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Design System of the Two-step Gear Reducer on Case-based Reasoning

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Abstract: The design of the two-step gear reducer is a tedious and time-consuming process. For the purpose of improving the efficiency and intelligence of design process, case-based reasoning(CBR) technology was applied to the design of the two-step gear reducer. Firstly, the current design method for the two-step gear reducer was analyzed and the principle of CBR was described. Secondly, according to the characteristics of the reducer, three key technologies of CBR were studied and the corresponding methods were provided, which are as follows: (a) an object-oriented knowledge representation method, (b) a retrieval method combining the nearest neighbor with the induction indexing, and (c) a case adaptation algorithm combining the revision based on rule with artificial revision. Also, for the purpose of improving the credibility of case retrieval, a new method for determining the weights of characteristics and a similarity formula were presented, which is a combinatorial weighting method with the analytic hierarchy process(AHP) and roughness set theory. Lastly, according to the above analytic results, a design system of the two-step gear reducer on CBR was developed by VC++, UG and Access 2003. A new method for the design of the two-step gear reducer is provided in this study. If the foregoing developed system is applied to design the two-step gear reducer, design efficiency is improved, which enables the designer to release from the tedious design process of the gear reducer so as to put more efforts on innovative design. The study result fully reflects the feasibility and validity of CBR technology in the process of the design of the mechanical parts.

Key words: two-step gear reducer, case-based reasoning(CBR), weights of characteristics, similarity

1 Introduction

The traditional design method of the two-step gear reducer is a time-consuming process. Even now CAD is used in its design process, restriction of the traditional design method is not eliminated up to now. For the sake of changing this kind of situation, many people have done research on the design method of reducer, mainly including the parametric design of reducer and expert system(ES). These two kinds of methods have respective shortcomings: for parametric design, every part's relation need to be fully considered, because a parameter's change can cause a change of a reducer's other parameters or structure, which requires designer to acquaint with a reducer and be able to use a design software including the function of the parametric design. Furthermore knowledge acquirement is very difficult in reducer's ES, because some expert knowledge is very difficult to express with rules. Case-based reasoning(CBR) can improve these two kinds of shortcomings. A new case is finished on the base of an existed case in CBR, so the new case can be achieved by modifying some parts or directly making use of the existed case, and case acquirement is easier than rule acquirement, because the primary knowledge is cases in CBR[1–2]. In fact, case usually provides more information than rule or model[3]. Many researchers have done a lot of work for applications of CBR in engineering. SUN, et al[4], developed an intelligent fixture design system on CBR. KWONG, et al[5], introduced a approach to determine proper injection moulding parameters by developed CBR system. LIU, et al[6], proposed a retrieval algorithm integrated with the clustering technique to locate the similar cases in the case-base and gave a case-base to illustrate the feasibility of the CBR system in the mechanical design. PETER[7] developed an automated knowledge-based system on CBR for intelligent support of the preprocessing stage of engineering analysis in the contact mechanics domain. XIONG, et al[8], provided an applied and creative conceptual design method based on CBR that embodies the industrial design knowledge. The system developed abbreviates the conceptual design process, help designers, and provides a base for the following development of product. However the works described above paid attention to the theoretical research on CBR superior to the combination of CBR technology with mechanical product.

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So, taken the two-step gear reducer as example, the whole process of mechanical parts on CBR will be discussed.

2 Key Technologies in CBR

The CBR is a kind of similar or analogical method. When a CBR system solves a new problem, it retrieves one or more cases from the antecedent cases that are the most similar to the new problem, and modifies the cases to satisfy the new situation[4]. The flowchart of the CBR is shown in Fig. 1. According to the flowchart of the CBR, the development of the product design system on CBR needs to solve some problem, including case description, case retrieval, case modification, case study and case base maintenance where case description, case retrieval and case modification are called three key technologies.

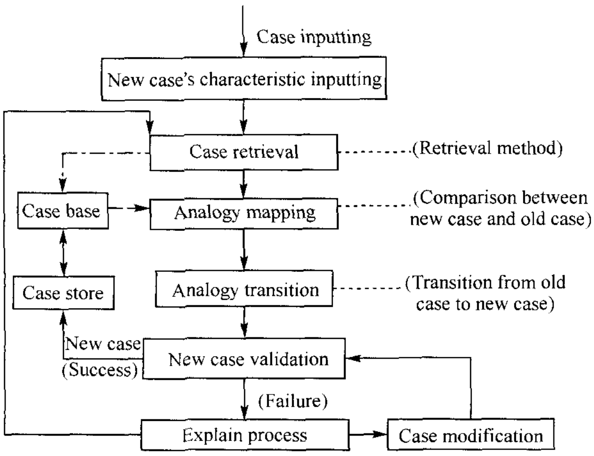


Fig. 1. Flowchart of CBR

Case description is the action that cases are coded to data structure accepted by computer with some conventional signs. Case can be described by some methods including frame, object, predicate, semantic network and rules, etc., among which, frame and object are most commonly used.

Case retrieval is a process finding out one interrelated case or more similar cases by characteristic index and similarity[9]. Ref. [9] divides case retrieval into three parts: characteristic identification, preliminary match, and best selection. The paper divides case retrieval into four parts: key characteristics extraction, characteristic identification, preliminary match, and best selection. Dataset of data mining often includes many characteristic attributes, and some attributes are irrelevant to data mining. Those irrelevant attributes influence efficiency of data mining. Removing those irrelevant attributes can improve efficiency of data mining and make the result of data mining easier to understand. The purpose of key characteristics extraction is to select key characteristics to establish valid index from the case base. The purpose of characteristic identification is to select key characteristics of new case. Characteristic identification can be often made reference to key characteristic extraction. Because it includes a plentiful characteristic attributes, the key characteristic extraction of the two-step gear reducer is more important. These typical methods of case retrieval include nearest neighbor, induction indexing, knowledge-guided, neural indexing on knowledge and template retrieval[10].

Case modification is the process modifying the best-match case to meet the new design requirements, and the most used methods include artificial modification, knowledge-intensive modification and knowledge-lacking modification[10].

3 Design of the Two-step Gear Reducer on CBR

3.1 Case base building

3.1.1 Case description

The paper uses a case representation model of object-oriented layer[11–12], which provides an uniform object-oriented data model to the upper software, namely, provides all kinds of object-oriented concept, data structure, maintenance operation and flexible expansion, and provides a relation model of shielding concrete database to bottom, and establishes a transparent object conversion mechanism by mapping principle and carries on reasonable and valid management. Mapping principle of object model is a relation of the conversion between a upper object-oriented data model and a bottom relation model of database. The relation among object model layer, database, and other function module is shown in Fig. 2.

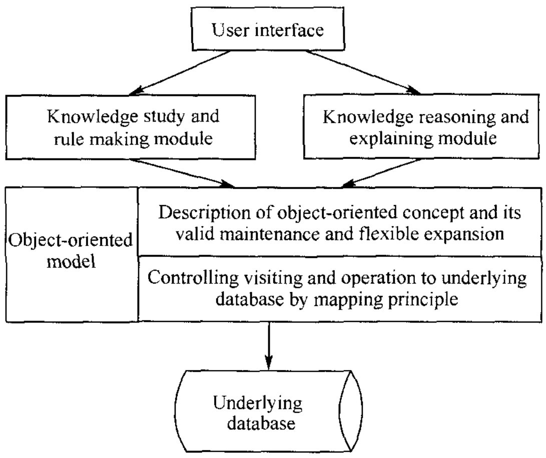


Fig. 2. Object-oriented module representation

The two-step gear reducer is a complicated assembly, for the sake of convenience of case representation, the two-step gear reducer is divided into five component classes and two part classes. The five component classes are made of high speed gear group, low speed gear group, high speed shaft and bearing, middle shaft and bearing and low speed shaft and bearing, and the two part classes are made of the cover and the housing. These component classes can be broken up part classes. Finally, every part class is mapped to its table in the underlying relation database. Therefore, the object-oriented knowledge model on the two-step gear reducer is given in Fig. 3.

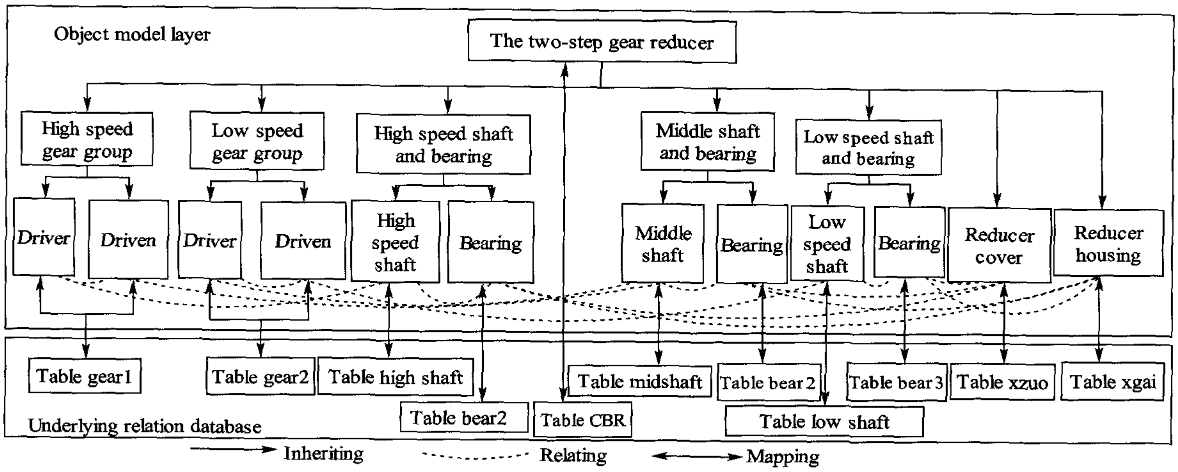


Fig. 3. Object-oriented knowledge model on the two-step gear reducer

3.1.2 Case base building

According to the case representation model of the two-step gear reducer in Fig. 3, characteristic attribute values of the two-step gear reducers and their components are mapped to the underlying database, thus the case base is built. In the underlying database, each table includes a "case number" field. The relation is established by "case number" between the tables mapped by every part and by the reducer. Fig. 4 shows the storage mode of case base of the two-step gear reducers in the database software of Access. Due to the limited space, the paper doesn't list successively the parts' storage mode in Access.

Case Number	TransmissionPower	TransmissionRatio	Life-span	TransmissionEfficiency	Similarity	First-stepGearRatio	Two-stepGearRatio	3D model
1	5.74	18.74	380000	.98	0	4.2	4.46	E:\jiansuqi\instance1\1_1
2	15.45	23.54	420000	.97	0	5.2	4.52	E:\jiansuqi\instance1\2_1
3	5.38	11.07	300000	.94	0	3.8	2.92	E:\jiansuqi\instance1\3_1
4	23.47	28.54	450000	.92	0	3.4	8.39	E:\jiansuqi\instance1\4_1
5	21.17	28.64	350000	.95	0	7.5	3.82	E:\jiansuqi\instance1\5_1
6	9.89	12.34	350000	.93	0	3.2	3.86	E:\jiansuqi\instance1\6_1
7	5.69	11.05	450000	.94	0	5.1	2.45	E:\jiansuqi\instance1\7_1
8	27.67	30.04	470000	.91	0	8.3	3.62	E:\jiansuqi\instance1\8_1
9	17.33	20.17	370000	.98	0	3.6	5.6	E:\jiansuqi\instance1\9_1
10	18.79	35.84	300000	.99	0	9.2	3.9	E:\jiansuqi\instance1\10_

Fig. 4. Storage mode of the two-step gear reducers case base in the database software of Access

3.2 Case retrieval

The paper applies a retrieval method of the combination of the nearest neighbor and the induction indexing, because the design of the two-step gear reducer is an experience process with a long history, two-step gear reducer includes many cases. So, it is better to use the induction indexing to have a rough retrieval, and use the nearest neighbor to have a fine retrieval. Fig. 5 shows the detailed retrieval process.

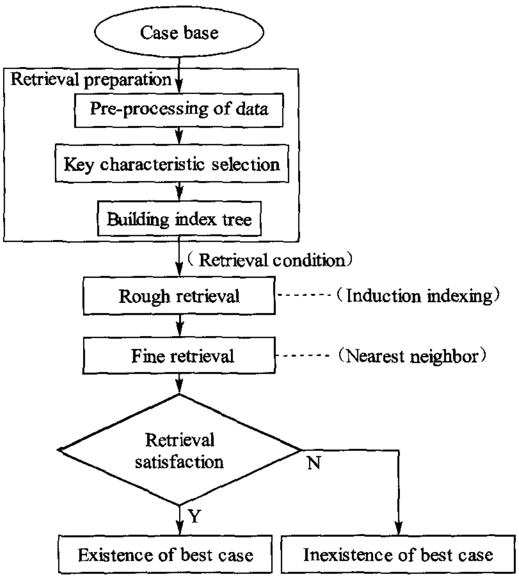


Fig. 5. Flowchart of case retrieval process

Now the paper describes the child process and method to case retrieval of the design system of the two-step gear reducer on CBR in turn.

3.2.1 Key characteristic extraction

The characteristics of original case base are pre-processed before the key characteristic extraction.

(1) Pre-processing of data. The discrete normalization processing of the quantitative parameters are transformed into the qualitative parameters by equal-frequency-intervals[13]. The principle of equal-frequency-intervals is to divide original interval into N small intervals (N is a discrete number given by user), while each small interval has the almost same number of data. The first and last intervals are expanded in the paper: the upper limit of the first interval is changed to zero, and the lower limit of the last interval changed to infinity, which ensures that a attribute value of a new case has a corresponding small interval with it, because CBR is a process of uninterrupted study (the amount of case will uninterruptedly increase), and avoid that small interval is divided again whenever a new case is added and retrieval of new case is not made beyond the attribute value of original case base. N intervals are identified with 0, 1, 2, $\cdots$, n–1. The qualitative characteristic attributes are assigned to [0, 1] by an increasing or decreasing order. For example, "precision grade of reducer" has three options for user to select in the

original case base: the class of 7, the class of 8 and the class of 9. The classes of 7, 8, 9 are expressed with 1, 0.5, 0, respectively according to the above-mentioned method. The attribute value of the Boolean attribute is easy to ascertain: the same is 1, the other is 0.

(2) Key characteristic selection. These clearly irrelevant characteristics are not directly considered in the data mining. However many characteristics are difficult to identify their significance in the data mining. These characteristics are selected by the valid strategy. The paper uses decision tree to select key characteristics by the size of information gain. Decision index tree is established by key characteristics. The algorithm on the information gain of decision attributes may be referred to Ref. [12].

The key characteristic selection on the two-step gear reducer is shown as follows. The original case base is given in Table 1.

Table 1. Original case base

Case No.	Transmission power P/kW	Transmission ratio i	Life-span $L_h/10^3$h	Transmission efficiency η	Layout of gear drives
1	6.60	20.00	380	0.93	Developed style
2	17.00	20.00	420	0.97	Developed style
3	5.38	11.07	300	0.91	Developed style
4	26.40	6.50	450	0.94	Developed style
5	22.00	18.00	350	0.92	Reverted style
6	9.10	12.50	350	0.98	Reverted style
7	3.80	12.50	450	0.95	Reverted style
8	25.00	14.00	470	0.94	Reverted style
9	17.00	20.00	370	0.94	Developed style
10	16.00	16.00	300	0.96	Developed style

Firstly, the clearly irrelevant characteristics to data mining are directly eliminated. The other characteristics by the discrete normalization processing are changed into qualitative attributes, and then selected by the above-mentioned algorithm of information gain. Secondly, the attribute of transmission power is divided into three small intervals according to the above-mentioned equal-frequency-intervals: (0, 10), [10, 20] and (20, ∞). The qualitative numerical ranges are represented respectively with 0, 1, 2. The attribute of transmission ratio, life-span and transmission efficiency are respectively divided into several corresponding small intervals (transmission ratio: (0, 15) and (15, ∞); life-span: (0, 350 000), (350 000, 420 000) and (420 000, ∞); transmission efficiency: (0, 0.94) and (0.94, 1). Each interval numerical range is represented with 0, 1, ⋯, n, in turn. The attribute of the layout of gear drives is divided into two types. The developed configuration is represented with 0, and the reverted configuration is represented with 1. The result of discrete processing is obtained in Table 2.

Table 2. Result of discrete processing

Case No.	Transmission power	Transmission ratio	Life-span	Transmission efficiency	Layout off gear drives
1	0	1	1	0	0
2	1	1	1	1	0
3	0	0	0	0	0
4	2	0	2	0	0
5	2	1	0	0	1
6	0	0	0	1	1
7	0	0	2	1	1
8	2	0	2	0	1
9	1	1	1	0	0
10	1	1	0	1	0

The attribute of arrangement form is viewed as identification attribute, and the other attributes are viewed as decision attribute. The case base is divided into two classes (m=2) according to identification attribute. The first class is comprised of six cases whose arrangement form is expanding form (r_1=6), and the second arrangement is comprised of other cases whose arrangement form is coaxial form (r_2=4). According to the algorithm of information gain, it is easy to acquire the information gains of all attributes as follows: G_P=0.29, G_i=0.12, G_{L_h}=0.29, G_η=0.01; where, G_P is the gain of transmission power, G_i is the gain of transmission ratio, G_{L_h} is the gain of life-span, G_η is the gain of transmission efficiency. Thus the attribute of transmission power, transmission ratio and life-span can be selected as key characteristics from the value of all characteristic attributes.

3.2.2 *Preliminary match*

The preliminary match is the process that a group of cases interrelated to the current design case are selected from the case base. The process is realized by index tree built by all key characteristics and decision information gain calculation. The index tree is built up as shown in Fig. 6. The preliminary match of case is fulfilled based on the index tree.

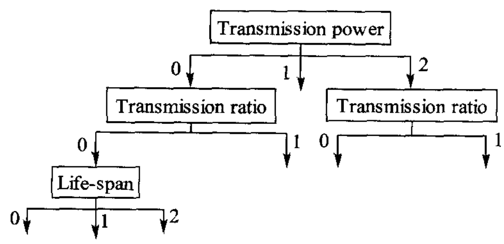


Fig. 6. Index tree of key characteristics

3.2.3 *Best selection*

The best selection is the process which the best case is selected from the cases acquired by the preliminary match.

The best case is selected by the nearest neighbor, so it is indispensable for calculating the weight of the key characteristics and case's similarity.

(1) Weight of characteristic

The weight of characteristic is used to evaluate significance of characteristic. It can influence the accuracy of reasoning result. According to the source of original information, the method of determining the weight of characteristic is divided into two classes: the subjective method and the objective method. The information of the subjective method comes from experts, and the information of the objective is from statistical original data. The representative approaches of the two-class method are the analytic hierarchy process(AHP)[14–15] and roughness set theory[12]. AHP is a kind of decision method that the decision problem is divided into some hierarchies including target, rule, project, etc, and qualitative analysis and quantitative analysis are conducted. Let a_{ij} be importance degree of the characteristic i compared with the characteristic j. The weight ω_{1i} of characteristic i acquired by AHP can be calculated by the following formula:

$$\omega_{1i}=\frac{\left(\prod\limits_{j=1}^{n}a_{ij}\right)^{\frac{1}{n}}}{\sum\limits_{k=1}^{n}\left(\prod\limits_{j=1}^{n}a_{kj}\right)^{\frac{1}{n}}},\quad i=1,2,\cdots,n. \tag{1}$$

Roughness set theory is a kind of data reasoning method in view of knowledge classification, which mainly applies to analysis of the dependence between reduction of knowledge and characteristic attribute, and solves the problem about the weight of characteristic attribute of similarity measure. It judges the importance of all characteristic by existent information according to specific classifying. Relevant formulas of the weight calculation are given as follows:

$$\gamma(C,D)=\frac{|POS(C,D)|}{|U|}, \tag{2}$$

$$SGF(a,C,D)=\gamma(C,D)-\gamma(C-\{a\},D), \tag{3}$$

$$\omega_{2i}=\frac{SGF(C-\{i\},D)}{\sum\limits_{i=1}^{n}SGF(C-\{i\},D)},\quad i=1,2,\cdots,n, \tag{4}$$

where $\gamma(C, D)$—Dependence degree between attribute set C and D,
$|POS(C, D)|$—Number of elements in the union set,
$|U|$—Number of the object set,
$SGF(a, C, D)$—Importance of attribute a attribute set D, $a\in C$,
$SGF(C-\{i\}, D)$—Importance degree of the characteristic i,
ω_{2i}—Weight of the characteristic i acquired by roughness set theory.

The paper applies a method of combination of AHP and roughness set theory in order to compensate the defect of the two methods. The combined method is assembled according to the linear superposition principle. The material combined form is shown in Eq. (5):

$$\omega_i=\alpha\omega_{1i}+(1-\alpha)\omega_{2i}, \tag{5}$$

where ω_{1i}—Weight of characteristic acquired by AHP,
ω_{2i}—Weight of characteristic acquired by roughness set theory,
α—Coefficient.

According to the combined method, the three weights of key characteristics of the reducer is respectively obtained, such as the attribute of transmission power, ω_1=0.52; the attribute of transmission ratio, ω_2=0.28; the attribute of life-span, ω_3=0.20 (suppose α=0.5).

(2) Similarity

The characteristic values of the two-step gear reducer are comprised of quantitative parameters and qualitative parameters. The paper uses Eqs. (6) and (7) to calculate the similarity[16] of quantitative characteristic, and the similarity of qualitative and Boolean characteristic have two conditions: 0 (different) or 1 (same). So the paper presents a new algorithm of case similarity, which is expressed as follows.

Relative distance:

$$d_{nk}^{i}=\sum_{i=1}^{n}\frac{|V_{ni}-V_{nk}|}{V_{ni}}; \tag{6}$$

Characteristic's similarity:

$$SD_{nk}^{i}=1-d(V_{ni}-V_{ki})=1-d_{nk}^{i}; \tag{7}$$

Similarity between two cases:

$$\mathrm{sim}(n,k)=\frac{\sum\limits_{i=1}^{k}\omega_i SD_{nk}^{i}}{\sum\limits_{i=1}^{n}\omega_i}. \tag{8}$$

Where d_{nk}^{i}—Relative distance of the ith attribute of case n and case k,
V_{ni}—Characteristic value of the ith attribute of case n,
V_{ki}—Characteristic value of the ith attribute of case k,
SD_{nk}^{i}—Similarity of the ith attribute of case n and case k,
sim(n, k)—Similarity between the case n and the case k,

ω_i—Weight of the ith characteristic,

n—Number of the characteristic.

Suppose to design the two-step gear reducer whose design conditions are shown in Table 3, and retrieve two cases which are obtained in Table 4.

Table 3. Design conditions

Key characteristic	Transmission power P/kW	Transmission ratio i	Life-span L_h/h
Value	5.33	11.06	310 000

Table 4. Two retrieved cases

Case No.	Transmission Power P/kW	Transmission ratio i	Life-span L_h/h
1	5.38	11.05	300 000
2	5.69	11.07	450 000

The weights of each key characteristic are 0.52, 0.28, 0.20, respectively. The similarity of the cases can be obtained according to Eqs. (6)–(8), which is described as follows:

$$\mathrm{sim1} = 0.52\times\left(1-\frac{|5.33-5.38|}{5.33}\right)+0.28\times\left(1-\frac{|11.06-11.05|}{11.06}\right)+$$

$$0.20\times\left(1-\frac{|310\ 000-300\ 000|}{310\ 000}\right)=$$

$$0.515+0.280+0.194=0.989,$$

$$\mathrm{sim2} = 0.52\times\left(1-\frac{|5.33-5.69|}{5.33}\right)+0.28\times\left(1-\frac{|11.06-11.07|}{11.06}\right)+$$

$$0.20\times\left(1-\frac{|310\ 000-450\ 000|}{310\ 000}\right)=$$

$$0.485+0.280+0.110=0.875.$$

3.3 Case modification

The paper uses the combination of the revises on rule and artificial revises to modify case. The flowchart of the case modification is given in Fig. 7. Rules include experience formulas, calculation formulas. For example, the width of a pinion often is that of a gear with the addition of 5–10 mm. And restrictions are main measures of evaluating design feasibility, just as the check formula of the gear tooth contact fatigue strength, the gear tooth-bending fatigue strength, etc.

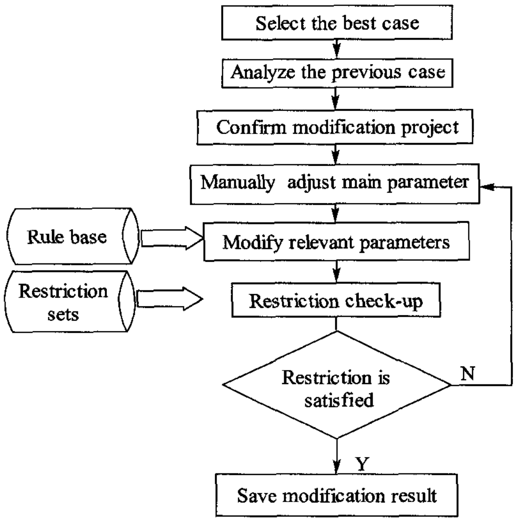


Fig. 7. Flowchart of case modification

4 System Development

The flowchart of the design system of the second-class cylinder decelerator on CBR is shown in Fig. 8.

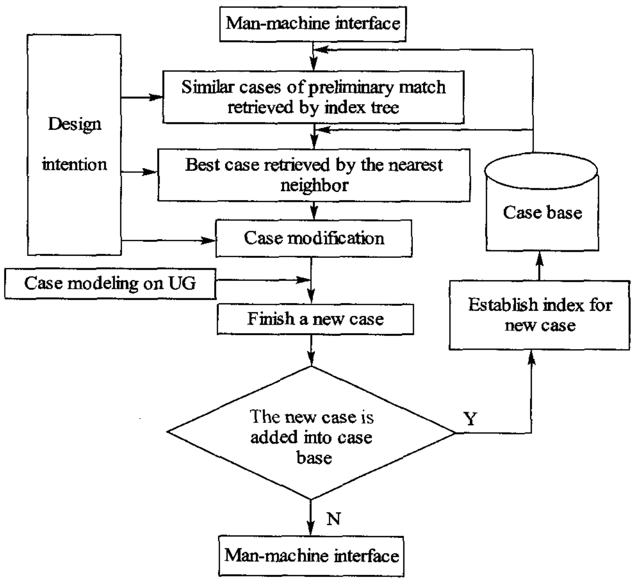


Fig. 8. Flowchart of system working

The design system of the two-step gear reducer on CBR is developed by using VC++, UG and Access2002 as tool[17–19], which includes five modules of file management, case retrieval, case modification, entering UG, and help as shown in Fig. 9. The module of file management is used to manage relevant files about cases. The module of case retrieval is used to retrieve cases and look over information of retrieved case. The module of case modification is used to modify case retrieved by case number. The module of entering UG is used to call modified parameter from case base and finish 3D modeling by the subsystem redeveloped by ODBC technology and UG/Open++ tool.

A practical example is given to illustrate the operation of the developed system on CBR as follows. Suppose to design the two-step gear reducer, and its design requirements: transmission power 5.36 kW, transmission ratio 11.06, life-span 310 000 h. The operation process of the system is described as follows.

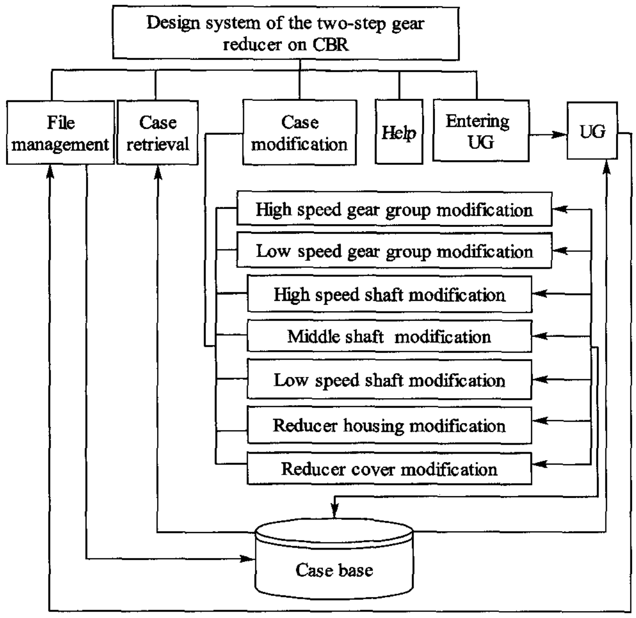
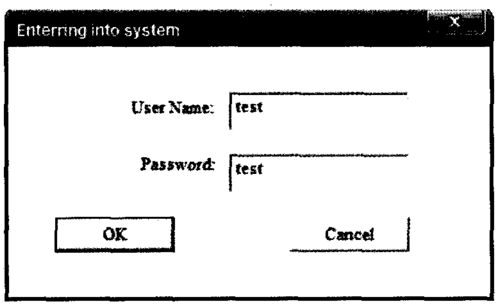
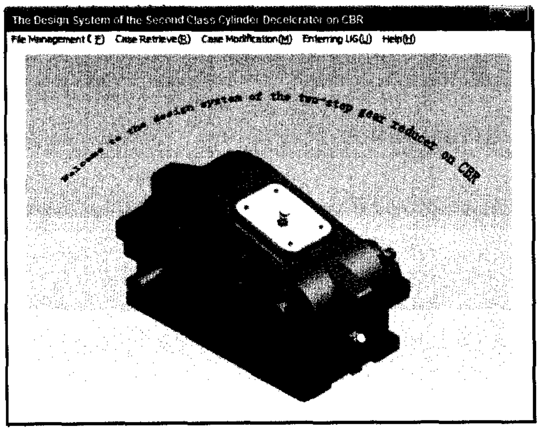


Fig. 9. Frame of the system

(1) In login and main interface shown in Fig. 10, enter the system and input the user name and the password.



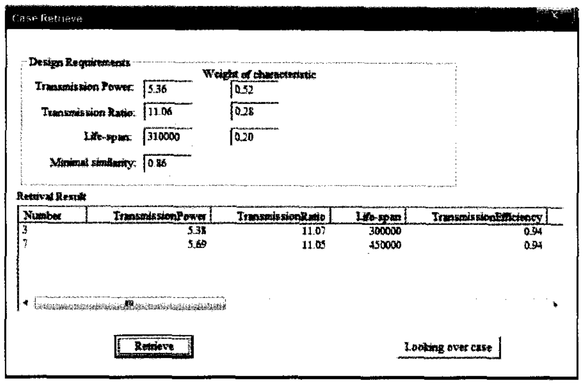
(a) Login interface



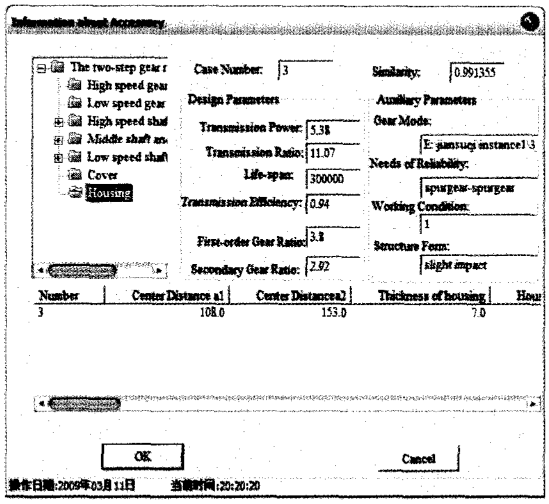
(b) Main interface of system

Fig. 10. Login interface and main interface

(2) Input retrieval conditions to retrieve case, and select the case of maximal similarity to look over its information in Fig. 11. Select case 3 from retrieved results, because its similarity is largest. According to analysis, it is easy to know that the tolerance between case 3 and the case to be designed is less than 5%. So the case 3 can be the result of new design.



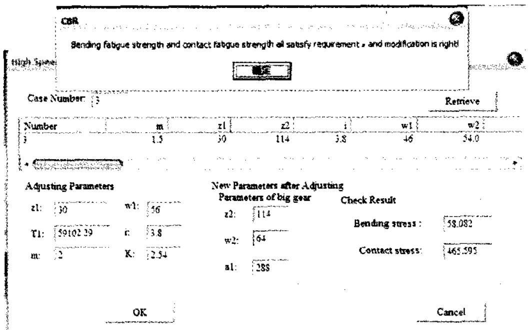
(a) Case retrieval



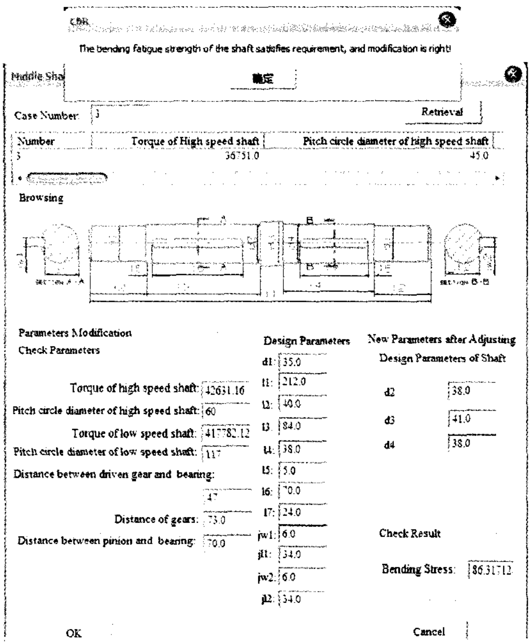
(b) Looking over the information of retrieved case

Fig. 11. Case retrieval and information of case

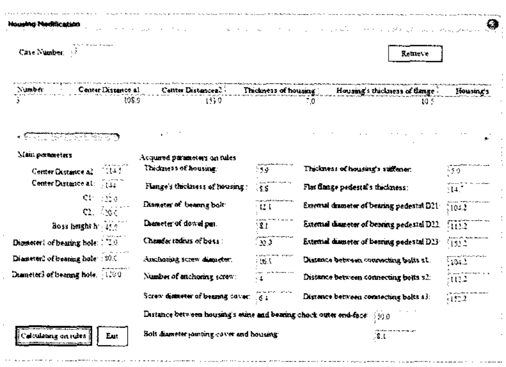
If the tolerance between the retrieval result and the case to be designed is more than 5%, the retrieval result needs to be modified. Case modification includes completive modification and local modification. When the tolerance of the attribute of transmission power is more than 5% between the retrieval result of maximal similarity and the case to be designed, it denotes that there is not a best case and the case to be designed need to be redesigned. After finishing the design, it is necessary to establish the corresponding index for the new case, and the new case is saved in the case base to become an original case for next retrieval. The above process is called as case study. When the tolerance of the attribute of transmission power is less than 5% between the retrieval result of maximal similarity and the case to be designed, and other two attributes' tolerance is more than allowed tolerance, the case is finished by adjusting gear transmission ratio and parameters of relevant gears. The adjusting principle is modifying the parameters of gear group and support shafts while keeping the parameters of other parts unchangeable. It is necessary to check up the strength of the modified gear and shaft. The parts are modified in retrieved case by the combination of rules which are the check formula of the gear fatigue strength, the check formula of the shaft strength, and manual modification, etc. Finally, the modified case is saved in the case base. For example, the required design data is transmission power 6.50 kW, transmission ratio 11.07, life-span 310 000 h. The case 3 was retrieved. It is known by computing that the transmission power error between the retrieval case and the case to be designed is 21.95 %, which is out of the error range of 5 %. This means the case 3 needs to be modified. Modification parts are given in Fig. 12.



(a) High speed shaft gear group modification



(b) Middle shaft modification



(c) Reducer housing modification

Fig. 12. Case modification

After finishing modification, the software of UG is run by the module of entering UG and the 3D modeling is finished by using the second developed program of UG to acquire parameters of modified part. The parameters of the modified gear are listed in Fig. 13.

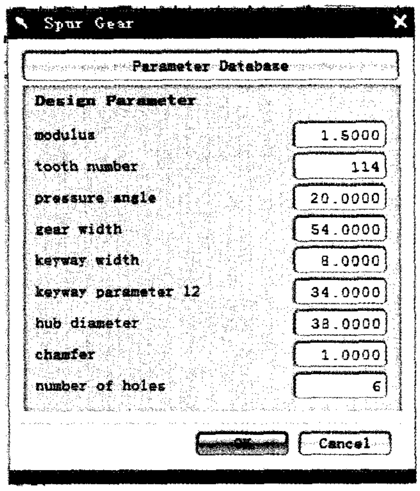


Fig. 13. Parameters of the modified gear

Finally, the modified part is saved in the case base. Input its name in the dialog box as shown in Fig. 14, in which naming rule of the part is seen in the note of the interface.

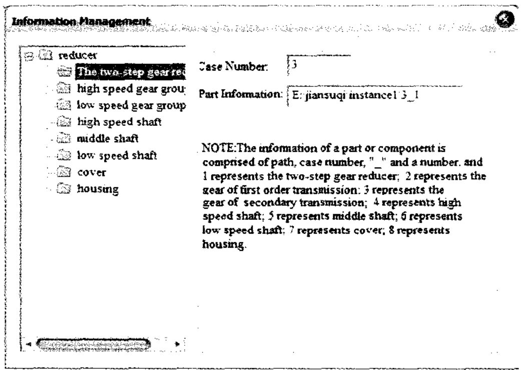


Fig. 14. Management of the modified parts

5 Conclusions

(1) The case of the two-step gear reducer is represented by the object-oriented knowledge model, which is more convenient and accurate to express the knowledge for the reducer, and beneficial to the case retrieval.

(2) According to the actual situation of the two-step gear reducer design, the combinatorial weighting method with AHP and roughness set theory was proposed, which can improve the credibility of case retrieval.

(3) The design system of the two-step gear reducer on CBR was successfully developed. The system makes the design of the two-step gear reducer easier, rapider and more intelligent. The approach can be used as the development of other components on CBR for reference.

(4) That the sufficient cases in case base is the premise condition of running the design system of the two-step reducer on CBR. If the design requirements of special two-step reducer are met, the related cases must be added

to the case base.

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