Optimal design of impact based non-linear energy dissipation mechanism in pipeline systems

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Summary. Numerous techniques exist to control vibrations and dissipate energy in pipes that are supported by rack structures. Impacts are often used as a means of dissipating energy. In this research, we optimize two design parameters, gap and coefficient of restitution (COR), of a pipeline supported in a rack that is allowed to hit bumpers. For a given loading characteristic, indeed, the energy dissipation from such a non-linear system is dependent on the gap and the COR. The ratio of the total energy dissipated through impacts to the energy dissipated by material and structural damping of the pipe-rack is used as a measure of the energy dissipation efficiency. However, excessive number of impacts of the pipe against the bumper can damage or produce dents in the pipeline. The objective functions are therefore conflicting because it is to be ensured that the optimized system provides the least number of impacts while dissipating the maximum amount of energy. A kriging metamodel is used to interpolate the experimental points that are calculated for the values of gap and COR that are chosen after application of the central composite design (CCD). Finally, the Pareto front of the two response surfaces is calculated.

Introduction and problem statement

There are various mechanisms to dissipate energy and control the response of pipeline systems. The use of tuned mass damper is probably the most commonly adopted approach. In this work, impact is used as an energy dissipation mechanism. As an example, this kind of systems were previously used in the Trans-Alaskan pipeline systems which passes through major seismic faults [1]. During impact, a part of the input energy is dissipated in the form of heat, sound, plastic deformation of the material, etc. The COR is a measure of this dissipation.

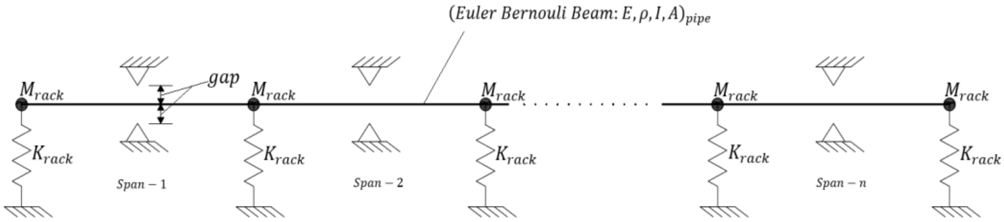

Figure 1: Analytical model of a pipe in a rack

In this study, a typical pipe-rack structure is analyzed and analytically modeled as shown in Figure 1. The pipe is allowed to hit bumpers placed at the center of each span. The energy dissipation in this case is dependent on two design variables, gap and COR.
Let $x \in \mathbb{R}^{n\,x\,1}$ and $\dot{x} \in \mathbb{R}^{n\,x\,1}$ be the displacement and velocity respectively of the pipe-rack system where n is the total number of degrees of freedom. For a given seismic excitation of duration t_d, a given gap and COR, the net energy dissipated by virtue of the internal structural damping (non-conservative) at time t_d is given by,

$$E_{damping}(t_d) = \sum_{t=0}^{t=t_d} dx_t{}^T . C . \dot{x}_{t_d}$$

where $C \in \mathbb{R}^{n\,x\,n}$ is the damping matrix of the system and $dx_t = x_t - x_{t-dt}$. The energy dissipated through impacts during this duration is given by,

$$E_{impact}(t_d) = \frac{1}{2}\sum_{i=1}^{N_d}\left(\dot{x}_{+_i}{}^T M \dot{x}_{+_i} - \dot{x}_{-_i}{}^T M \dot{x}_{-_i}\right)$$

where $\dot{x}_{+_i}$ and $\dot{x}_{-_i}$ is the velocity after and before the i^{th} impact, which are related by the COR. M is the mass matrix of the system and N_d is the number of impacts in time t_d. At time t_d, two objective functions are defined for the design of the energy dissipation mechanism, as follows:

i. Ratio of total energy dissipated through impact to the energy dissipated by the internal damping of the structure, given as,

$$O_1 = \frac{E_{impact}}{E_{damping}}$$

ii. The number of impacts required for dissipating unit amount of energy,

$$O_2 = \frac{N_d}{E_{impact}}$$

In this study it is aimed to dissipate the maximum energy through impacts. However, when the number of impacts increases, there are more chances for the pipeline to suffer damage or dents. Hence, it is also aimed to achieve a desired energy dissipation with a minimum number of impacts. Thus, for a given seismic input, the function O_1 is maximized, or equivalently, $-O_1$ is minimized, whereas O_2 is minimized.

Methodology and preliminary results

Non-linear time history analyses are used to evaluate the objective functions O_1 and O_2 for a given input motion characteristic, and for given values of gap and COR. A CCD[2] provides the number of experiments that have to be carried out and also the corresponding values of gap and COR. The response surfaces, as shown in Figure 2, are subsequently evaluated by a surrogate kriging model that spatially interpolates the experimental outputs.

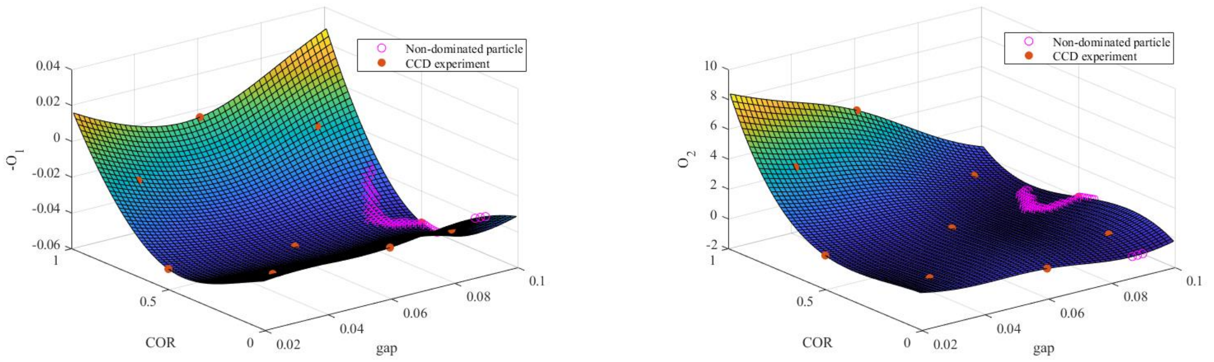

Figure 3: Response surfaces for (a) Objective function 1 and (b) Objective function 2

We finally find the Pareto front. The non-dominated particles, as shown in Figure 3, correspond to the solutions of this multi-objective optimization problem, for certain optimal values of gap and COR.

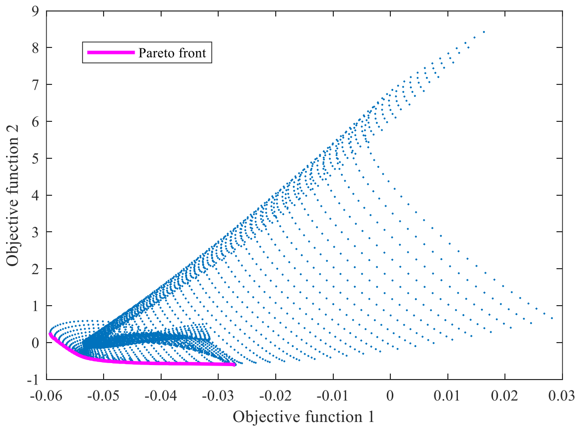

Figure 4: Representation of the Pareto frontier

References

[1] Douglas G. Honegger, Douglas J. Nyman, Elden R. Johnson, Lloyd S. Cluff, and Steve P. Sorensen. (2004) Trans-Alaska Pipeline System Performance in the 2002 Denali Fault, Alaska, Earthquake. Earthquake Spectra, 20(3), 707–738.

[2] Raymond H. Myers, Douglas C. Montgomery and Christine M. Anderson-Cook. Response Surface Methodology: Process and Product Optimization Using Designed Experiments, 4th Edition, ISBN: 978-1-118-91601-8, Wiley.