An Analytical Approach to Model-Based Parametric Design of Mechatronic Systems with Modelica: A Case Study

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Abstract Parametric study is a crucial step in the design process of a mechatronic system. In fact, it helps designers to describe the model parameters, the physical phenomena and to modify the design parameters to reach more satisfactory results in the predesign phase. The main idea of this paper is to develop a novel pre-designing approach to perform parametric studies concerning complex interactions among the different internal components of a system. In this paper, we are interested only in the vibration constraint between the different components embedded in a mechatronic system. To illustrate our approach, we used a specific case study: the vibration interaction between a dynamic excitation and a flexible beam as a support structure, having simply supported boundary conditions is investigated. The position of the perturbation source over the beam is parametrized and the feedback effect between components is taken into consideration. Our methodology is based on a pure analytical approach with Modelica/Dymola as an object oriented modeling language. This model can help designers to perform a parametric study and to examine the

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impact of the design variables on the mechatronic system response at an early stage of design. Object-oriented approach is used to produce a reusable component-based architecture.

Keywords Pre-designing · Parametric study · Mechatronic system · Modelica

1 Introduction

Mechatronic system is based on the close interaction of mechanical and electronic components. It exhibits both discrete and continuous dynamic behaviors, which can all be defined by systems of differential algebraic equations representing the exchange of signals, energy or other continuous entities between system devices (Zheng et al. 2016; Hammadi and Choley 2015; Hamza et al. 2015).

Mechatronic systems are facing several physical constraints like vibration and temperature, thus interaction phenomena between components becomes emergent at the system level.

Disturbance may cause several problems induced by vibration like as structural degradation and failure, malfunction of components, noise transmission, human discomfort and different other problems (Hamza et al. 2017). Therefore, it might be of important to decrease vibration from a certain part of the structure more than the other. Furthermore, the vibration existence in some structures which contain sensitive elements such as electronics cards may weaken their performance (Buchacz 2008; Veprik 2003).

A novel pre-dimensioning approach to investigate the vibrational aspects of a multibody system has been proposed in the previous works (Hamza et al. 2015b). In fact, the vibration interaction between electronic cards and motors has been studied. The location of these components is on a flexible continuous structure. Components positions over the support structure are parametrized. We assumed that motor creates perturbation over a well-defined rectangular area of the plate. To model the electronic card, a rigid mass mounted fixed on the plate is considered.

The influence of boundary conditions on the system's response is investigated in (Hamza et al. 2018b). In this research work, clamped–clamped (C-C) and simply supported–simply supported (S-S) configurations are investigated. to build a reusable component-based architecture, object-oriented approach is implemented. This methodology supports system designers to define concepts and solutions.

Beam type structures are often used in machinery industries and steel construction. Several engineering problems can be modelled as simple degree of freedom system (sdof)-beam copled system, like as the case of an engine or electric motor mounted elastically on a structure (a beam or a plate). The literature concerned is abundant (Tang et al. 2008; Wu and Chen 2000; Inceao and Gürgöze 2001). There are many approaches which are used in order to study this kind of problems such as the assumed mode methods, Laplace transform, Lagrange's multipliers, numerical and analytical combined method and even a pure analytical solution for simple cases. For example, Tang et al. (2008) studied the vibration transmission in a coupled system including of a sdof system and a beam using on the recurrence equation approach. The parametric analysis of this system was discussed in this work.

In this paper, new mechatronic system predesign methodology is presented. To achieve this, parametric models are developed in Modelica/Dymola. The organization of this paper is as follows. A short presentation of the analytical development of the problem is shown in Sect. 2. Section 3 describes the modeling of the system. Some results are presented in Sect. 4. The last section summarizes and concludes the paper.

2 Analytic Formulation of the Beam Vibration

This section presents the theory of determining the “steady” response amplitude of a beam carrying a concentrated element, considering the feedback effect based on an analytical method.

The system Fig. 1 consists of a spring–damper–mass system. Simply mounted on beam at position x = a.

The mass block is subjected to a harmonic excitation $Fe^{-j\omega t}$ is applied to the mass block, where *m*, *k* and *c* are the mass, stiffness and damping coefficient of the sdof system. The beam has a uniform structure with a constant rectangular cross-section (Tang et al. 2008).

The vibration equation governing the beam transverse motion is the following (Tang et al. 2008):

$$EJ\frac{\partial^4 w(x,t)}{\partial x^4} + \rho S\frac{\partial^2 w(x,t)}{\partial t^2} = Fe^{-j\omega t}\delta(x-a) \tag{1}$$

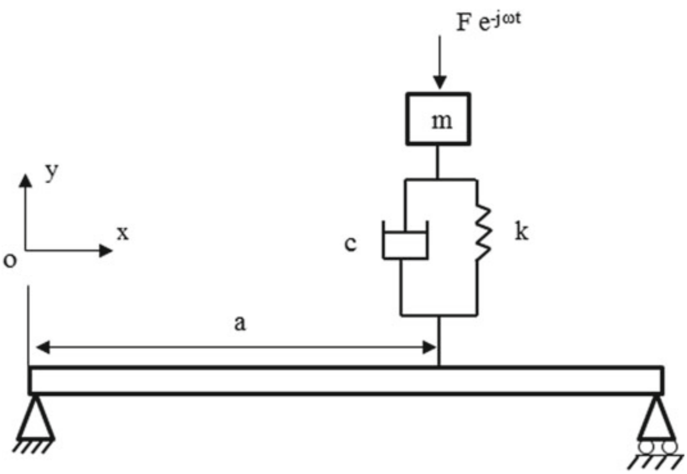

Fig. 1 Schematic representation of a coupled beam-sdof system

In this equation *E*, *S*, ρ and *J* are respectively, the Young's modulus, the beam cross-sectional area, the constant density of the beam material and the moment of inertia. *x* is the spatial coordinate *t* is the time and δ represents the Dirac–delta function.

$W(x, t)$ denotes the beam transverse deflection (displacement), *L* is the beam length. The Euler–Bernoulli beam model was assumed which the effects of rotary inertia and shear deformation are neglected.

The natural frequency of the beam without the sdof system is:

$$\omega_n = n^2\pi^2/L^2\sqrt{EJ/\rho S} \tag{2}$$

The beam boundary conditions are the following:

$$w(0, t) = w(L, t) = 0, \frac{\partial^2 w(0, t)}{\partial^2 x} = \frac{\partial^2 w(L, t)}{\partial^2 x} = 0 \tag{3}$$

Assuming,

$$w(x, t) = w(x)e^{-j\omega t} \tag{4}$$

The analytical solution of transverse amplitude for a simply supported beam carrying a sdof system, in the steady–state situation, is (Tang et al. 2008):

$$w(x) = \frac{FH/(1 - GD)}{c^2\omega^2 + (k - m\omega^2)^2} \frac{-2}{\rho SL} \sum_{n=1}^{\infty} \frac{\sin(n\pi a/L)\sin(n\pi x/L)}{\omega^2 - \omega_n^2} \tag{5}$$

where,

$$D = \frac{1}{c^2\omega^2 + \left(k - m\omega^2\right)^2} \frac{-2}{\rho AL} \sum_{n=1}^{\infty} \frac{\sin^2(n\pi a/L)}{\omega^2 - \omega_n^2} \tag{6}$$

$$G = k^2 m\omega^2 + c^2 m\omega^4 - km^2\omega^4 + jcm^2\omega^5 \tag{7}$$

and,

$$H = k^2 + c^2\omega^2 - km\omega^2 + jcm\omega^3 \tag{8}$$

3 Modelica System Modeling

Modelica as an object oriented free language has been considered to implement the analytical models developed above. The system is composed of a set of particular connected entities Fig. 2. We have developed in Modelica a new component called "*flexible beam*". The component has been implemented with a connector which is of *Flange* type; makes the element compatible with components, belong to the Modelica translational library (Modelica library to model one dimensional mechanical system).

The perturbation source is represented by a sdof system linked to the beam. to model the excitation source, Modelica Components library are used (the linear 1D model composed of a damper and spring in parallel and a sliding mass). The mass is subjected to a harmonic force. A sensor is used to measure the motion of the mass with respect the beam structure.

The position of the dynamic exciter over the beam is parametrized. Thus, the user can select the location as well as the model characteristics (mass of the sliding mass, dumping coefficient and spring constant).

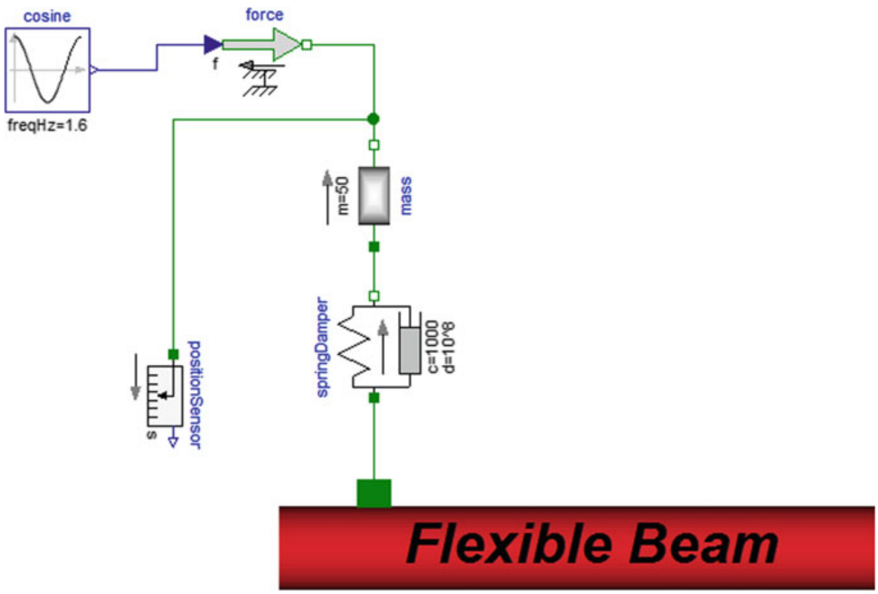

Fig. 2 Model of the system developed in Modelica/Dymola

4 Results and Discussion

After the multibody system modeling in Modelica, an analysis has been performed. The system design parameters have been listed in Table 1. Some simulation tests were carried out.

Figure 3 displays the displacements for two different points are plotted against time t where as the perturbation source is located at the mid span of the support

Table 1 Simulation parameters

Parameters	Value
Beam length	l = 5 m
Density of the beam material	$\rho = 7850$ kg/m^3
Young's modulus	E = 2,10,000 MPa
Force amplitude	F = 10^6 N
Damping coefficient	$c = 10^3$ N s/m
Stiffness coefficient	$k = 10^8$ N/m
Applied excitation frequency	$\omega = 10$ rad/s

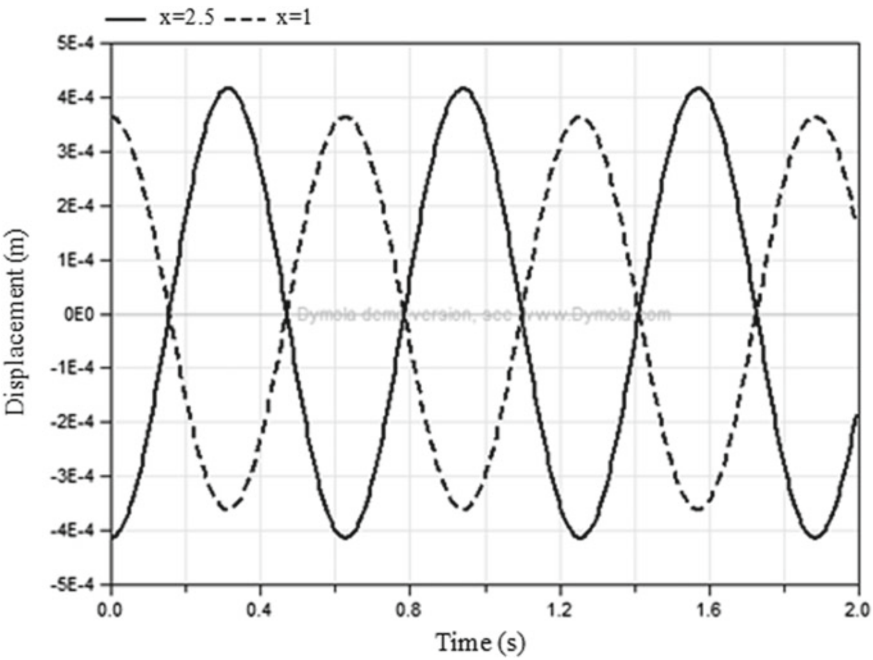

Fig. 3 Response of the simply supported beam under the excitation source

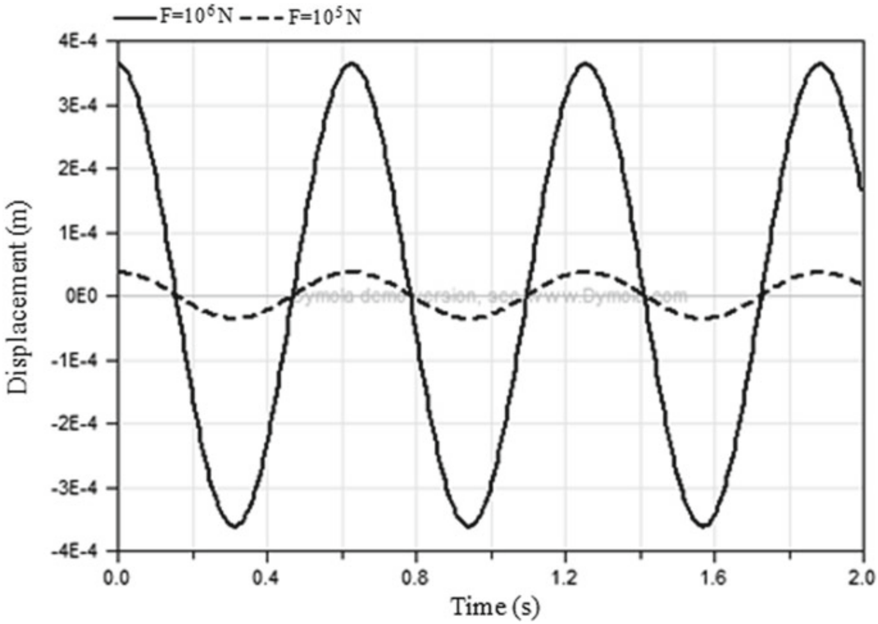

Fig. 4 Response of the simply supported beam for diverse values of the load amplitude

structure. It can be noted that the motion is depending on the point position. The two curves have the same oscillation frequency which corresponds to the excitation of the external force.

Figure 4 shows the motion in the mid span of the beam for diverse amplitudes values of the external load. It can be depicted that the motion amplitude increases with the growth of the load amplitude.

5 Conclusion

We have presented in this paper, a new pre-designing method to model-based parametric design of mechatronic system. Our study is based on the object oriented modeling language Modelica/Dymola to establish models. A case study is considered in our investigation. In fact, the vibration interaction between a dynamic excitation and a beam as a support structure is studied, where the excitation source position is parametrized. The preliminary results presented in this paper are quite encouraging. In fact, the aptitude to modify the parameters and to evaluate the possible missions represents a strong positive point for this new approach. This method requires less time and resources and permits for greater repeatability.

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