vibrating plate structures subject to initial excitations for minimum dynamic performance index. Deng et al. [19] combined topology optimization and optimal control method to find the optimal match between the material topology and control.

In many cases, the maximum dynamic response, rather than the mean dynamic response or mean squared dynamic response, is desired to be minimized in engineering applications, so it is necessary to develop a topology optimization method for reducing the

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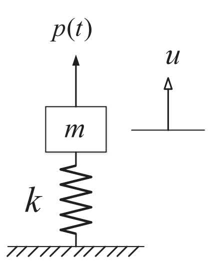
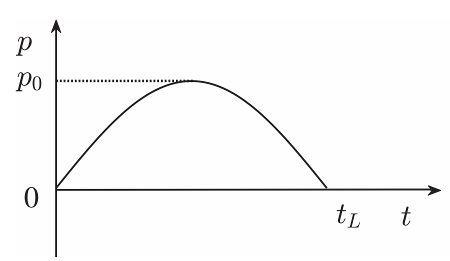
maximum dynamic response of structures. There are at least two difficulties in solving such problems. The first is that the maximum dynamic response may be non-differentiable with respect to the design variables and the time point where the maximum dynamic response occurs may vary significantly during the optimization process. Here an undamped SDOF system with at-rest initial conditions is used to demonstrate the possible non-differentiability of the maximum dynamic response with respect to the design variables. As shown in Fig. 1(a) and (b), a half-cycle sine pulse force is applied on the system. The response spectrum for the displacement of the system is shown in Fig. 1(c), where t_L is the duration of the load, T_n is the oscillation period of the system, $u_{st} = p_0/k$ is the displacement yielded by a static load of magnitude p_0, u_o is the maximum displacement response of the system over the complete time history. It is easy to find and prove that R_d is non-differentiable with respect to t_L/T_n when $t_L/T_n = 2.5$ or 4.5, and the details can be found in [20]. Conversely, if we want to reduce the overall maximum displacement response of the system under a given half-cycle sine pulse force, the loading time t_L will be fixed and the stiffness of the spring k could be chosen as a design variable. It is easy to figure out that u_o is non-differentiable with respect to k when $k = 16\pi^2 m/25t_L^2$ or $16\pi^2 m/81t_L^2$, since $u_o = R_d u_{st}$ and $T_n = 2\pi\sqrt{m/k}$.

The second difficulty is that the number of design variables is quite large for topology optimization problems, so usually the gradient-based optimization algorithms are used to update the design variables[21] and the adjoint variable method(AVM) is employed to perform sensitivity analysis, but AVM generally can only be applied to responses in an integral form[22]. In addition, when solving the maximum dynamic response topology optimization problems in the time domain, there are two issues to be considered. First, the response of a structure under a transient load will be divided into forced-vibration phase and free-vibration phase, so in order to minimize the maximum response over the complete time history, the integration time should be large enough to ensure that the maximum response has been captured, which may need a large number of integration time steps and result in large computational cost [12]; second, a large number of intermediate densities may appear in the obtained designs for some cases [5].

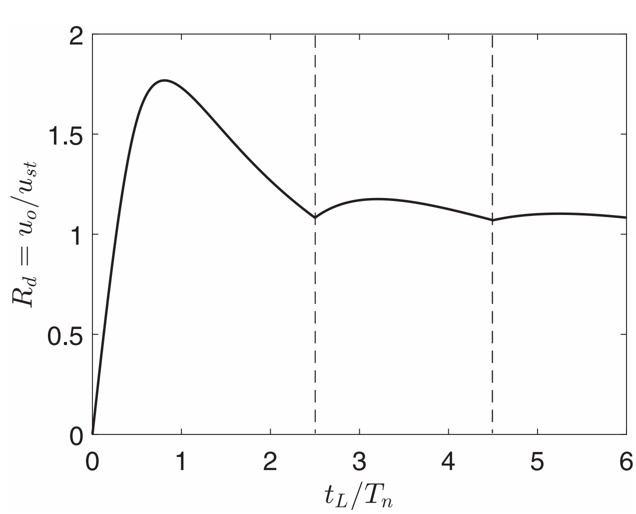
In this paper, an efficient approach to solving the dynamic response topology optimization problems in the time domain will be developed. The objective is to minimize the maximum response of the structure over the complete vibration phase. The density-based approach will be used to solve the topology optimization problems. In order to alleviate the difficulties due to the max operator in the objective function, an aggregation functional will be employed to transform the original problem formulation into one that is computational tractable. The traditional adjoint variable method will be used to perform sensitivity analysis and the method of moving asymptotes (MMA) will be used to update the design variables. The reason why the maximum dynamic response may occur in the free vibration phase for transient load will be uncovered and strategy to reduce the maximum dynamic response over the complete vibration phase will be discussed. The effectiveness of the proposed approach as well as the time-dependent characteristic of dynamic loads and inertia effect on the topology optimization results will be demonstrated by numerical examples.



(a) An undamped SDOF system



(b) Half-cycle sine pulse force



(c) Displacement response spectrum

Fig. 1. Non-differentiability of overall maximum displacement response.

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