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Crane hook stress analysis upon boundary interpolated reproducing kernel particle method

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ABSTRACT

The mechanical property of a crane hook is analyzed by using the boundary interpolated reproducing kernel particle method (BIRKPM). It is deduced by combining the interpolated reproducing kernel particle (IRKP) method with the boundary integral equation (BIE) method which aims to solve elastic mechanics plane stress. In the BIRKPM, the shape function constructed by the IRKP method possesses interpolation character at any scatter node. Because of this property, the boundary conditions can be applied directly for the BIRKPM and the new method has high precision and less computing time. When using this method to analyze a laminated crane hook, the results could agree well with the results concluded from the finite element method, and this could prove the validity of the new method.
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1. Introduction

The laminated hook is an important part for a crane to bear lifting load. Casting crane usually lifts a steel ladle by two laminated hooks. The stress analysis for a hook is important in engineering. Because of the hook's irregular shape, the analytical solution is difficult to obtain, thus an alternative way is proposed, that is the new numerical method.

The meshfree methods have been developed very well in recent years [1]. These meshless methods have been used to solve various problems as the dynamic stability analysis of carbon nanotube-reinforced functionally graded cylindrical panels [2], the buckling analysis of functionally graded carbon nanotube-reinforced composite thick skew plates [3], and the vibration solution of functionally graded carbon nanotube-reinforced composite thick plates resting on elastic foundations and so on [4–9].

The shape function in the most of meshfree methods is formed with moving least-squares approximation or its improved forms at nodes [10–12]. Some of meshfree methods have employed the reproducing kernel particle method and others to form the shape functions at nodes or particles [13–15]. The core of these methods is how to distribute a set of scattered nodes in the solving domain instead of a set of elements or meshes used in the finite element method, but all of these methods have the same weakness: the more nodes, the more calculation amounts. Recently, a complex variable meshfree method has been established by Cheng Yumin, and this method has been applied in various mechanical problems [16–33], and the calculation amounts of this algorithm have been declined greatly. Actually, the meshfree method of local boundary integral equation is also a full domain type algorithm [34]. While its calculation amounts is great, it can get rid of the dependence on the meshes completely [35–39]. Worth mentioning, the interpolation type of meshfree method has the advantage that the displacement boundary conditions can be applied directly such as the finite element method, as a result it saves multifarious workload when dealing with the boundary conditions [40–48]. In particular, the meshfree method of the boundary integral equation (BIE) has currently turned into the important branch of the meshfree methods. Because it just configures nodes on the boundary of analysis object, the calculation amounts of the shape functions at nodes and the number of the formed basis unknown equations can be reduced significantly [49–61]. The advantage of these boundary meshfree algorithms is the equation group has less unknown quantities, so it can save solving time.

In order to retain the interpolation attribute of interpolated reproducing kernel particle (IRKP) method and the dimensionality of a BIE method, this paper proposes a combination of the former and latter methods [62–64]. This new boundary meshfree method, called the boundary interpolated reproducing kernel particle method (BIRKPM), has the advantages such as semi-analytical, reducing dimension and great precision besides the advantage of the meshfree method, and all of these advantages can avoid the

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failure of solving ill-conditioned equations and the difficulty of dealing with boundary conditions, which are shortcomings of more meshfree methods when the shape functions at nodes are constructed by moving least-squares method [65]. The new method is applied in the stress analysis of a large crane hook and compared with the results of the finite element analysis, and the effectiveness of the proposed method can be verified.

In this paper, Section 2 gives the BIRKPM firstly, it is formed by coupling the boundary integral equation method for two-dimensional elastic mechanics problems and the interpolated reproducing kernel particle method. Then in Section 3, the stress analysis for a crane hook with the complex boundary shape is done based on a BIRKP method, and the analysis results respectively formed by this BIRKPM and FEM are compared. Section 4 contains some conclusions.

2. BIRKPM for plane stress problems

2.1. The shape function of interpolated reproducing kernel particle method

When the number of nodes contained by compact support domain is more than the number of monomial basis functions, the node shape functions of the original reproducing kernel particle method (RKPM) can not get the true value of a polynomial by interpolation. If strengthening the shape functions of the RKPM, the new shape functions of interpolated RKPM obtains the interpolation features.

In the IRKPM approximation, assuming that the trial function $u(\mathbf{x})$ is

$$u^a(\mathbf{x}) = \sum_{I=1}^{NP} \Psi_I(\mathbf{x}) u_I, \tag{1}$$

where a is the measurement of compact support domain size, NP is the total number of particles, $u_I = u(\mathbf{x}_I)$,$\Psi_I(\mathbf{x})$ is the shape function of the IRKPM, and

$$\Psi_I(\mathbf{x}) = \hat{\Psi}_I(\mathbf{x}) + \overline{\Psi}_I(\mathbf{x}), \tag{2}$$

there $\overline{\Psi}_I(\mathbf{x})$ is an enhancement function satisfied with the reproducing conditions of RKPM, $\hat{\Psi}_I(\mathbf{x})$ is the simple function with Kronecker Delta feature. $\hat{\Psi}_I(\mathbf{x})$ can be written as the following simple form

$$\hat{\Psi}_I(\mathbf{x}) = \frac{\hat{\Phi}_{\hat{a}_I}(\mathbf{x}-\mathbf{x}_I)}{\hat{\Phi}_{\hat{a}_I}(\mathbf{0})}, \quad \hat{a}_I < \min\{\|\mathbf{x}_I - \mathbf{x}_J\| \ \ \forall J \neq I\}, \tag{3}$$

and $\overline{\Psi}_I(\mathbf{x})$ is generated by n steps reconstruction conditions of the shape function $\Psi_I(\mathbf{x})$, as follows

$$\sum_{I=1}^{NP} \left[\hat{\Psi}_I(\mathbf{x}) + \overline{\Psi}_I(\mathbf{x})\right] x_I^{\alpha} = x^{\alpha}, \quad |\alpha| \le n. \tag{4}$$

The enhancement function is obtained by reconstruction condition Eq. (4), as

$$\overline{\Psi}_I(\mathbf{x}) = \mathbf{H}^T(\mathbf{x}-\mathbf{x}_I)\mathbf{Q}^{-1}(\mathbf{x})[\mathbf{H}(\mathbf{0}) - \hat{\mathbf{H}}(\mathbf{x})]\overline{\Phi}_{\overline{a}_I}(\mathbf{x}-\mathbf{x}_I), \tag{5}$$

there

$$\mathbf{H}(\mathbf{x}-\mathbf{x}_I) = [1 \ \ \mathbf{x}-\mathbf{x}_I \ \ (\mathbf{x}-\mathbf{x}_I)^2 \ \ \ldots \ \ (\mathbf{x}-\mathbf{x}_I)^n]^T, \tag{6}$$

$$\hat{\mathbf{H}}(\mathbf{x}) = \sum_{I=1}^{NP} \mathbf{H}(\mathbf{x}-\mathbf{x}_I)\hat{\Psi}_I(\mathbf{x}), \tag{7}$$

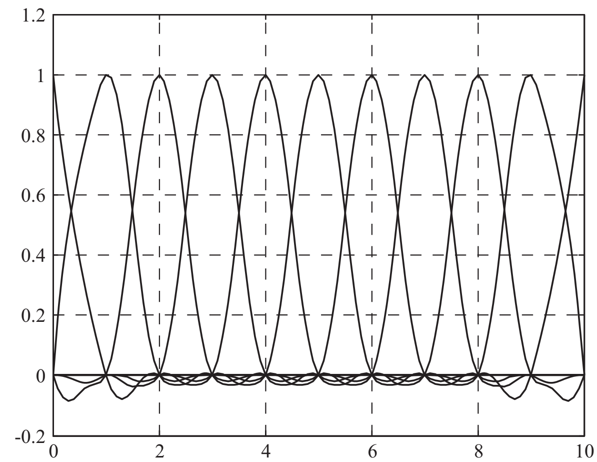

Fig. 1. The IRKPM shape function of every node.

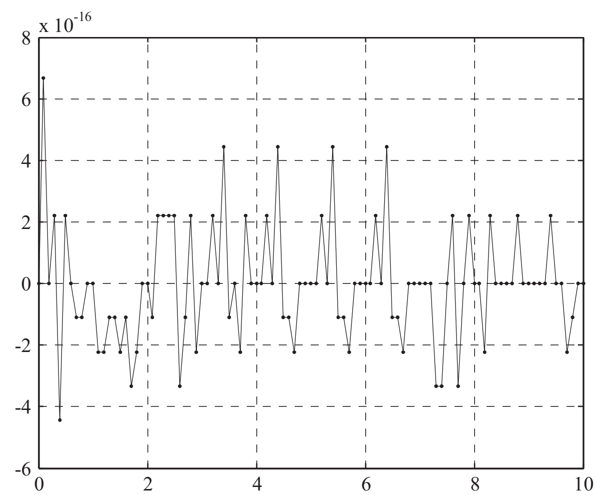

Fig. 2. The calculated value distribution of $\sum_I \Psi_I(\mathbf{x}) - 1$.

$$\mathbf{Q}(\mathbf{x}) = \sum_{I=1}^{NP} \mathbf{H}(\mathbf{x}-\mathbf{x}_I)\mathbf{H}^T(\mathbf{x}-\mathbf{x}_I)\overline{\Phi}_{\overline{a}_I}(\mathbf{x}-\mathbf{x}_I), \tag{8}$$

it is thus clear that $\mathbf{Q}(\mathbf{x})$ is nonsingular.

The one-dimensional IRKPM interpolation shape function with $x \in [0, 10]$ which has the interval of $\Delta x = 1$ and distributes evenly eleven nodes or particles is constructed, as $\overline{\Phi}_{\overline{a}_I}(\mathbf{x}-\mathbf{x}_I) = \Phi(\mathbf{x}-\mathbf{x}_I;\ \overline{a}_I)$ and $\hat{\Phi}_{\hat{a}_I}(\mathbf{x}-\mathbf{x}_I) = \Phi(\mathbf{x}-\mathbf{x}_I;\ \hat{a}_I)$ are selected as the kernel functions, and as $n = 2$, $\hat{c} = 1$, $a = \overline{a}_I = 3\Delta x$ and $\hat{a}_I = 0.8\Delta x$, and the weight function gets exponential function

$$\Phi(\boldsymbol{x}-\boldsymbol{x}_I;\ a) = \begin{cases} \dfrac{e^{-(a_I/\hat{c})^2} - e^{-(a/\hat{c})^2}}{1 - e^{-(a/\hat{c})^2}} & \tilde{a} \le 1 \\ 0 & \tilde{a} > 1 \end{cases}, \tag{9}$$

where $\hat{c}$ is a constant, $a_I = |\boldsymbol{x}-\boldsymbol{x}_I|$, $\tilde{a} = a_I/a$, the IRKPM interpolation shape function $\Psi_I(\mathbf{x})$ is shown in Fig. 1 as the weight function covers four nodes.

And the calculated value distribution of "$\sum_I \Psi_I(\mathbf{x}) - 1$" is shown in Fig. 2. The non-zero value is the calculation error in Fig. 2, $\sum_I \Psi_I(\mathbf{x})$ is 1 in theory.

When the weight function covers a series of nonuniform scatter particles, the interpolation shape function at arbitrary particle is constructed by IRKPM as well, as shown in Fig. 3.

In Fig. 3, the node shape function constructed by IRKPM is complexity, but its smoothness is no lower than that of the weight

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