International Journal of Multimedia and Ubiquitous Engineering
Vol. 9, No. 12 (2014), pp. 293-306
http://dx.doi.org/10.14257/ijmue.2014.9.12.27

Ontology-Based Exchange of Product Data Semantics between CAD and CAE

Qinyi Ma, Yajun Wang, Yan Lv, Xin Jin and Maojun Zhou

School of Mechanical Engineering and Automation,Dalian Polytechnic University,Dalian
maqy@dlpu.edu.cn, wangyajun2004@hotmail.com, lvyan@dlpu.edu.cn, jinxin@dlpu.edu.cn, zhoumj@dlpu.edu.cn

Abstract

The interoperation of various applications will need a representation that goes beyond the traditional geometry-based one, which is inadequate for capturing semantic information. This paper proposes an approach to annotate the CAD models based on ontology with the aim of making the design intent understood by computer and applied in engineering analysis, such as FEA. The paper presents the design domain ontology and FEA domain ontology, and applies feature technologies and the semantic Web to complete annotation. Semantic markup can embed the engineering semantic information such as product function, and design principle into the CAD geometry data through annotating, it makes the analyzers reuse design ideas quickly and conveniently to increase efficiency. The semantic file is proposed to support an exchange of product data semantics between CAD and CAE. The main idea of the approach is presented and key technologies are elaborated, including the creation of the FEA solution template, and the matching algorithm between semantic markup file and FEA template file. Finally, the feasibility and effectiveness of the approach is empirically validated by a case study.

Keywords: *Semantic, Ontology, CAD, CAE, Annotation*

1. Introduction

In modern engineering processes, a product development activity requires cross-functional teams with the expertise of a broad range of disciplines to work collaboratively. Consequently, this leads to the development and usage of a wide variety of heterogeneous design modeling tools, such as CAD and CAE systems, which represent the same design object with different models. These models are not independent of each other; for example, mesh data for FEA is closely related to shape data of a solid model.

Furthermore, current CAD models are largely limited to the design stage [1]. The design intent should be reflected in the product model. In a traditional CAD based design environment, the knowledge generated in the geometric design stage is inaccessible to the FEM pre-processing process due to the fact that data transfer formats are incapable of capturing this knowledge [2] and a significant gap typically remains between computer aided design (CAD) and computer aided engineering (CAE) [3].

The question is how to pass product data semantic between different programs and the whole product lifecycle .The Core Product Model (CPM) [4] was developed at NIST as a high level abstraction for representing product related information. The Product Lifecycle Management (PLM) concept that was proposed [5, 6] to extend CPM holds the promise of seamlessly integrating all the information produced throughout all phases of a product's life

ISSN: 1975-0080 IJMUE

cycle. Other research efforts have focused on the special transfer interface of CAD and CAE software. In an industry survey, Liker, *et al.*, [7] confirm this observation and identify 'an iterative and seamless link between CAD and CAE' as one of the 'unfulfilled promises of CAD'. However, the transfer formats are incapable of capturing design intent and making use of such information still depends on personal experiences. So, the product representation needs to be enhanced.

This paper proposes a product representation approach to annotate the CAD models based on ontology with the aim of making the design intent understood by computer and applied in follow product development process, such as FEA, and make a tighter integration of design and finite element analysis based on the semantic file.

2. The Ontology

Design domain ontology and FEA domain ontology are developed. Design ontology is responsible for the definition of the physical structure and engineering problems, which reflect the design intent and help to reduce analysis efforts. FEA ontology abstracts physical problems solving by an FEA method.

2.1. Design Domain Ontology

This phase involves identifying key concepts and relationships in the domain of product design. The CPM is extended and key concepts concerned are briefly described in Figure 1. Common Product Object is the top level abstract class. Design Entity is the base class of Artifact and Feature. Design Property is a base class, and it derives various classes as Function, Form, View, Geometry and Material. The Artifact represents a distinct entity in the design whether that entity is the entire product or one of its subsystems, parts or components. The Feature is an integrated unit which contains specific shapes and other property information such as analysis and manufacture. One artifact can have design feature, analysis feature and manufacture feature *etc.*, It is determined by its function. Feature also has its own structure hierarchies, so one combined feature can be established on other features. The Function specifies what the Artifact is supposed to do. The Form may be viewed as the proposed design solution to the problem specified by the function and consists of the artifact’s Geometry (shape and structure may be synonymous to geometry in some contexts) and the Material it is composed of. Geometry is the 3D description of Artifact. Behavior represents how the artifact’s form implements its Function; one or more causal models, such as Finite Element Analysis (FEA) or Computational Fluid Mechanics (CFM) models, may be used to evaluate it. Specification describes the information of Artifact related to design, these information come from the users or engineering requirements. The Master Model serves as the global repository of information on a product; in practice, it may be implemented as a centralized, distributed, federated or virtual database. Each Engineering Model represents an abstraction of the product of interest to a specific functional domain at a particular stage in the lifecycle of a product. Problem Solution Model describes the solution of specified Engineering Model. FEA Object is the top level abstraction of general analytical ontology.

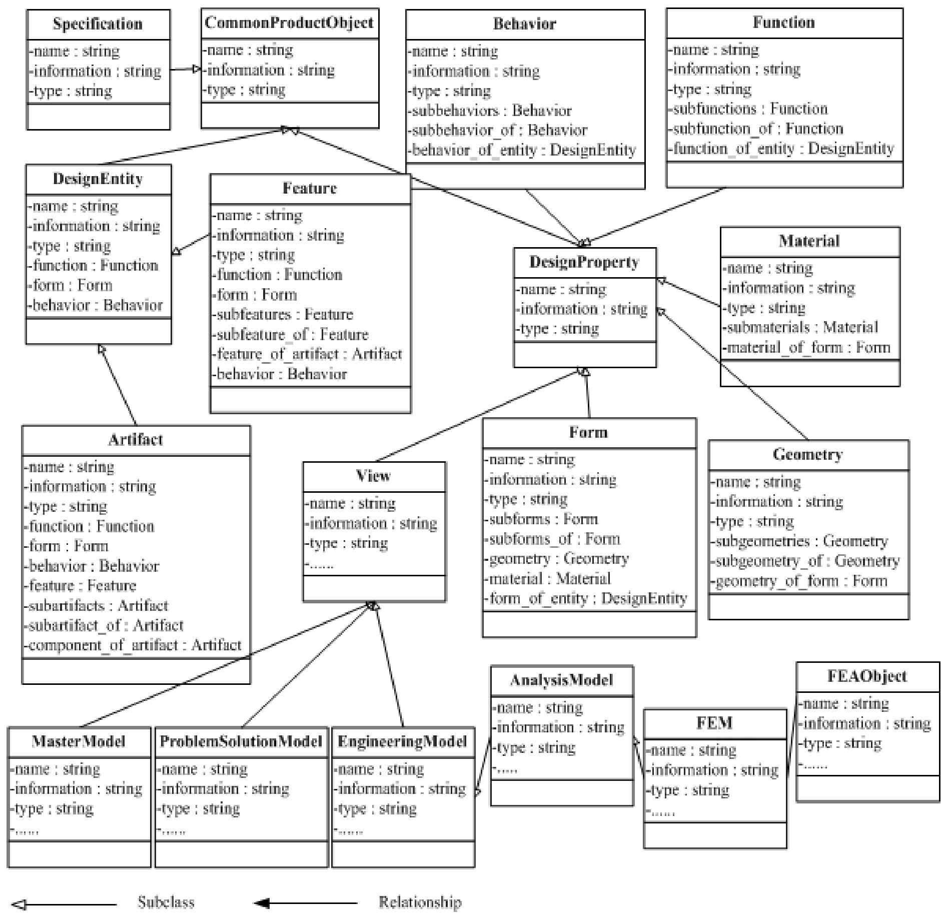


Figure 1. The Design Domain Ontology

2.2. FEA Domain Ontology

The FEA domain ontology is intended to present a generic FEA activity. We present the formal ontology for the representation of FEA knowledge as Figure 2, after extracting analysis modeling knowledge from engineers and incorporating this knowledge into a computational environment.

An FEA Object represents a distinct entity in FEA. It is an aggregation of Global, Analysis Type, Idealization, Load, Constraint, Mesh, Solution, and Result. The Global describes the global information of FEA, including document specification, the unit system and the coordinate system. The Analysis Type specifies the type of analysis problem, such as Structural Static Analysis, Kinetic Analysis and Thermodynamic Analysis. The Idealization represents how to make geometry simplifications for building a solid model. Constraint and Load describe how to apply boundary conditions and load on idealization geometry. Mesh appoints meshing type, finite elements type and size selection. The Solution describes the algorithm selection, an interactive control of algorithm parameters, and the Result represents results visualization, and results interpretation in the domain terms.

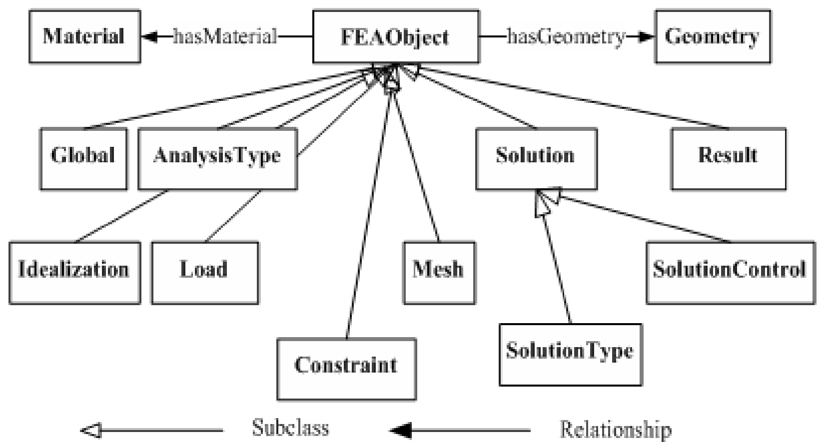


Figure 2. The Class Diagram for the FEA Domain Ontology

3. Markup of CAD Models

This paper uses feature and semantic technology to complete semantic annotation of CAD model. The engineering semantic information expressed by ontology is added onto the feature in the form of attributes. Meanwhile, the handle of the feature is also written in the attributes. This can not only avoid traverse all the features of geometric model, but also do not need to use additional database to set up corresponding relations between engineering semantic and geometric features, So it can effectively associate the engineering semantics with the model.

While writing engineering semantic as properties into geometric features, relevant information of the current coordinate system is also included. If loads and boundary conditions are directional, the vector of coordinate system is used to describe the direction. Coordinate system can be global or local; type and origin of the coordinate system and each coordinate axis direction of the coordinate system are also specified.

When reading engineering semantic, loads and constraints are numbered, and these serial numbers are as the child element of the tag of loads and boundary conditions. The geometric features are also numbered as its own child element. Meanwhile, the tag of loads and constraints contain one attribute called featureid. The value of featureid is just the serial number of the feature which loads or boundary condition is applied. The connection between engineering semantic and geometric features in XML files is achieved by featureid. The detailed definition is shown as follows:

```
<Feature>
    <FeatureName featureid=" " supportid=" Corresponding Load&ConstAttr id" >
        <Type>……</Type>
        <OtherParam>……</OtherParam>
        ……
         <KeyPoint>pointx,pointy,pointz</KeyPoint>
         ……
    </ FeatrueName>
</Feature>
<LoadAndConstraint>
```



```
        < Load&ConstAttr id=”0” name="LoadAndConstraint Name "
        function="LoadAndConstraint Function" featureid="Corresponding Feature id">
      < LoadAndConstraintPara >……</ LoadAndConstraintPara>
      ……
        </ Load&ConstAttr >
</ LoadAndConstraint >
```


For different types of geometric features, the number of key points extracted is different, and relevant parameters extracted from the feature are also different. Taking the bearing hole with bearing loads as example, the extracted engineering semantics of XML files include following fragments:


```
<Feature>
    ……
    <face featrueid="5" supported="2">
        <Type>16</Type>
        <pointx>281.458256</pointx>
        <pointy>-162.500000</pointy>
        <pointz>35.000000</pointz>
        <dir>0.000000</dir>
        ……
        <KeyPoint>(191.458256,-162.500000,70.000000)</KeyPoint>
        <KeyPoint>(371.458256,-162.500000,70.000000)</KeyPoint>
        <KeyPoint>(191.458256,-162.500000,0.000000)</KeyPoint>
        <KeyPoint>(371.458256,-162.500000,0.000000)</KeyPoint>
          </face>
……
</Feature>
<LoadAndConstraint >
        <BearingLoad id="2" name="Bearing(2)" function="thebearinghole65"
        featureid="5">
        <BearingL65>14770.000000</BearingL65>
        <RegionB65>80.000000</RegionB65>
        <RegionAng65>120.000000</RegionAng65>
         ……
    </BearingLoad>
</ LoadAndConstraint >
```


4. The Method of Product Data Semantics Exchange based on the Semantic File

4.1. The Core Concept

The idea of the method is presented in Figure 3 adapted from [1]. The CAD and FEA models are associated by geometry data. So, if the geometry features are marked with engineering semantic, then by feature geometry data mapping between different models during the process, the semantic information integration of a whole design-analysis process can be implemented.

There are four issues to resolve, semantic annotation, FEM analysis semantic representation, semantic information matching based on features, and the algorithm for generating FEA command flow. For the limit of the paper length, semantic annotation and the algorithm for generating command flow are not included in this paper.

4.2. FEM Analysis Semantic Representation

For the purpose of reusing FEA solution, the analysis routine of similar artifacts needs to be parameterized and expressed into a template, which includes three aspects of parameterization below.

4.2.1. Quantitative Value Parameterization: Quantitative value parameterization means to parameterize the numerical-value of FEA models, for example, the material attributes, the grid size, and the value and direction of load etc. Parametric technology is used to express the contents mentioned above. When using the FEA template, it only needs to modify the parameters to control the material attributes, grid size, and load parameters *etc.*

4.2.2. Qualitative Value Parameterization: Qualitative value parameterization refers to make the important term in the FEA process variable. For example, cell type of grids, and the results item of FEA etc. Variable technology is applied to the contents mentioned above. While using the FEA template, it is supposed to assign the variable of the cell type and the FEA results item to control the analysis program.

4.2.3. Feature Parameterization: If the load or boundary condition is applied on the specific feature in FEA template, the feature identity, for example, the surface number should be parameterized. When the action area of load or boundary condition is changed, it only needs to modify the corresponding feature parameters.

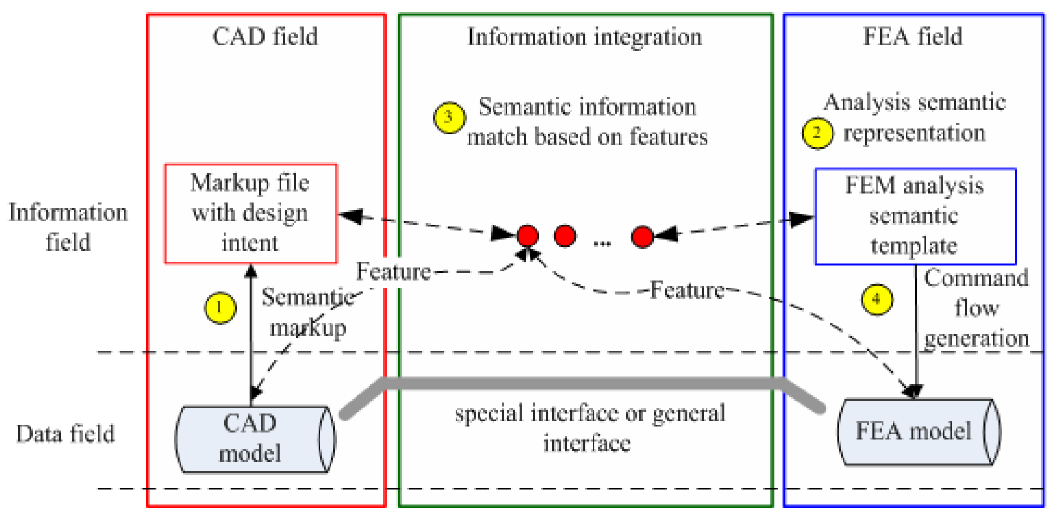


Figure 3. The Main Idea of CAD/FEA Semantics Exchange based on the Semantic File

5. Semantic Information Match based on Features

5.1 Engineering Semantic Extraction

The principle of extracting the engineering semantic is shown in Figure 4: (1)First, the attributes of parts are read, and the handles of geometry features annotated with engineering semantics are found; (2)Then, the geometry features annotated with engineering semantic are found according to the handle; (3)The engineering semantic which saved in the features is loaded and the key geometry descriptions of features are extracted and can be identified by "featureid".

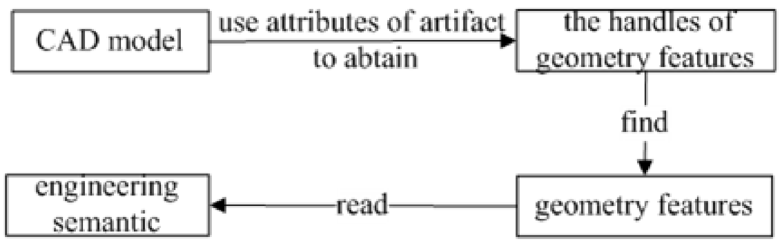


Figure 4. The Method for Extracting the Engineering Semantic Markup

5.2 Feature Extraction

The key points establish the relations between the geometrical model and the FEA model, the main idea is shown in Figure 5.

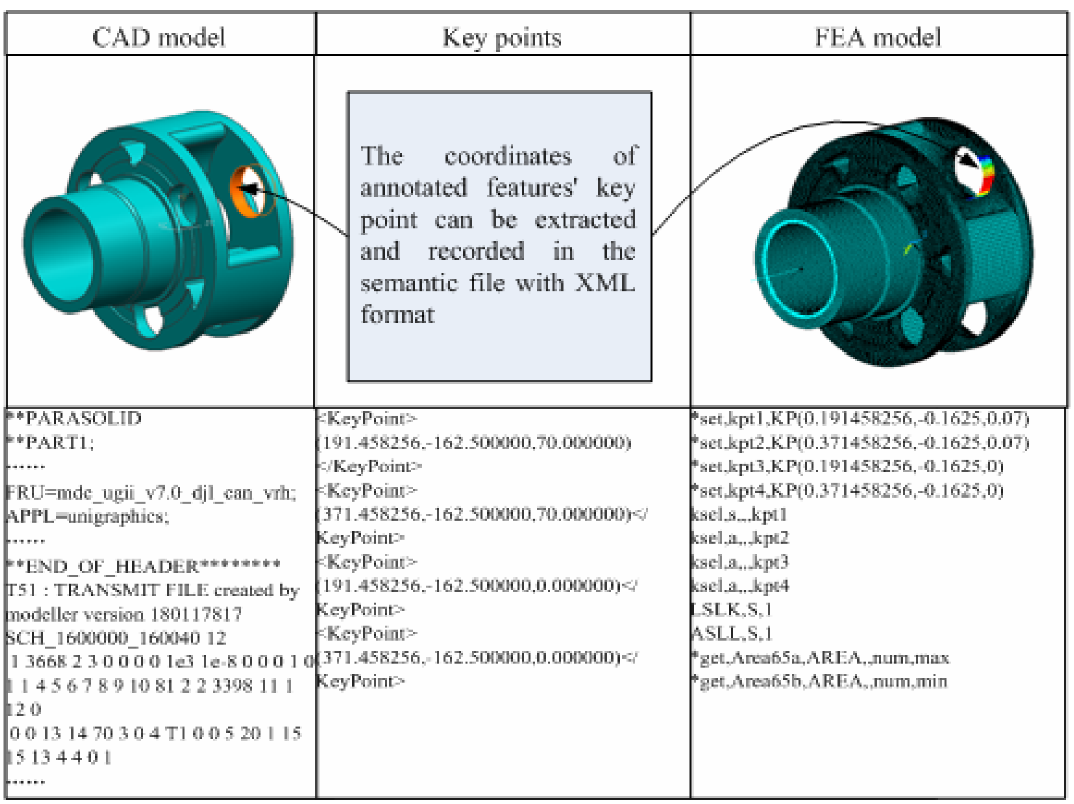


Figure 5. The Key Points Establish the Relations between the Geometrical Model and the FEA Model

The designers express the analysis requirement through selecting geometry features and apply the load and boundary conditions on them in a developed CAD environment. The model then is not only the geometry model but the physical model with the engineering semantic. The coordinates of annotated features' key point can be extracted and recorded in the semantic file with XML format.

The file will be used to generate the FEA command flow and define the action area in the FEA environment with the feature extraction process shown in Figure 6. According to the coordinates of key points, the line or curve can be selected, then the surface and solid.

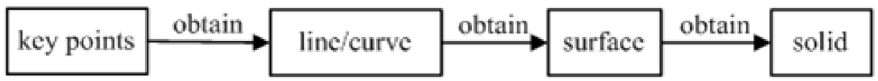


Figure 6. The Method of Finding Features which is Marked Engineering Semantic

5.3 XML Mapping Algorithm

XML mapping is to match the engineering semantic XML files which generated after user marked with FEA parameterized template XML files.

Concept of tree[8]: Tree is a finite set of $n(n \geq 0)$ elements, one tree can be represented as T , $T = (V, E, root(T))$, among this , V represents a finite node points set, $root(T) \in V$ indicates the tree's root node point, E represents frontier set, it is binary relation of V , satisfy irreflexive, dissymmetry, transferability. If $(u, v) \in E$, u is the parent node of v , denoted as $u = parent(v)$ or $v = child(u)$. If there is no meaning on the order for any node in the tree, then the tree is called unordered tree.

The concept of mapping of tree [4]: Suppose $T_1 = (V_1, E_1, root(T_1))$, $T_2 = (V', E', root(T_2))$ are two unordered trees, f is the mapping from T_1 to T_2 , defined as $f \in V \times V'$, and all (v_1, v_1'), $(v_2, v_2') \in E \cup E'$ meet below conditions: $v_1 = v_2 \Leftrightarrow v_1' = v_2'$, then the nodes participated the mapping in two trees are one-one correspondence; $v_1 = ancestor(v_2) \Leftrightarrow v_1' = ancestor(v_2')$, represents the ancestors relationship between mapping nodes.

The definition domain of mapping f is defined as $domain(f) = \{v \in V \mid \exists v \in V' : (v, v') \in E'\} \subseteq V$. The range domain of mapping f is defined as $range(f) = \{v' \in V' \mid \exists v \in V : (v, v') \in E'\} \subseteq V'$.

Fig.7 is an example of the mapping. XML files have the tree structure, when using the engineering semantic annotated XML files to map the FEA template files based on XML, the FEA template act as query tree Q , engineering semantic files act as data resource tree D . Suppose Q_{sub} is a subset of Q node points set, and D_{sub} is a subset of D node points set. Three following conditions could be satisfied, mapping f is called the mapping that Q qualifies as one text definition of D : $v_1 = v_2 \Leftrightarrow f(v_1) = f(v_2)$, $v_1, v_2 \in Q_{sub}$ and the labels of v_1, v_2 are not Command; $v_1 = parent(v_2) \Leftrightarrow f(v_1) = parent(f(v_2))$; If the parent node

D does not contain "featureid" attribute, the parent node of all the sub nodes in Q exists in D , moreover, the nodes in D all are sub nodes. If the parent node D contains "featureid" attribute, the parent nodes of all the sub nodes in Q exist both in D and the nodes set corresponding to "featureid", moreover, D and the nodes set corresponding to "featureid" are all sub nodes.

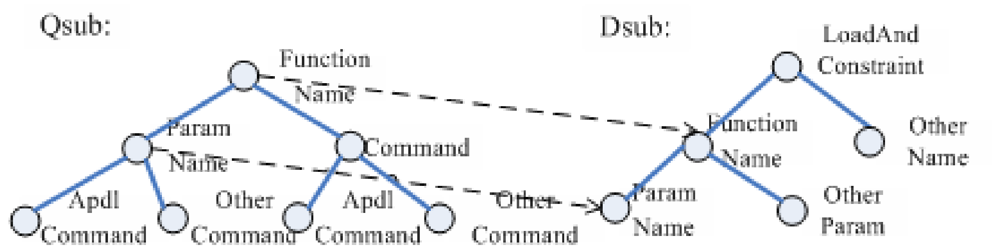


Figure 7. An Example of the Matching

6. A Case Study

The current task is to carry static analysis on win power gear box. The main forces on the box include, the gravity of the box itself, bearing loads caused by gear meshing force, the gravity of the moving parts such as gears and shafts at bearing hole, and gear mesh force at inner gear ring. According to engineering semantic description system: meta-model layer, model layer, instance layer, this paper takes the bearing hole as example. The Figure 8 is the segment of the concept relation among design domain ontology, FEA domain ontology, gear box ontology, and instances.

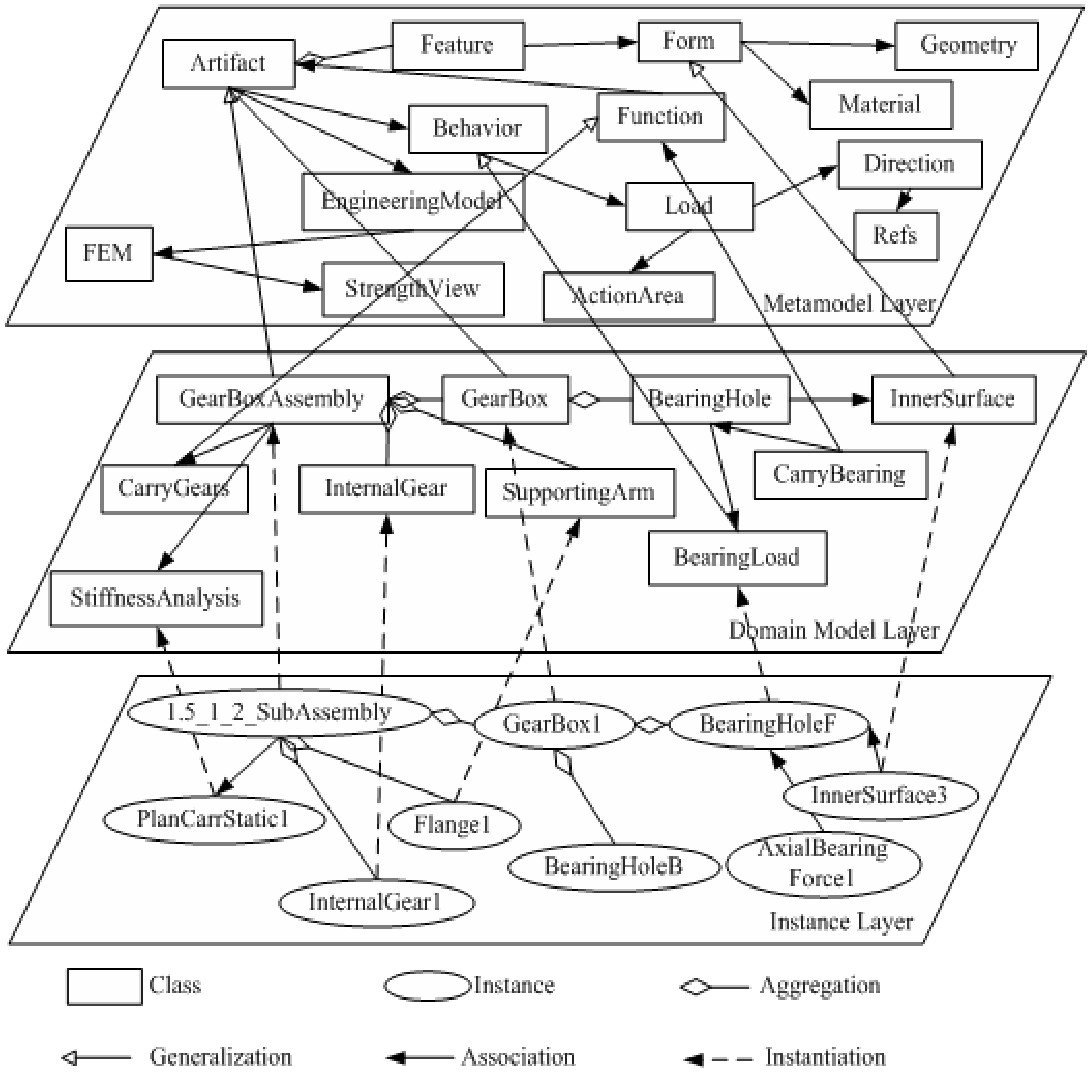
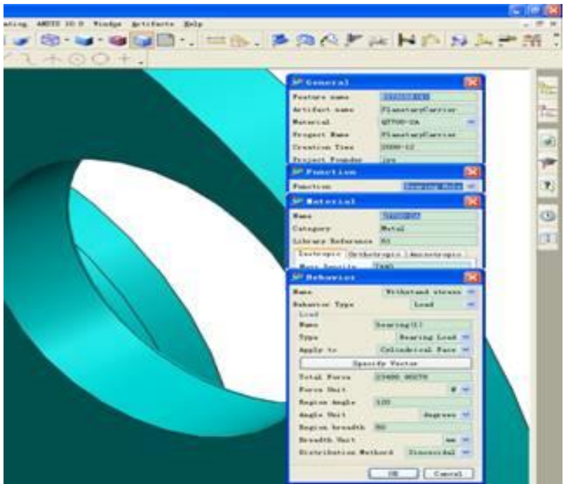


Figure 8. Ontology Structure Model of the Gear Box

The process of using the ontology above to semantically annotate CAD model of the gear box is shown in Figure 9. Semantic markup of geometric model has been finished by UGNX3 API. The interface of problem definition is showed in Figure 9a. After the designers establish a domain product model through the CAD tool, product model is associated with XML. The semantic markup of component model is showed in Figure 9b, according to the tag template file to generate engineering semantic table as shown in Figure 9c, and uses the schema file to check the generated XML files in accordance with the standard format. The markup can identify the constraints, loads and materials, which are used for the analysis. An internal Application Programming Interface (API) program was written to search for this markup in the model and execute the analysis producing the results shown in Figure 9d.

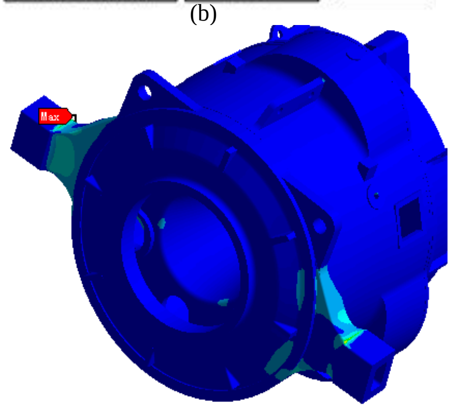


(a)

(b)


```
......
<LoadsAndConstraints>
    <BearingLoad  id="2" name="BearingHoleB" function="Bearing Hole"
featureid="5">
        <LoadType>RadialBearingLoad</LoadType>
        <BearingL>96400</BearingL>
        <RegionB>85</RegionB>
        <vecPointx>281.458256</vecPointx>
        <vecPointy>-162.500000</vecPointy>
        <vecPointz>70.000000</vecPointz>
        <vecx>-0.915873</vecx>
        <vecy>-0.401468</vecy>
        <vecz>0.000000</vecz>
        ......
    </BearingLoad>
    ......
<LoadsAndConstraints>
......
```


(c)



(d)

Figure 9(a). The Interface of Engineering Semantic Markup (b) a Sketch of Planet Carrier after Markup (c) the Result of Annotation (d) the Result of FEA

This article takes the static analysis of planet carrier as example, to explain the flexibility of utilizing semantic file to realize CAD and FEA information integration. As shown in Figure 10, the system reads the semantic annotated XML files which defines the load, boundary conditions and other information and FEA parameterized template files for analyzing the current issue. By semantic mapping, the semantic variables are instantiated in the parameterized template files. In fact, every semantic variable in FEA parameterized template files is assigned from the input at the design stage, After analyzing the engineering semantic XML files and FEA parameterized template files, the FEA command flow is generated. In this case, use ANSYS as the FEA software, therefore, the APDL command of ANSYS is generated.

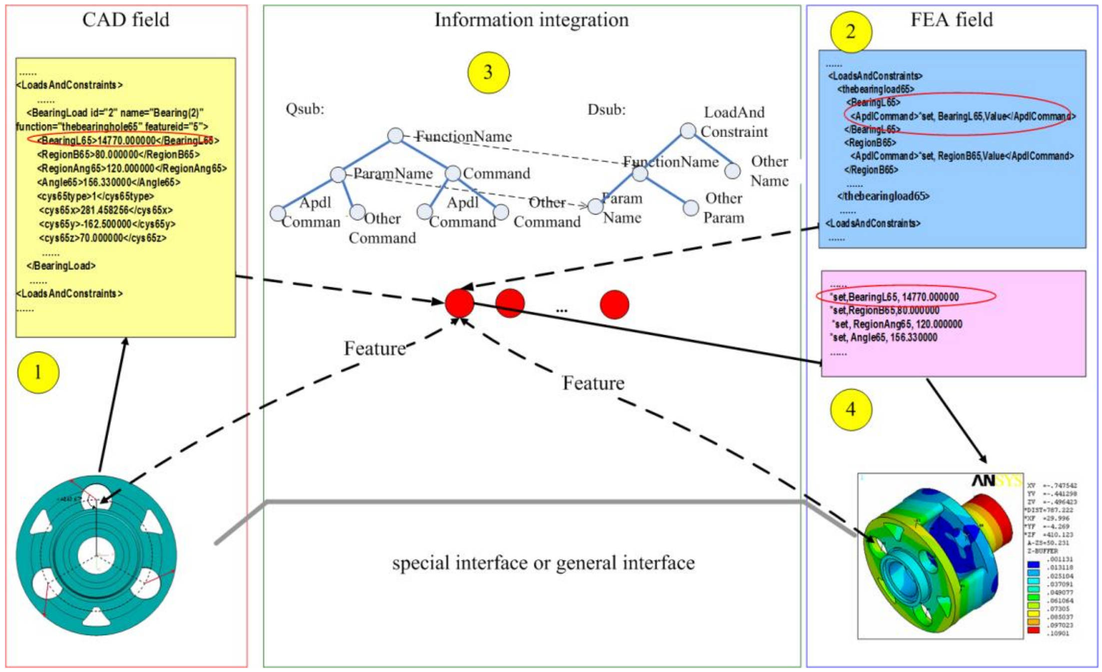


Figure 10. The FEA Results of the Planet Carrier

7. Conclusion

The concept of CAD model semantic markup is presented which assumes the use of an ontology-based approach. These involve the development of a shared design and FEA ontology, annotation of Feature-representations of a product and utilize the markup information in the FEA process. By semantic information mapping between CAD annotated files and finite element analysis solution files with XML format, the FEA template is instantiated into the concrete FEA solution and turns into executable command flow after. After the execution, it can be completed that the forward information from design domain integrated into analysis domain.

ACKNOWLEDGEMENTS

This work was financially supported by National Natural Science Foundation of China (No.51305051), the Liaoning Province Scientific Research Project Foundation (L2012189), and the Liaoning Province Natural Science Foundation (2014026006).

References

[1]. L. Ding, D. Davies and C. A. McMahon, Res Eng Design, vol. 3, no. 20, **(2009).**
[2]. M. Nawijn, M. J. L. Van-Tooren, J. Berends and P. Arendsen, "Automated Finite Element Analysis in a Knowledge Based Engineering Environment", Proceedings of the 44th AIAA Aerospace Sciences Meeting and Exhibit, **(2006)** January 9-12, Reno, Nevada.
[3]. R. S. Peak, R. E. Fulton, I. Nishigaki and N. Okamoto, Eng. with Comput., vol. 14, **(1998).**
[4]. S. J. Fenves. "Core Product Model for Representing Design Information", US Department of Commerce, Technology Administration, National Institute of Standards and Technology, **(2001)**.
[5]. R. Sudarsan, R. J. Fenves, R. D. Sriram and F. Wang, Computer-Aided Design, vol. 13, no. 37, **(2005).**
[6]. S. Szykman, S. Fenves, W. Keirouz and S. Shooter, Computer-Aided Design, vol. 7, no. 33, **(2001).**
[7]. J. Liker, M. Fleischer and D. Arnsdorf, Sloan Management Review, vol. 3, no. 33, **(1992)**.
[8]. Q. Z. Yao, X. C. Ding and Z. J. Ran, Application Research of Computer, vol. 4, no. 25, **(2008).**

Authors

Ma Qinyi, she is currently a lecturer in the school of Mechanical Engineering, in Dalian Polytechnic University of China. She holds a PhD (2011) in Engineering from Dalian University of Technology in China. Her research interests include knowledge-based product digital design, interoperability and the application of ontologies in CAD/CAE. E-mail: maqy@dlpu.edu.cn

Wang Yajun, she is a lecturer in the school of Mechanical Engineering in Dalian Polytechnic University of China for the last 4years. She studied Mechanical Engineering at Dalian University of Technology of China (1993) and followed post-graduate studies (1999). She holds a PhD (2009) in Enterprise Management from Dalian University of Technology of China. Her research interests extend to the fields of Enterprise Resource Planning, Enterprise Informationization. E-mail:wangyajun2004@hotmail.com

Lv Yan, Female, born in 1981, lecturer, major research interest covers digital measurement and control technology and intelligent instruments, green manufacturing and remanufacturing, etc. E-mail: lvyan@dlpu.edu.cn

Jin Xin, Female, born in March 1978 in Changchun City, Jilin Province, PhD, Lecturer of the School of Mechanical Engineering, Dalian Polytechnic University. She graduated from the School of Transportation, Jilin University, Ph. D. in July 2013. Her major is in Computer Aided Manufacturing of automobile manufacture area, include process designer, process simulate, logistics planning and procedure simulate. E-mail: jinxin@dlpu.edu.cn

Zhou Maojun, he is currently a professor in the School of Mechanical Engineering, Dalian Polytechnic University, China. His main research interests include management information system, knowledge-based product digital design, design, CAD/CAM/CAE, management of product design resource and process. E-mail: zhoumj@dlpu.edu.cn

