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Modelling of structures with developing discontinuity

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ABSTRACT

Discontinuity is one of the most important factors which contribute to the nonlinearity, challenging both methods of nonlinear analysis and its application for the analysis of interacting mechanical processes. The problem becomes more complicated when the discontinuity is developing under the influence of dynamic processes in the structures. This paper presents the methodology for analysis and simulation of the systems with the developing discontinuity based on the combination of analytical technique and the Matlab–Simulink computation. As an example, model of a cracked bar subjected to longitudinal excitation is used to analyse a nonlinear response as a way to monitor structural health. Different strategies of monitoring are compared based on the tracking the qualitative transformation of the bar's vibration.

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1. Introduction

The presence of developing discontinuity in the structure affects its dynamic behaviour under working conditions. The developing discontinuities can be observed in various mechanical processes such as slackening of joints, machining process and emergence of crack or delamination of material. The emergence of propagating crack has the significant effect on the dynamic characteristics of the structure which can ultimately lead to failure of structure causing significant loss in terms of life and money. Hence there is a need to develop a proper understanding of monitoring of structures with developing discontinuities, i.e. propagating crack in structure. Few researchers have tried to address the issue of crack as static and developing discontinuity on the dynamics of the structure. In [1], to simulate the effect of the behaviour of fully open and fully closed crack, it was modelled as a rotational spring between two un-cracked beam segments and a beam finite element was used to model the uncracked portion of beam. The element stiffness matrix was obtained by integrating the stress intensity factor and the finite element model was developed [2]. In that, it was found that eigen frequencies obtained for the different crack length and location in finite element simulation were in well agreement with the experimental results. The higher order frequency response function defined from the Volterra series representation were used to study the effect of nonlinearity due to closing crack on the dynamics of the system [3]. In this, it was assumed that there is instantaneous change in crack behaviour from fully open to fully closed state which gave rise to bilinear stiffness nonlinearity. Their analysis showed that higher order FRFs are highly dependent upon the size and the position of crack and thus can be used for the damage assessment of cracked beam. In [4], the concepts of model updating that are recast to include an evolutionary modal model to deal with the non-stationarity of the dynamic response arising from the nonlinearity of opening and closing of crack were considered. It was found that to assess the crack type and severity, evolutionary stiffness of damaged elements and their variations and global excursions can be used. The behaviour of cracked cantilever beam under

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harmonic loading was studied using two dimensional finite element analyses in [5]. In this study, they showed that frequency did not change with oscillation amplitude, but the steady state response obtained was rich in multiple sub-harmonic and super harmonic components. They also found that in super-harmonic resonance, due to the impacts between cracks faces there were significant wiggles in phase portraits. In [6] effect of crack closure was studied on the dynamic behaviour of cracked cantilever beam. It was found that there was decrease in eigen frequency with increase in crack length at much slower rate than in case of an open crack. The bilinear character of the crack, i.e., opening and closing of the crack results in the generation of higher harmonics of forcing frequency revealing the nonlinear behaviour of the cracked beam under consideration as found in [7,8]. A bilinear equation of motion for each mode of vibration of a simply supported beam was formulated using the Galerkin procedure in [9]. The results indicated the presence of nonlinearity in the time history and frequency spectrum for each mode of vibration. It was concluded that changes in dynamic behaviour of structure could be used to deduce the size and location of the crack. In [10], it was considered that the crack in the cantilever beam splits the beam in to two uncracked portions/subsystems. These two subsystems in the cantilever beam were considered as two Timoshenko beams, one with clamped-free boundary condition and other with free-free boundary condition. These two subsystems were related to one another by time varying connection matrices representing the interaction forces. It was found that results obtained were in good agreement with the previous studies by other researchers. A single degree of freedom bilinear spring mass system was used to model cracked beam revealing the nonlinear effects in the Fourier spectra of displacement [11]. Similarly in [12], a piecewise linear system of cracked bar was modelled using perturbation method to obtain nonlinear vibration associated with periodic motion. In this, they found that the bilinear frequency formula is a good approximation for the effective natural frequency of cracked beam. In [13], equation of motion and boundary condition were developed by considering the cracked bar as one dimensional continuum based on Hu-Washizu–Barr formulation [14]. They found that breathing cracks result in a smaller drop in the dominant system frequency as compared to the natural frequencies of linear system with open cracks. A closed form solution based on 2-square function was extended to study the dynamics of cracked structures to model the bilinear behaviour of crack due to the cracks faces interaction i.e. opening and closing of crack under low frequency excitation [15]. They showed that the proposed solution may be used to predict efficiently the spectrum patterns of damaged structures. The cracked beam was modelled as an oscillator with a bilinear restoring force to study the effect of crack closure on the dynamics of beam [16]. Bispectral analysis was performed on the obtained response, which showed high sensitivity to the nonlinear behaviour of the system compared to other techniques. In [17], dynamic response of the cracked beam vibrating at its first mode was analysed in both time and frequency domain. They found that the side peaks appeared in the frequency response function near the resonance peak due to the fatigue crack. They also observed anti-resonance frequency shifts and super/sub-harmonic vibration phenomena in the experimental study of naturally grown fatigue cracks. Similarly in [18], it was found that influence of elastic nonlinearity of crack on the bending vibration encountered in a cracked aircraft wing under external harmonic excitation results in the generation of super harmonic vibrating regimes. Harmonic balance method and numerical integration were used to solve nonlinear systems of algebraic equations of the cracked cantilever beam with several breathing cracks to study the vibration response [19]. They found that nonlinear dynamic behaviour gives rise to the super-harmonics in the spectrum response signal. In [20] bending vibration of beam with a closing crack was modelled and distribution functions of vibration characteristics of damage based on the estimation of nonlinear distortions of the displacement, acceleration, and strain waves for the first three mode shapes were evaluated. They found that the closing crack essentially caused nonlinearity of these distribution functions which might serve as a diagnostic indication of damage. Hilbert transform and empirical mode decomposition was used to study the free and forced vibration response of beam with a breathing crack [21,22]. In free vibration analysis, it was revealed that instantaneous frequency allowed an efficient and accurate description of nonlinearities of the system which can be effective in vibration based diagnostics of cracked structures. In forced vibration analysis, it was observed that instantaneous frequency oscillates between frequencies corresponding to an open and closed state of the crack. They also found that harmonic distortion increased with crack depth following definite trends that could be used as an effective indicator of crack size. The general perturbation approach was used to evaluate frequency sensitivity for any beam like structure of undamaged system [23]. They found that frequency sensitivity was proportional to the potential energy stored, for the relevant mode shape, at the cross section where the crack occurs. They also found that the ratios of the frequency changes of various orders are independent of severity of crack which can be useful in localisation of damage. In [24] an integrated technique was used to non-destructively identify two discrete cracks in a simply supported beam based on vibration theory. They investigated the two different types of model for crack induced damage. In first model they used the massless infinitesimal spring to represent discrete cracks and in second model they used continuum damage concept. Their findings suggested that the continuum damage model can be used first to identify the discrete elements of a structure that contains cracks. Then the spring model can be used to quantify the location and severity of discrete crack in each damage element.

The influence of discontinuities in composite rods and beam on Lamb wave propagation was analysed [25]. It was found that change in propagating wave depends on the type of discontinuity. In [26], wave propagation problems in multi-rod systems with nonlinearly behaving rod-rod interfaces has been investigated and evaluated. Comparative study between the finite element and eigen function solutions of the stress wave propagation problem in axially moving and interacting rod systems revealed that the finite element and eigen function modelling is an efficient and accurate method in solving stress wave propagation problems in an axially moving multi-body system. Nonlinear Non-Destructive Evaluation (NDE) was proposed to detect small fractured defects invisible by linear NDE techniques in [27]. It was found that contact vibrations led to threshold nonlinear distortion due to the “clapping” and “kissing” (grazing) mechanism of crack faces interactions. Vibro-impact interactions of these types in structures with discontinuities were described earlier in [28].

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