ANALYSIS OF CRANKSHAFT MECHANISM OF AGRICULTURAL ENGINE UNDER THE APPLICATION OF COMPOUND SUPERCHARGING TECHNOLOGY
/
复合增压技术应用下的农用发动机曲轴机构分析

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DOI: https://doi.org/10.35633/inmateh-63-38

Keywords: *crankshaft mechanism, optimization, agriculture, tractor engine*

ABSTRACT

With the development of engine supercharging technology and the application of in-cylinder direct injection technology, engines with high power and torque have become a trend. Crankshaft, as one of the most important and expensive parts in tractor engine, plays the role of transforming linear motion into circular rotation. The damage and destruction of crankshaft will lead to the damage of other parts of the engine, which makes the engine unable to work normally, and its stability affects the reliability of the whole engine to a great extent. The main failure form of tractor engine crankshaft is bending fatigue failure, so alternating bending stress occurs in crankshaft, which may cause fatigue failure of crankshaft. Crankshaft is one of the important components of tractor engine, and its stress is complex, which is the key and difficult point of engine design. In this paper, the crankshaft of tractor engine is analysed and studied based on compound supercharging technology, so that the dynamic characteristics of the engine are deeply understood, the action law of dynamic working load is mastered, the response analysis and evaluation of the system are carried out, and the optimization method of crankshaft mechanism of agricultural tractor engine is found out.

摘要

随着发动机增压技术的发展和直喷技术的应用，大功率大扭矩发动机已成为一种发展趋势。曲轴作为拖拉机发动机中最重要、最昂贵的零件之一，起着将直线运动转化为圆周运动的作用。曲轴的损坏和破坏会导致发动机其他部件的损坏，使发动机不能正常工作，其稳定性在很大程度上影响到整个发动机的可靠性。拖拉机发动机曲轴的主要失效形式是弯曲疲劳失效，曲轴产生交变弯曲应力，可能导致曲轴疲劳失效。曲轴是拖拉机发动机的重要部件之一，其受力复杂，是发动机设计的重点和难点。本文以复合增压技术为基础，对拖拉机发动机曲轴进行了分析和研究，以便深入了解发动机的动态特性，掌握动态工作载荷的规律，分析和评价系统的响应，并找出了农用拖拉机发动机曲轴机构的优化方法。

INTRODUCTION

Crankshaft is one of the important components of engine, and its stress is more complex, which is the key and difficult point of engine design. Traditional design methods can't meet the actual needs, and the bearing capacity of crankshaft can be accurately analysed by using 3D solid modeling software and finite element software *(Wei W. et al., 2021)*. The research on structural strength of engine is first carried out on large heavy-duty diesel engine, because this kind of diesel engine usually not only bears large load, but also has small batch size, long manufacturing cycle and high cost *(Deng D.W. et al., 2019)*. Among all parts of tractor engine, the core position of crankshaft is self-evident. Its performance directly affects the reliability and life of the engine. The evaluation of crankshaft also represents the evaluation of the whole engine. Crankshaft is one of the most important parts of the engine. It has the characteristics of complex structure, rapid structural change and extremely complex working conditions. It bears the alternating stress of torsion and bending under the periodically changing gas force. In the process of engine operation, the explosion pressure and inertia load of gas are transmitted, and then the torque is transmitted to the flywheel end, which is the output power of the engine *(Chen Y.M. et al., 2021)*. The main failure mode of tractor engine crankshaft is bending fatigue failure, so alternating bending stress in crankshaft may lead to fatigue failure of crankshaft, and other parts may be damaged once crankshaft fails.

In the working process of tractor crankshaft, it bears complex loads, including reciprocating mass inertia force, rotating mass inertia force, inertia force caused by dead weight and counterweight *(Shu P.P., 2019)*. Furthermore, due to the periodicity of the internal combustion engine, the magnitude and direction of these loads on the crankshaft will change periodically *(Yu L.C. et al., 2021)*. In the past, generally speaking, for the large-scale production of small and medium-sized internal combustion engines, the degree of strengthening was not high, and the design could be based on experience. However, with the continuous development of small and medium-sized internal combustion engines to high speed and high power, this situation has undergone major changes *(Qiuju X. et al., 2021)*. With the development of engine supercharging technology and the application of in-cylinder direct injection technology, engines with high power and high torque have become a trend. With the continuous increase of the maximum explosion pressure in the cylinder, the reliability requirements of the engine are continuously improved, the working conditions of the crankshaft are worse, and the strength requirements of the crankshaft are also higher *(Jhih Y.C. et al., 2021)*. Modal analysis is used to determine the vibration characteristics of design mechanism or mechanical components, that is, the natural frequency and mode shape of structure, which are important parameters in structural design under dynamic load. If improving its dynamic characteristics is an important goal of dynamic design and structural optimization, engine design can be changed from experience, analogy and static design method to dynamic and optimal design method, thus improving the design level of products.

Crankshaft is the key component of diesel engine. The quality characteristics of crankshaft directly affect the service life, safety and reliability of diesel engine. Strength analysis and finite element analysis of crankshaft have become an indispensable link in new product development and design *(Dong J.H. et al., 2018)*. Therefore, the multi-body dynamics analysis of diesel engine has certain guiding significance for the development and design of new products. The problems are always complicated for medium and small supercharged engines with high heat load and mechanical load *(Liu Y.W. et al., 2020)*. As in the past, it is impossible to study the crankshaft directly through the comprehensive test of prototype. The results of finite element static analysis and dynamic analysis can truly and effectively obtain the stress distribution of crankshaft under all dangerous working conditions. Through this result, the danger can be predicted, which can reveal the mechanism and provide basic data for optimizing the crankshaft strength *(Meng R.G. et al., 2018)*. It is of great significance to study the dynamic performance of crankshaft and master the vibration law and load change law of crankshaft in the working process for improving the reliability and service life of the crankshaft. Through the analysis and research of crankshaft, we can deeply understand the dynamic characteristics of tractor engine, master the law of dynamic workload, analyse and evaluate the response of the system, and find out the problems in dynamic performance.

In the aspect of crankshaft research, *Yuan Z.Y. et al.* used simulation technology to analyse the static strength of crankshaft *(Yuan Z Y et al., 2019)*. *Peng F. et al.* carried out finite element analysis on fatigue strength of 368Q engine crankshaft *(Peng F., 2020)*. *Cai Y.Q. et al.* used the experimental method to study the crankshaft modal of small diesel engine *(Cai Y.Q. et al., 2018)*. *Liu Z.T.* used finite element analysis technology to analyse the strength of X6135 diesel engine crankshaft, thus exploring a new method combining continuous beam method and finite element method *(Liu Z.T. et al., 2020)*.

Yang Z.L. studied that the bending stress of crankshaft is affected by the change of its structural parameters *(Yang Z.L. et al., 2019)*. At this time, the finite element method has been applied, but the method of measuring stress with strain gauge is still applied at the same time, which is used to compare with the results of finite element. Because the load of crankshaft changes violently in the actual working condition, in order to obtain the stress distribution as detailed as possible, a lot of working condition calculation must be done. However, due to the large structure of crankshaft, the number of three-dimensional nodes needed to be divided is very large *(Hong W.L. et al., 2021)*.

MATERIALS AND METHODS

Parametric model and finite element static analysis of crankshaft

Crankshaft is the core component of the engine group, which is constantly affected by the interaction of cylinder, piston, body and other parts in the working process. Before the analysis of crankshaft, the matching engine must be analysed theoretically, including the selection of dangerous working conditions and the calculation of cylinder aerodynamics.

Crank and connecting rod mechanism is one of the main motion mechanisms of the engine group. It can transform the reciprocating linear motion of the piston into the rotary motion of the crankshaft around the rotation centre, so as to output the explosive force of the cylinder to the transmission system in the form of torque. The core theory of virtual prototyping technology is multi-body system dynamics. Multi body system is a complex mechanical system connected by multiple objects through motion pairs. Multi body system dynamics is composed of multi rigid body system dynamics and multi flexible body system dynamics. As one of the important moving parts of engine, piston works under severe conditions, such as high temperature, high pressure, high speed and poor lubrication. Therefore, it is necessary to require the piston to have enough stiffness and strength, reliable force transmission *(Li J.J., 2020)*. Although solid mechanics and structural mechanics have developed quite well, when it is necessary to analyse complex structural analysis problems such as crankshafts, the classical methods are still powerless. However, the finite element method can overcome this difficulty well, and it has developed into a powerful and practical general numerical analysis method in structural analysis.

Crankshaft dynamic model mechanism is mainly crank connecting rod mechanism, including piston connecting rod group, crankshaft flywheel group and other main operating components of internal combustion engine. Its function is to convert the reciprocating motion of the piston into the rotary motion of the crankshaft, and convert the air pressure acting on the piston into torque. Among all the loads on the crankshaft, the thrust from the connecting rod is the largest, which will directly affect the peak stress. Therefore, the analysis of crank and connecting rod mechanism is very important. The application of displacement boundary conditions is usually based on the actual support of crankshaft. The interaction between automation objects and automation customers is shown in Figure 1.

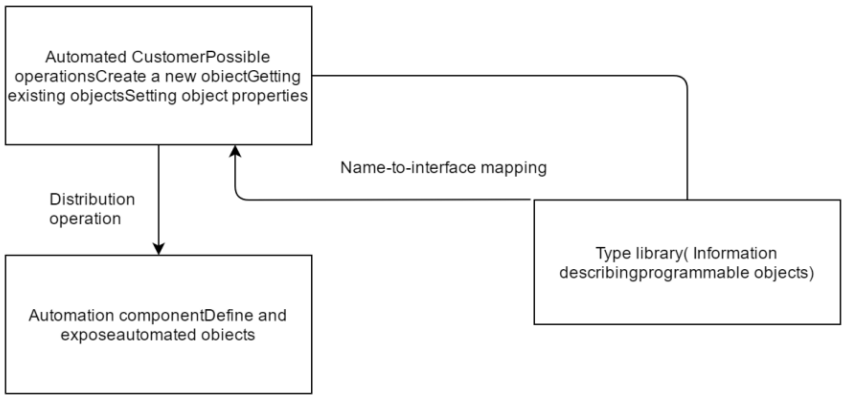

Fig. 1 – Interaction between automated customers and automated components

The crankshaft of multi cylinder tractor diesel engine is supported by several main bearings. Therefore, in the process of analysis, more than one main journal support should be set according to the actual situation. The static analysis of crankshaft is to calculate the displacement and stress of crankshaft under fixed load. Because the influence of inertia and damping is not considered, the static analysis can provide an important reference for the structural optimization of crankshaft.

Now, with the rapid development of computer, the configuration of computer hardware is higher and higher, and the calculation speed reaches trillions of times, which makes the application scope of finite element analysis more and more widely. Three dimensional finite element method can accurately determine the stress of any part. Before determining how to simplify the model, firstly, under the same working conditions, loading mode and mesh accuracy division method, the full axis model with oil hole and without oil hole is compared and analyzed.

From the cloud diagram, the maximum stress values and stress distribution of the two structures are similar, and the peak stress of the oil hole model does not appear in the oil hole position. The boundary element method (BEM) is a common method to analyze the internal combustion engine related problems. However, for parts with complex geometry and loads, such as crankshafts. In order to obtain accurate results, the mesh should have accurate shape, appropriate density and small distortion. However, such a grid is not only difficult to partition, but also has a large number of nodes, long solving time and consumes a lot of computing resources.

Using the existing technology to establish a multi-mode collaborative work environment, the operation process of collaborative design is shown in Figure 2.

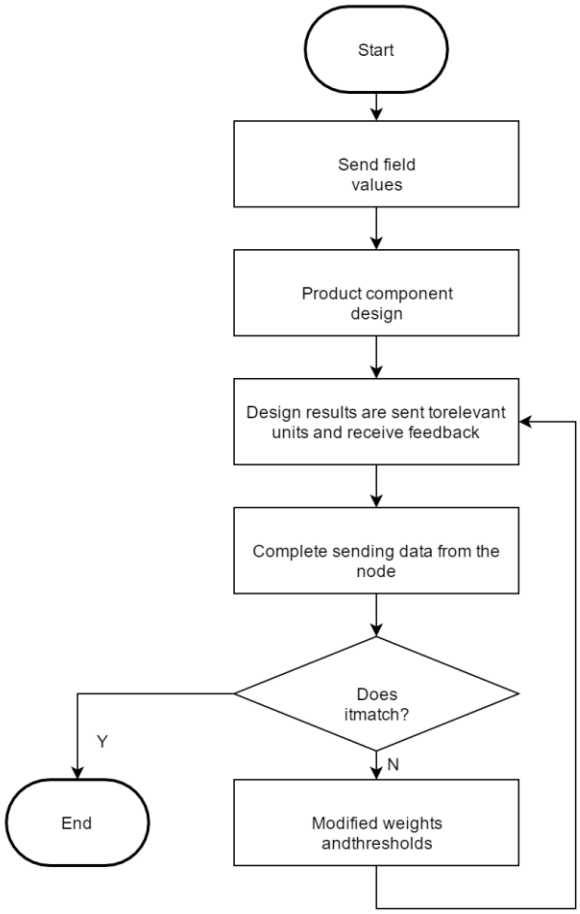

Fig. 2 – The operation process of mechanical processing cooperative design

As the gas pressure gradually rises to the highest value, the gas force will far exceed the inertial force. Because the pressure in the cylinder is higher than atmospheric pressure, the direction of gas force is vertically downward, and because the direction of inertia force is always opposite to the direction of mass movement, the inertia force is also vertically upward. For the local areas with serious stress concentration, smaller elements are used, and the rest areas are larger elements, which realizes a rapid transition between grid density and mesh density.

The finite element method is a discrete numerical method. The discrete elements are only connected by nodes, and all forces and displacements are calculated by nodes. For each cell, an appropriate interpolation function is selected, so that the function satisfies certain conditions in the subdomain, the inner boundary on the subdomain interface and the outer boundary between the subdomain and the external interface. Forged steel crankshafts with high tensile strength and high elongation are generally selected for the crankshafts of traditional supercharged direct injection engines to meet the performance requirements of high power and high torque.

For crankshafts, stress concentration is often concentrated in areas with irregular geometric shapes such as oil holes and transition fillets.

The fundamental purpose of multibody system dynamics is to apply computer technology to dynamic analysis and simulation of complex mechanical systems. To study the dynamics of these systems, it is necessary to establish nonlinear motion equations, energy expressions, kinematic expressions and other quantitative formulas. Through the use of network technology, workers can quickly understand the demand of automation market, the development direction and the information of product feedback, so as to provide reference direction for the design work of related mechanical design and manufacturing enterprises.

Figure 3 is an example of communication in a three-dimensional network.

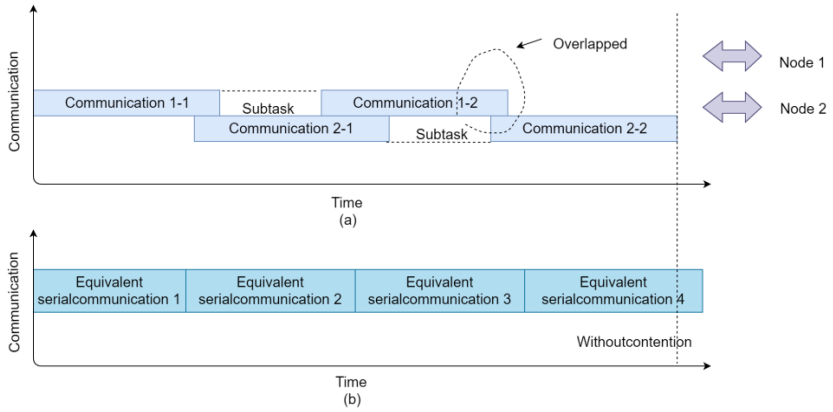

Fig. 3 – Communication example in a three-dimensional network

Project quality control refers to the control of the progress of each stage and the final completion period of the project in the process of project implementation. In which the process duration obeys lognormal distribution. Figure 4 shows the planning results of critical chain method.

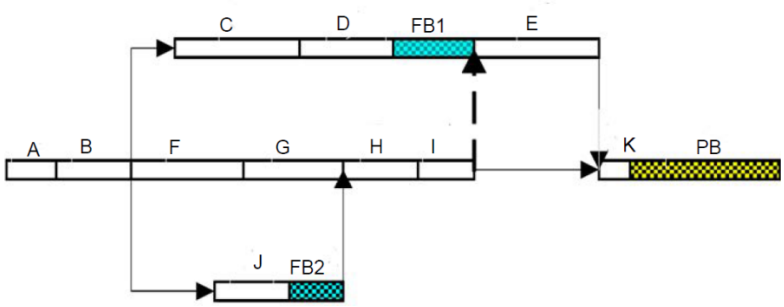

Fig. 4 – Critical chain method planning results

The traditional calculation method generally determines the stress concentration coefficient through experiments. However, most of the stress concentration coefficients are empirical formulas, and some related test conditions and parameter conditions must be considered when using them. Discretization is the basis of finite element method. The type, number, shape, size and arrangement of units must be determined according to the actual situation of the structure. The purpose is to divide the structure into small enough units, so that the simple displacement model can represent the exact solution approximately enough. Due to the complexity of the shape and the sharp change of the structure of the tractor crankshaft, serious stress concentration will occur at the transition fillet from crank arm to main journal and from crank arm to connecting rod journal, so it is necessary to adopt appropriate technology to strengthen the strength of the excessive fillet. The stress situation of crankshaft mainly refers to the stress analysis of crank-connecting rod mechanism. During the working stroke, the crank connecting rod bears both bending force and torsion force. It can be said that the working environment of crankshaft is extremely harsh and complex. Piston is the “heart” of tractor engine, which bears alternating mechanical load and thermal load, and is one of the key components in the engine with the worst working conditions. The function of the piston is to bear the gas pressure and inertia force, and transmit the gas pressure to the connecting rod through the piston pin, so as to drive the crankshaft to rotate and do work externally.

RESULTS

Dynamic analysis of crank and connecting rod mechanism

Because of the characteristics of finite element technology, the pre-and post-processing software of finite element software becomes a relatively independent and very important part. Optimum size sensitivity analysis is to use the change of sensitivity value to reflect the degree of influence of each parameter on the target value, so as to optimize the design of crankshaft according to the size and positive and negative of sensitivity value.

Pretreatment is an important link in finite element analysis and calculation, and the quality of pretreatment will directly affect the accuracy of calculation results and the scale of calculation. The discretization of computational objects divides the computational model to be analysed into finite elements, and sets connection nodes between the elements, so that the relevant parameters of adjacent elements have certain continuity, and then forms a collection of elements to replace the original computational objects, and replaces the elastic body boundary constraint with the node constraint on the boundary. Multi-body dynamics has something in common with classical mechanics. For example, the simplest system free particle in multi-body dynamics is also the research object of classical mechanics. The task of multibody system dynamics is to establish a mathematical model that can be identified and solved by computer for the dynamics and operational analysis of complex multibody systems, and on this basis, to seek an accurate and stable numerical solution method.

Rod force is the most critical of all loads borne by tractor crankshaft. It is the combination of cylinder burst pressure and piston reciprocating mass inertia force, and its magnitude will directly affect the maximum stress value. In most cases, pre-processing software has a good interface with CAD software, and can be combined with numerous finite solution software, so that users can solve problems faster and more conveniently. The parametric model of crankshaft is shown in Figure 5.

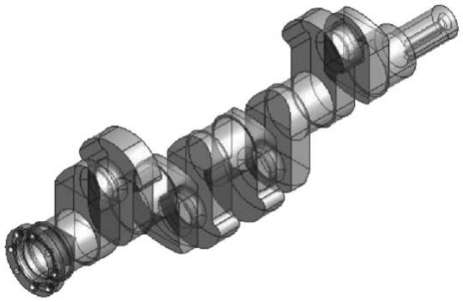

Fig. 5 – Parametric model of crankshaft

Aiming at the medium access constraint of wireless communication network, the agent node scheduling protocol is designed by using binary sequence. And the scheduling protocol is used to schedule the qualified agent nodes to access the network at the sampling time. Figure 6 shows the structure of agent nodes.

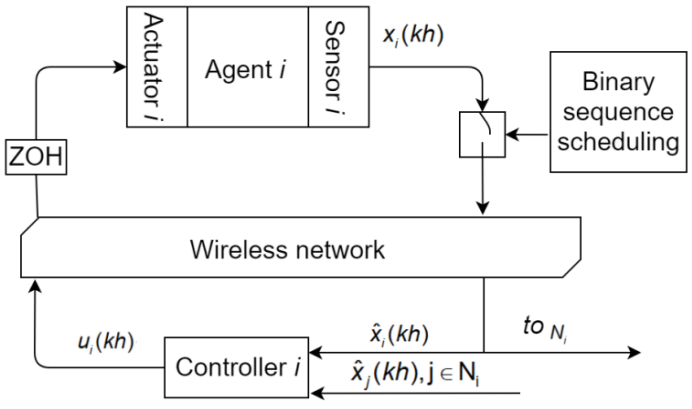

Fig. 6 – The structure of the agent node

The finite element static analysis of the crankshaft model was carried out, and the stress results under various working conditions were calculated. In the preprocessing step, the same simplified model, meshing accuracy and material parameters are used to accurately compare and summarize the results.

Establishment of finite element model

Before meshing, the geometric model should be processed, for example, some features which have little influence on the results of structural analysis and greatly increase the workload should be simplified, such as chamfers, local holes, etc. In the research of this subject, the oil holes of crankshaft have been cleaned. Assembled parts of mechanical products are often connected with each other by fastening bolts, bearings, pins and supports. This is completely different from the connection mode between general structural members. The two members in contact with each other are neither rigid connection which can transmit torque nor hinge which can transmit tensile force. Only pressure and friction force can be transmitted between two contact surfaces, and the tension force can be transmitted. Adjacent parts are either separated or contacted and cannot penetrate. Polynomials are usually chosen as the displacement mode, because the mathematical operation of polynomials is convenient, and all local functions can be approximated by polynomials. As for the choice of terms and order of polynomial, the degree of freedom of element and the convergence of solution should be considered. Because the contact force between contact pairs varies with the degree of compression deformation of the parts in contact with each other, and the deformation displacement of the structure is determined by the structural load including the contact force, the structural analysis of the structure with contact pairs by calculating the displacement through the load is no longer a general linear analysis problem, but a contact nonlinear analysis problem requiring iterative calculation.

In order to reduce the cost of crankshaft and improve the cost performance and competitiveness of engine, it is an effective method to change the blank and process of crankshaft from non quenched and tempered steel and forging process to ductile iron and casting process. In order to describe the displacement of any point in the element, it is necessary to assume that the displacement distribution in the element is a simple coordinate function, i.e. displacement mode or interpolation function. After determining the input vector of the finite element optimization model, the distribution of variables is checked, and these data are transformed to facilitate network learning. For continuous variables, the common normalization methods are as follows:

$$\frac{Y(s)}{N(s)} = \frac{G_D(s)G(s)}{1+\mathrm{C}(s)H(s)} \tag{1}$$

The network convergence time is greatly shortened and the performance of the network is improved. The transformation method is:

$$\frac{I(s)}{U(s)} = \frac{Js+b}{JLs^2+(bL+JR)s+bR+K^2} \tag{2}$$

Find the heat transfer coefficient:

$$f(x) = \sum_{j=1}^{n} \alpha_j N\left(\mu, \sigma_j^2\right) \tag{3}$$

Under the joint action of machining control law and multi-machining control law, multi-system successfully realized machining treatment and machining control in the machining process. There are many cognitive radio networks, and each cognitive spectrum is allocated by the cognitive base station. The change of success rate with cycle times is shown in Table 1.

Table 1

Success rate varies with the number of cycles

Number of calculations	Success rate of prompt function (%)
2000	80.97
2800	81.33
6000	81.78
9000	87.65

Calculate the activation value of the output layer unit:

$$BH(p,q) = \sum_{u=1}^{n} \sqrt{p_u(f)q_u} \tag{4}$$

The sample is sent to the hidden layer unit through the connection weight, and a new activation value of the hidden layer unit is generated:

$$E(x,y,z)=\frac{xL_{LED}A_{LED}}{\left[(x-x_0)^2+(y-y_0)^2+(z-z_0)^2\right]^{3/2}} \quad (5)$$

The change of success rate with cycle times is shown in Table 2.

Table 2

The success rate varies with the number of cycles

Number of calculations	Prompt function success rate (%)
3000	80.75
3700	81.11
7000	81.58
8000	87.43

Improve and meet the performance requirements of machining from four aspects: solidity, economy, energy saving and coordination. The relation number, overall density and degree centre potential are analysed, as shown in Table 3. With the increase of node relations, the shortest path between nodes decreases, as shown in Figure 7.

Table 3

Analysis of processing material network structure

Network	Number of relationships	Overall density	Degree central potential
Meet information	413	388	0.871
Mutual information	455	372	0.798
Weighted summation	346	365	0.842

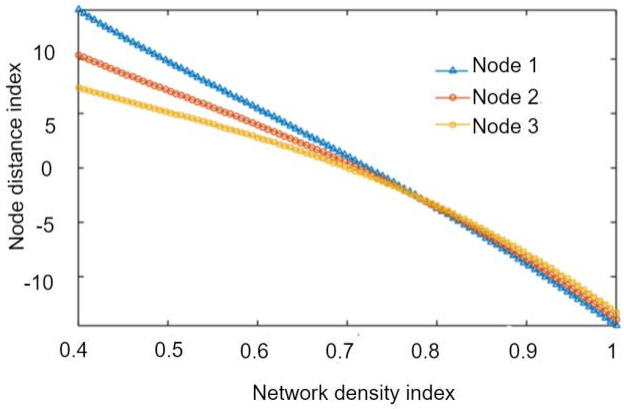

Fig. 7 - Distance analysis of network nodes during processing

According to the crankshaft of small displacement supercharged direct injection engine, on the premise of meeting the requirements of crankshaft strength and reliability, the design concept of changing crankshaft from non-quenched and tempered steel to nodular cast iron and optimizing tractor crankshaft structure to improve the fatigue strength of crankshaft is adopted for design optimization. In order to meet different analysis needs, different cell types should be selected. When selecting the element type, the selected element can simulate the shape of the geometric model to be analysed more accurately, and avoid causing larger calculation errors.

Under the same cell density, tetrahedral elements are not as accurate as hexahedron elements, while pentahedral elements are used as transitional elements. The emergence of computational multibody system dynamics has completely changed the traditional mechanism dynamics analysis method, so that engineers no longer need to carry out complicated manual calculations, only need to establish appropriate mathematical models according to engineering problems, and the next work can be handed over to computers. After the solution is completed, the post-processing program provided by computer software is used to provide various output modes of the solution results, which can help engineers to process the calculation results and realize automation and intelligence.

CONCLUSIONS

Crankshaft is one of the most important parts in agricultural tractor diesel engine, and its fatigue strength and safety factor directly affect the safe operation of the whole diesel engine. Different from the single-throw model analysis of crankshaft, the analysis of the whole shaft can not only get the value of the maximum stress on the crankshaft under a certain dangerous working condition, but also get the distribution law of the maximum stress on the whole shaft. The maximum stress of the whole crankshaft model is in the limit range under all dangerous working conditions. Although the maximum stress of crankshaft under various dangerous conditions is less than the limit value, the maximum stress distribution often appears in several fillets near the output end in a working cycle. It is an economic and effective scientific method to analyze the key parts of the mechanism by combining the digital prototype simulation technology with the finite element analysis. Using finite element analysis method to predict crankshaft strength can effectively save sample production and test time, reduce cost and improve product reliability.

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