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Crack modeling of rotating blades with cracked hexahedral finite element method

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ABSTRACT

Dynamic analysis is the basis in investigating vibration features of cracked blades, where the features can be applied to monitor health state of blades, detect cracks in an early stage and prevent failures. This work presents a cracked hexahedral finite element method for dynamic analysis of cracked blades, with the purpose of addressing the contradiction between accuracy and efficiency in crack modeling of blades in rotor system. The cracked hexahedral element is first derived with strain energy release rate method, where correction of stress intensity factors of crack front and formulation of load distribution of crack surface are carried out to improve the modeling accuracy. To consider nonlinear characteristics of time-varying opening and closure effects caused by alternating loads, breathing function is proposed for the cracked hexahedral element. Second, finite element method with contact element is analyzed and used for comparison. Finally, validation of the cracked hexahedral element is carried out in terms of breathing effects of cracked blades and natural frequency in different crack depths. Good consistency is acquired between the results with developed cracked hexahedral element and contact element, while the computation time is significantly reduced in the previous one. Therefore, the developed cracked hexahedral element achieves good accuracy and high efficiency in crack modeling of rotating blades.

1. Introduction

Crack failures continually occur in blades of rotor system, which cause severe loss and influence safety and reliability of rotating machinery [1–3]. To prevent the crack failures, dynamic analysis is more and more concerned in terms of modeling the cracked blades, analyzing the vibration features, establishing the effective features for condition monitoring of the rotor system, and detecting cracks in an early stage [4–10], where crack modeling is the basis for the dynamic analysis of the rotor system. Several crack modeling approaches are analyzed including the stress energy release rate (SERR) method and the finite element method (FEM).

The beam model is usually applied in the crack modeling of blades with stress energy release rate method, where the crack is introduced with stiffness reduction by calculating the additional flexibility [11–14]. The spring element is a simplified approach in modeling the crack with Euler–Bernoulli beam [15]. With stress energy release rate method, the strain energy near the crack front is included and the additional flexibility is computed. However, the profile of the blade is

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complex, and the crack modeling with the beam is difficult to get the accurate vibration features of the cracked blade. Therefore, finite element method is applied to model the crack blades in rotor system. Timoshenko beam is initially used with four degrees of freedom, where the influences of shear deformation and rotating inertia are compared [16–18]. To form more accurate model of cracked structures, hexahedral element with an open crack is presented, where influence of crack on element stiffness matrix is considered [19]. However, six degrees of freedom are constrained and symmetrical assumption is further applied. Therefore, only five dependent stiffness items are acquired. Also, the average load is assumed and applied in calculating the stress intensity factors, where influences of nodal loads in different nodes are not considered. These assumptions sacrifice its accuracy and validation of the element is not carried out. These studies apply the finite element method to model the cracked blade. However, reduced degrees of freedom result in low accuracy.

Recently, finite element method with contact element is more and more applied in modeling cracked blades with nonlinear crack model. The contact element method is suitable in modeling the crack structures to analyze dynamics of rotor system, where its accuracy is validated by comparing with the stress energy release rate method in cracked rotors [20]. Cracked beam is modeled with contact element, where breathing effects of opening and closure of crack area caused by alternating loads are considered and frequency characteristics are analyzed [21]. Crack beam model with full frictional contact effect is further formed to consider the breathing effects of the crack area [22]. The previous studies are more focused on the beam model with crack. Crack modeling of blades with practical profile in three dimensions is also analyzed. The coupled model with cracked blade and disk is established to analyze the nonlinear effects of the cracked blade [23,24]. Compared with the stress energy release rate method and finite element method with reduced degrees of freedom, the finite element method with contact element improves the modeling accuracy as it can form the detailed cracked model according to the profile of the blade and the crack front. Its disadvantage is that the contact element introduces high nonlinearity including constraint equations and additional load vectors in crack area. This makes the dynamic equations highly nonlinear and time-variant. Therefore, the computation scale is greatly increased and the solving efficiency is significantly deceased.

Therefore, the crack modeling approaches in state of art have the contradiction between accuracy and efficiency. The strain energy release rate method and the finite element method with reduced degrees of freedom are more efficient than the finite element method with contact element, but they cannot get the accurate cracked blade model with complex profile. The finite element method with contact element is more accurate in modeling cracked blade with complex profile, but its efficiency is low. To balance the accuracy and the efficiency, developing a cracked element in modeling the cracked blade is necessary.

This work carried out an improved cracked hexahedral finite element method to model cracked blade and other cracked structures. The hexahedral element is selected to form the cracked blade model as it can adjust the complex profile of structures. Strain energy release rate method is applied in deriving the stiffness matrix of the cracked element, where two improvements are implemented including correction of stress intensity factors and formulation of load distribution of crack

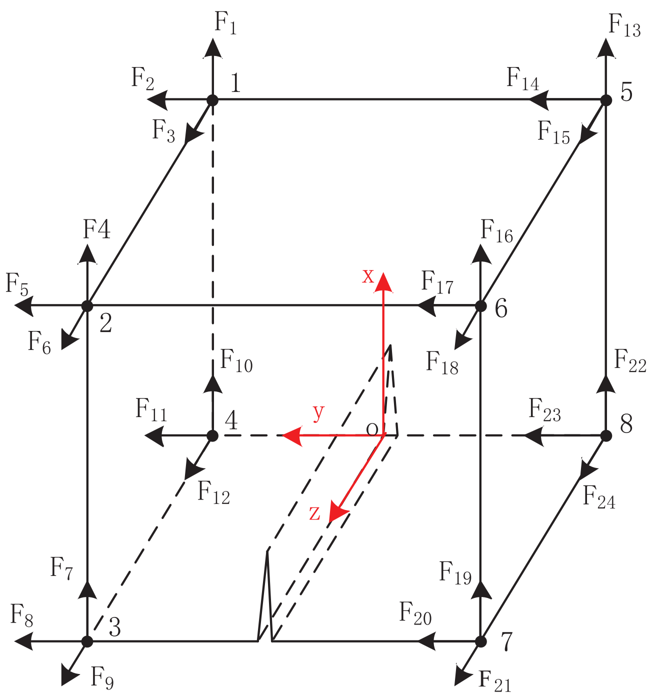

Fig. 1. Hexahedral element with crack.