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Parametric Study on Bellows of Piping System Using Fuzzy Theory

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Abstract

This paper describes a novel automated analysis system for bellows of piping system. An automatic finite element (FE) mesh generation technique, which is based on the fuzzy theory and computational geometry technique, is incorporated into the system, together with one of commercial FE analysis codes and one of commercial solid modelers. In this system, a geometric model, i.e. an analysis model, is first defined using a commercial solid modelers for 3-D shell structures. Node is generated if its distance from existing node points is similar to the node spacing function at the point. The node spacing function is well controlled by the fuzzy knowledge processing. The Delaunay triangulation technique is introduced as a basic tool for element generation. The triangular elements are converted to quadrilateral elements. Practical performances of the present system are demonstrated through several analysis for bellows of piping system.

Key Words : Piping System, Bellows, Automatic Mesh Generation, Fuzzy Theory, Computational, Geometry, Finite Element Method, Solid Geometry, Shell Geometry

1. Introduction

Bellows is a familiar component in piping systems as it provides a relatively simple means of absorbing thermal expansion and providing system flexibility. Also, the bellows joint which used as a absorber or safety equipment to prevent the deformation or fracture of a structure, have been analyzed by finite element method (FEM) using axi-symmetric conical frustum element.

The FEM has been widely utilized in simulating various engineering problems such as structural deformation, thermal conduction, fluid dynamics and so on. The main reason for this is its high capability of dealing with boundary-value problems in arbitrarily shaped domains. On the other hand, a mesh used influences computational accuracy as well as time so significantly that the mesh generation process is as much important as the FEM analysis itself. Especially, in such large scale nonlinear FEM analyses that approach the limitation of computa- tional capability of so-called supercomputers, it is highly demanded to optimize the distribution of mesh size under the condition of limited total degrees of freedom (DOFs). Thus, the mesh generation process becomes more and more time-consuming and heavier tasks.

Loads for pre-processing and post-processing are increasing rapidly in accordance with an increase of scale and complexity of analysis models to be solved. Particularly, the mesh generation process, which influences computational accuracy as efficiency and whose fully automation is very difficult in 3-D cases, has become the most critical issue in a whole process of the finite element analyses. In this respect, various researches [1-5] have been performed on the development of automatic mesh generation techniques. Among mesh generation methods, the tree model method [2] can generate graded meshes and it uses a reasonably small amount of computer time and storage. However, it is, by nature, not possible to arbitrarily control the changing rate of mesh size with respect to location, so that some smaller projection and notch etc. are sometimes omitted. Also, domain decomposition method [3] does not always succeed, and a designation of such subdomains is very tedious for uses in 3-D cases.

In recent years, much attention has been paid to fuzzy knowledge processing techniques [6], which allow computers to treat "ambiguous" matters and processes. Here, the node density distribution, which is a kind of a node spacing function, was well controlled by means of the fuzzy knowledge processing technique, so that even beginners of the finite element analyses are able to produce nearly optimum meshes through very simple operations as if they were experts.

2. Principle and Algorithms

The phase of pre-processing is very important in the sense that the generation of a valid mesh in a domain with a complex geometry is not a trivial operation and can be very expensive in terms of the time required. On the other hand, it is crucial to create a mesh which is well adapted to the physical properties of the problem under consideration, as the quality of the computed solution is strongly related to the quality of the mesh.

Various automatic and semi-automatic mesh generation methods have been investigated so far. The requirements for ideal fully automatic mesh generation systems may be summarized as follows [6] :

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(a) Arbitrarily shaped domain can be subdivided into elements.
(b) Mesh size and its changing rate with respect to location can be easily controlled.
(c) Distortion of element shape can be avoided as much as possible.
(d) Total number of nodes can be controlled.
(e) Number of input data is smaller.

The requirement (a) is fundamental, while (b) and (c) are strongly related to mesh quality. The requirement (d) corresponds to the controllability of computational time and storage. If any system satisfies the items (a) through (d), optimum meshes can be generated with the balance of computational accuracy as well as efficiency. The requirement (e) is also indispensable for any systems dealing with 3D complex geometries.

2.1 Control of optimum mesh patterns by fuzzy theory

In this section, the connecting process of locally- optimum mesh images is dealt with using the fuzzy knowledge processing technique. Performances of automatic mesh generation methods based on node generation algorithms depend on how to control node spacing functions or node density distributions and how to generate nodes.

In the present system, nodes are first generated, and then a finite element mesh is automatically built. In general, it is not so easy to well control element size for a complex geometry. The present system stores several local node patterns such as the pattern suitable to well capture stress concentration, the pattern to subdivide a finite domain uniformly, and the pattern to subdivide a whole domain uniformly. A user selects some of those local node patterns and designates where to locate them.

2.2 Fuzzy control of node position

The fuzzy rules employed here can be generalized as :

$$\mathrm{RULE}^i : \text{IF } p \text{ is } A^i \text{ , THEN } q \text{ is } B^i$$

where RULE^i is the i-th fuzzy rule, A^i and B^i the fuzzy variables, p the value of node, and $\triangle p$ the difference of the current and the next values of p, i.e. $|p(n+1)-p(n)|$(n : the iteration number of node), respectively. The labels of the fuzzy variables are defined as follows.

As for A^i,
LARGE → p is much larger than 1.0.
MEDIUM→ p is larger than 1.0.
SMALL → p is little larger than 1.0.

As for B^i,
LARGE → q is positive and large.
MEDIUM→ q is positive and medium.
SMALL → q is positive and small.

As shown in Fig. 1, trapezoid type membership functions are utilized as those of labels of A^i and B^i from the viewpoint of simplicity.

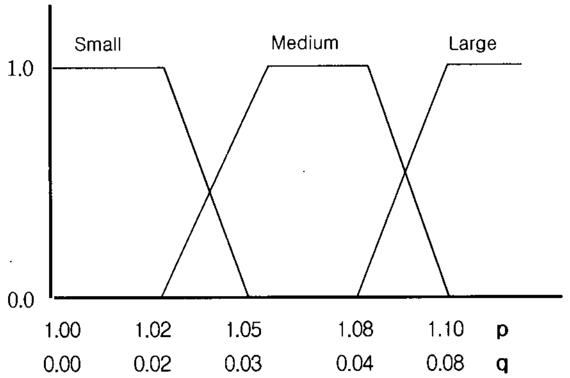


Fig. 1. Membership functions of labels of Ai(p) and Bi(q)

3. Outline of the System

3.1 Definition of Geometric Model

Geometric modelers are utilized to define geometries of analysis domains. One of commercial geometric modelers, Designbase [7] is employed for 3D solid structures. The advantage of Designbase is that a wide range of solid shapes from polyhedra to free-form surfaces can be designed in a unified manner. In these modelers, 3D geometric data are stored as a tree structure of domain - surfaces (free-form surfaces such as Bezier or Gregory type surfaces) - edge (B-spline or Bezier type curves) - vertices.

As an example, Fig. 2 shows a geometry model of 3D solid structures using Designbase.

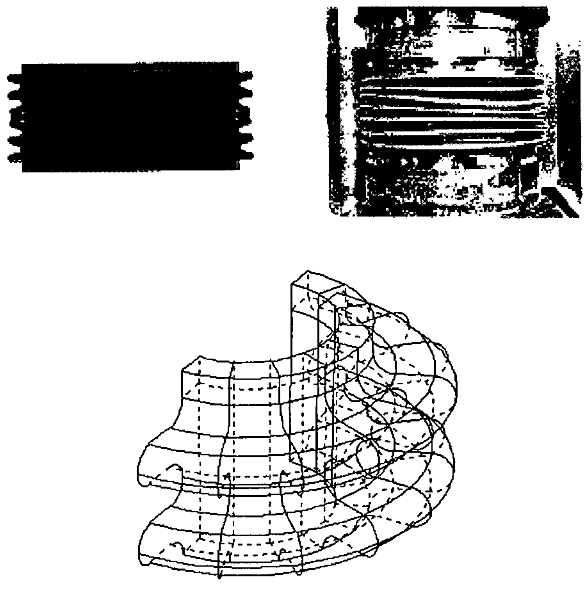


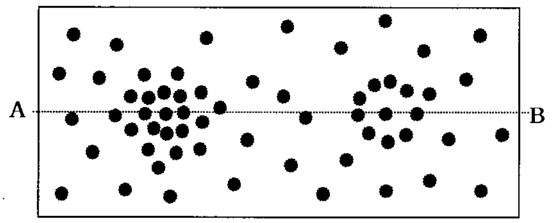
Fig. 2. Examples of geometry model

3.2 Attachment of material properties and boundary conditions

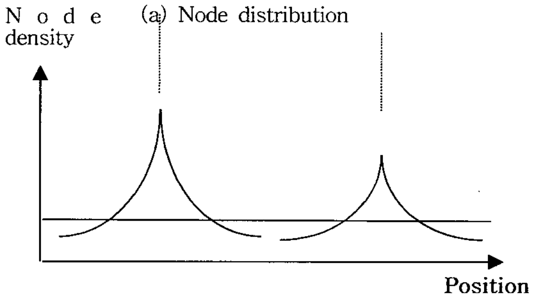
Material properties and boundary conditions are directly attached onto the geometry model by clicking the loops or edges that are parts of the geometric model using a mouse, and then by inputting actual values. The boundary conditions of the present system accept Direchlet's and Neumann's type. This system allows the user to enter mechanical loads in various forms for stress analysis. In a heat transfer analysis, the user can enter heat flux or temperature.

3.3 Designation of node density distribution

In the present system, nodes are first generated, and then an FE mesh is built. In general, it is not so easy to well control element size for a complex geometry. Example of node density function is shown in Fig. 3. A node density distribution over a whole geometry model is constructed as follows. The present system stores several local node patterns such as the pattern suitable to well capture stress concentration, the pattern to subdivided a finite domain uniformly, and the pattern to subdivide a whole domain uniformly. An user selects some of those local node patterns, depending on their analysis purposes, and designates their relative importance and where to locate them.



(a) Node distribution



(b) Node density function along line A-B

Fig. 3. Example of node density function

The concept of the fuzzy theory such as membership function is introduced here as follows.

Fig. 4(b) shows the membership functions corres- ponding to the node pattern around the hole and that of the crack tip respectively. For the purpose of simplicity, each membership function is given here to be a function of one dimensional location. In the Figs, the horizontal axis denotes the location,

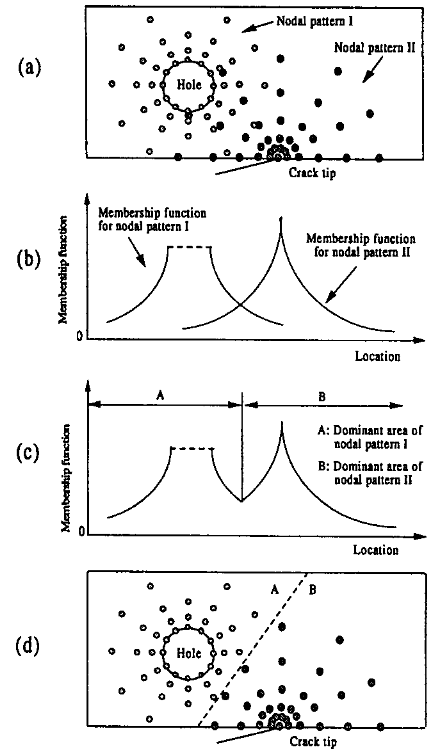


Fig. 4. Superposition of node patterns based on fuzzy knowledge processing

while the vertical axis denotes the value of the membership function, which indicates the magnitude of "closeness" or "membership" of the location to each stress concentration field. That is, a closer nodal location takes a larger value of membership function. Also, since finer node patterns are generally required to be placed near stress concentration fields, it is convenient to let the membership function correspond to a node density distribution. As shown in Fig. 4(c) and 4(d), the single analysis domain is automatically divided into two sub-domains A and B as a result of the fuzzy knowledge processing using membership functions. That is, the membership function with a larger value is employed through the comparison of values of both membership functions at each location. Both node patterns are placed in the sub-domain A and B as shown in Fig. 4(d). In other words, extra nodes are automatically removed from the superposed region of both node patterns.

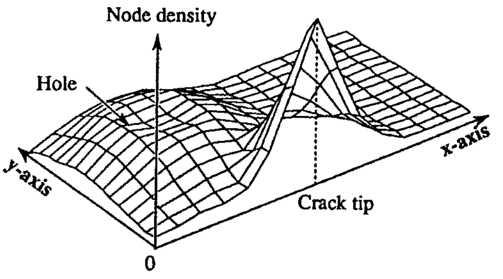


Fig. 5. Distribution of node density of whole domain

According to this definition, Fig. 5 also indicates the distribution of node density over the whole analysis domain including the two stress concentration fields. When designers do not want any special meshing, they can adopt uniformly subdivided mesh.

3.4 Node generation

Node generation is one of time consuming processes in automatic mesh generation. In the present study, the bucketing method [8] is adopted to generate nodes which satisfy the distribution of node density over a whole analysis domain.

Fig. 6 shows a schematic view of node generation. Candidate nodes are pick up one by one, starting from the left-bottom corner of the bucket, and are put into the bucket. A candidate node is adopted as one of the final nodes when it satisfies the following two criteria :

(a) The candidate node is inside the analysis domain (IN/OUT check).

(b) The distance between the candidate node and the nearest node already generated in the bucket satisfies the node density at the point to some extent.

Practically, the criterion (a) is first examined bucket by bucket. As for buckets lying across the domain boundary, the criterion (a) is examined node by node. It should be noted here that the nodes already generated in the neighboring buckets have to be examined for the criterion (b) as well when a candidate node is possibly generated near the border of the relevant bucket. Thanks to the bucketing method, the number of examinations of the criterion (b) can be reduced significantly, and then a node generation speed is remained to be proportional to the total number of nodes.

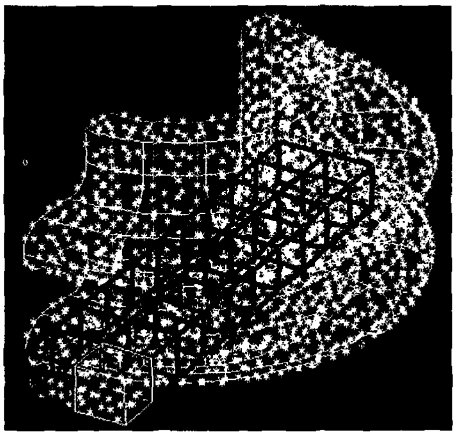


Fig. 6 A schematic view of bucket method

3.5 Element generation

The Delaunay triangulation method[1] is utilized to generate tetrahedral elements from numerous nodes given in a geometry. The speed of element generation by the Delaunay triangulation method is proportional to the number of nodes.

3.6 Additional techniques for 3-D shell geometries

The algorithms described in section 3.2 through 3.5 are sufficient for mesh generation of 3-D solid geometries. However, some additional techniques are necessary for mesh generation of 3-D shell geometries.

Using the Delaunay triangulation technique, one can generate triangular elements for shell geometry, which was selected surfaces in 3-D shell cases, while tetrahedral elements in 3-D solid cases. In this paper, the following technique to generate

quadri lateral elements is adopted.

Let us assume that an analysis domain is completely divided into a number of triangulars. Two neighboring triangulars are converted into a single quadrilateral. After this operation, a few triangulars still exist. Then, a triangular is divided into three quadrilaterals, and a quadrilateral divided into for smaller quadrilaterals. Finally, we obtain a complete quadrilateral mesh.

3.7 Preparation of input data

Through the interactive operations mentioned in section 3.2 and 3.3, an user designates material properties and boundary conditions onto the geometry model. Then these are automatically attached on nodes, edges, faces and volume of elements. Such automatic conversion can be performed owing to the special data structure of finite elements such that each part of element knows which geometry part it belongs to. Finally, a complete FE model consisting of mesh, material properties and boundary conditions is obtained.

4. Results and Discussion

To demonstrate actual performances of the present system, the system was applied to the analysis of a bellows. As an example, a deformation analysis was performed. Fig. 8 shows the example of the application of this mesh generator for 3-D geometry. It took about 25 minutes to define this geometry model by using Designbase. The mesh consists of 3,870 elements and 3,588 nodes. Nodes and elements were generated in about 15 minutes and in about 5 minutes, respectively.

Fig. 9 shows an example of attached non-uniform loads as a boundary condition in this analysis. Fig. 10 shows a calculated distribution of stress.

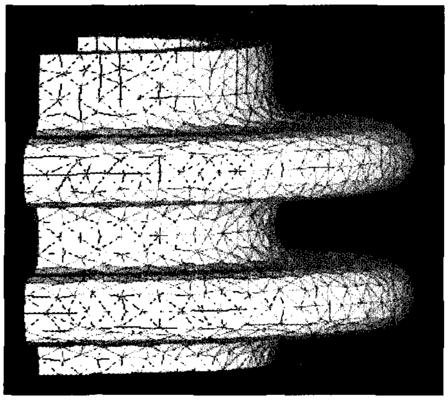


Fig. 8. Mesh for a symmetric 2 convolution of bellows

In general, mesh generation time increases in accordance with the increasing number of nodes or the number of total DOFs. Fig. 11 shows the measured processing time of a whole process plotted against the total number of nodes. It is observed that the node generation speed hear can be carried out in the averaged run time proportional to the number of nodes. Among the whole process, interactive operations to be done by a node patterns and the assignment of material properties and boundary conditions are performed in about 20 minutes. All the other processes are automatically performed.

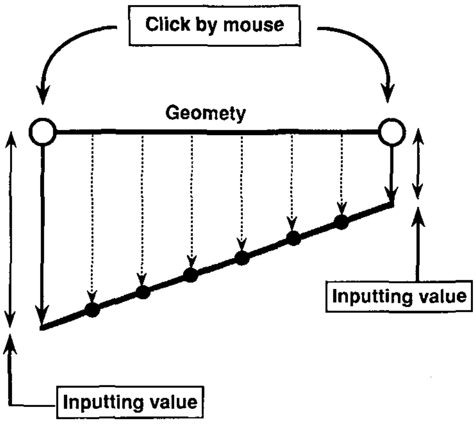


Fig. 9 Example of attached non-uniform loads as a boundary condition

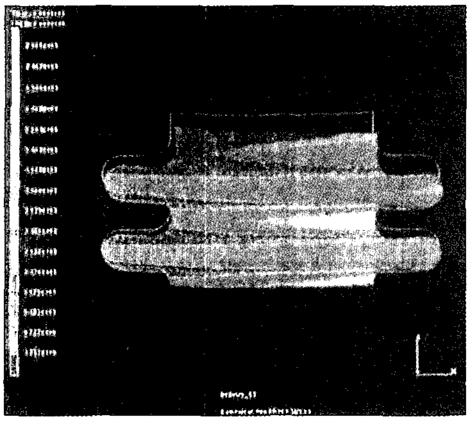


Fig. 10. Distribution of stress

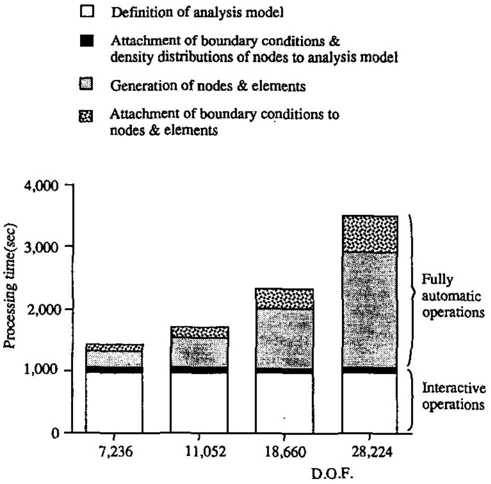


Fig. 11. Processing time vs. number of nodes

5. Conclusions

An automated FE analysis system for three- dimensional shell structures was developed. Here several local node patterns are selected and are automatically superposed based on the fuzzy knowledge processing technique. In addition, several computational geometry techniques were successfully applied to node and element generation, whose processing speed is proportional to the total number of nodes. To demonstrate practical performances of the present system, the system was used to an analysis of 3D structures such as bellows.

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