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Computational Mecanics as a Leading Technology:
Key Measure for Innovative Products

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Abstract

In the manufacture of components of industrial products, adequate efficiency, reliability, compactness as well as cost reduction have to be satisfied. Recently, in addition to the conventionally performed empirical or experimental methods, newly available numerical methods have been widely used in the process of designing such plants as nuclear, thermal and hydraulic power generators. Especially, the steady improvement of computer's capability has led to the emergence of the new method of computational science which can be used as an alternative for experimenting prototype, and consequently provides the different approach to create a concept for new products. The field of computer simulation we covered expands to many fields; structural analysis, fluid dynamics & heat transfer, electromagnetics and current circuit. And numerous fruitful results have obtained by the application of those technology. In this article, we will show you an overview of computational methods and some of their applications we have developed in Hitachi with a main attention to electric power plants.

1 Introduction

In recent years, the performance of computers drastically improved in both speed and memory size. Concurrently, numerous efficient computational schemes became available. Because of these preferable conditions, when highly advanced computing methods are properly applied, it has become practicable to comprehend or even predict previously intangible complicated phenomena. Computational mechanics has, thus, come to play a significant role in the progress of science and technology.

In enterprises, the method of computational mechanics has been widely used as an alternative way of testing prototype, and consequently great reduction in cost and time has attained. At the same time, this method has also provided the different approach to create a concept for new products.

In Hitachi, we have recognized the great importance of the computational mechanics since an early stage of its emergence. We have implemented original codes in several different fields and have utilized them for the exploitation of new products.

The involving technical fields for the programs we have developed are generally categorized as structural analysis, fluid dynamics, and electromagnetics. Structural analysis is used in a designing process of most of products. Computational fluid analysis and electromagnetic analysis are key to improve an efficiency of fluid machinery and equipment of power transmission system respectively. For the even better reliability, we have also provide the new codes which are appropriate for the calculation of phenomena occurred in or on products, where coupled analysis of either fluid-structure or fluid-electromagnetic field plays a critical role.

In the following section, we will give a brief description of the computational technology developed in Hitachi concentrating the topics to those on electric power plants.

2. General description of the infrastructure of a numerical analysis

Table 1 shows a table of the relating physical phenomena and target products, to which we have so far developed programs.

The method of structural analysis has been applied to almost every component of power plants. Recently, we concentrate especially on the development of techniques on dynamic model problems and on adaptive methods.

In the fluid analysis, we have developed several purpose-built programs specialized in such analysis as compressible flow, incompressible flow, multiphase flow or the flow with chemical reaction.

In the computation of static-electric field problems, we also have developed variety of techniques applicable to problems ranging from those on static electric/magnetic field and dynamic eddy current to those on electromagnetic radiation and electric circuit.

In addition, we have recently developed the numerical methods for both flow-induced vibration based on fluid-structure coupled analysis and for the electric breakdown (electrical insulation) based on fluid-electromagnetic-field coupled analysis.

Table 1. Fields of physics in computational mechanics and related industrial products

The following table shows the involving phenomena that can be (or will be able to be) treated with our codes. These computational methods are widely applied to estimate the performanceof products.

fields of physics	involving phenomenon	applied(target) products
Structural analysis	static (stress, deformation, buckling) destruction dynamic (vibration, impact) destruction	power generator any kinds of equipment
fluid analysis	incompressible fluid compressible fluid thermal transportation	gas turbine steam turbine combustor (combustion

	multi-phase flow multi-component flow chemical reaction combustion noise (flow-induced sound)	chamber) reactor equipment hydraulic turbine pomp heat exchanger piping system
Electromagnetics analysis	static electromagnetic field eddy current electromagnetic wave electric circuit	fusion reactor equipment transformer breaker rotating machine power converter
Multi-phenomena analysis	fluid-structure (vibration) fluid-electric field (current breakdown)	heat exchanger power transmission system

3. Structural Analysis

The importance of structural analysis has been increasing in order to retain structural reliability and rational designing process for such machinery as nuclear reactors, turbines and power generators. In practice, it is the most significant to analyze structurally complicated materials within a short term, considering those of physical characteristics precisely.

In this standpoint of view, we have developed nonlinear analysis techniques, which can treat complex phenomena with high nonlinearities: stress concentration, residual stress, thermal deformation, vibration, buckling and so on.

Furthermore, in order to reduce enormous efforts for mesh generations, we also have developed a completely automatic meshing system by integrating the concept of mesh-free techniques. With this system, efficient analyses became practicable, demanding only the minimum definition of shapes, loading and boundary conditions.

Moreover, we have developed an advanced system for more accurate analyses, based on the concepts of adaptive-mesh and automatic zooming. Adaptive-mesh method is a strategic procedure to obtain solutions with required accuracy by recursively refining meshes. In this process, discretization errors obtained from the calculation are used to refine meshes automatically. Zooming analysis is the alternative way to obtain accurate solutions. In this method, detailed analyses are conducted onto focused areas whose boundary conditions are derived from global-model simulations.

Figure 2 shows an example of an adaptive-mesh analysis. There, a crack tip near the fixed end of the nozzle is assumed. An adequately fine mesh is automatically generated around the crack tip, so that the stress concentration can be evaluated. These advanced simulation techniques for static and dynamic problems are widely applied in the designing process of power plants.

4. Flow analysis

As the prevalence of super-computers, recent trend in computational fluid analysis has also been shifted to a simulation of three-dimensional unsteady flow from that of more simplified model. In the calculation of turbulent flow, the Large Eddy Simulation or the direct simulation became popular. With those methods, unsteady behavior of fluids can be captured more accurately. Though there are still some difficulties in the simulation of turbulent flow at a high Reynolds number, we can utilize adequate numerical techniques according to the type of objectives and required accuracy.

An application of the flow analysis to a pump turbine runner in pumping mode is presented in Figure 2. Pump turbine can also work as a pump by inverting the rotation, and is also used at a pumped storage power plant. The reverse flow in the low-flow-rate range induces flow instability and can lead to hydraulic losses. With a highly accurate unsteady flow analysis, the mechanisms of the reverse flow has been able to be investigated. We can, thereby, improve the design of the blade profile that will extend operating range of flow rate and will enhance the hydraulic efficiency. Figure 3 and Figure 4 show the computational domain and the numerical results of the reverse flow at the inlet respectively.

Furthermore, the techniques of the computational fluid analysis has been widely applied to evaluate the characteristics of the main components of power plants and thus contributed to the improvement of their performance. In a piping system and a heat exchanger, vortex-induced vibration or fluid-elastic vibration can be a dominant factor of troubles. Thus, new analytical techniques which can be used to evaluate the effects of those vibrations were required. In order to meet the requirements, we have independently developed the code coping with the concept of the coupled analysis. In the code, the algorithm based on both fluid and structural analysis is integrated and applied in each time step of the calculation. By the elaborate calculation with the code, we have succeeded in computationally reproducing phenomena of fluid-elastic-vibration for the first time.

Figure 5 and 6 show the results of the fluid-elastic vibration in a typical configuration of tube arrays. The orbits in Figure 6 show that the tubes in the last row vibrate in comparatively large amplitudes at first. Then the energy of the vibration descends to the surrounding tubes and eventually causes the vibration of whole tubes. With this powerful new tool, it became feasible to computationally set the reliability standard in a design of a heat exchanger where a flow-induced vibration plays a significant role.

5. Electromagnetic Field Analysis

In recent years, the method of computational electromagnetics has been an indispensable key technology in a designing process of equipment in a power transmission system and of an electric circuit in a power electronic system. In Hitachi, we have developed some of so called composite programs for each simulation of substantially different, complicated phenomenon: there, techniques in variety of fields are employed in conjunction with the methods in electromagnetic-field analysis. These programs have been extensively utilized to optimize the shapes and configurations of devices and have served in the improvement of dielectric strength of the high voltage devices. In this section, we will show two of those methods: an analysis of particle motions under electrostatic field in the power transmission system and an analysis of electric circuits on the bus bars of a transistor inverter in the power electronic system.

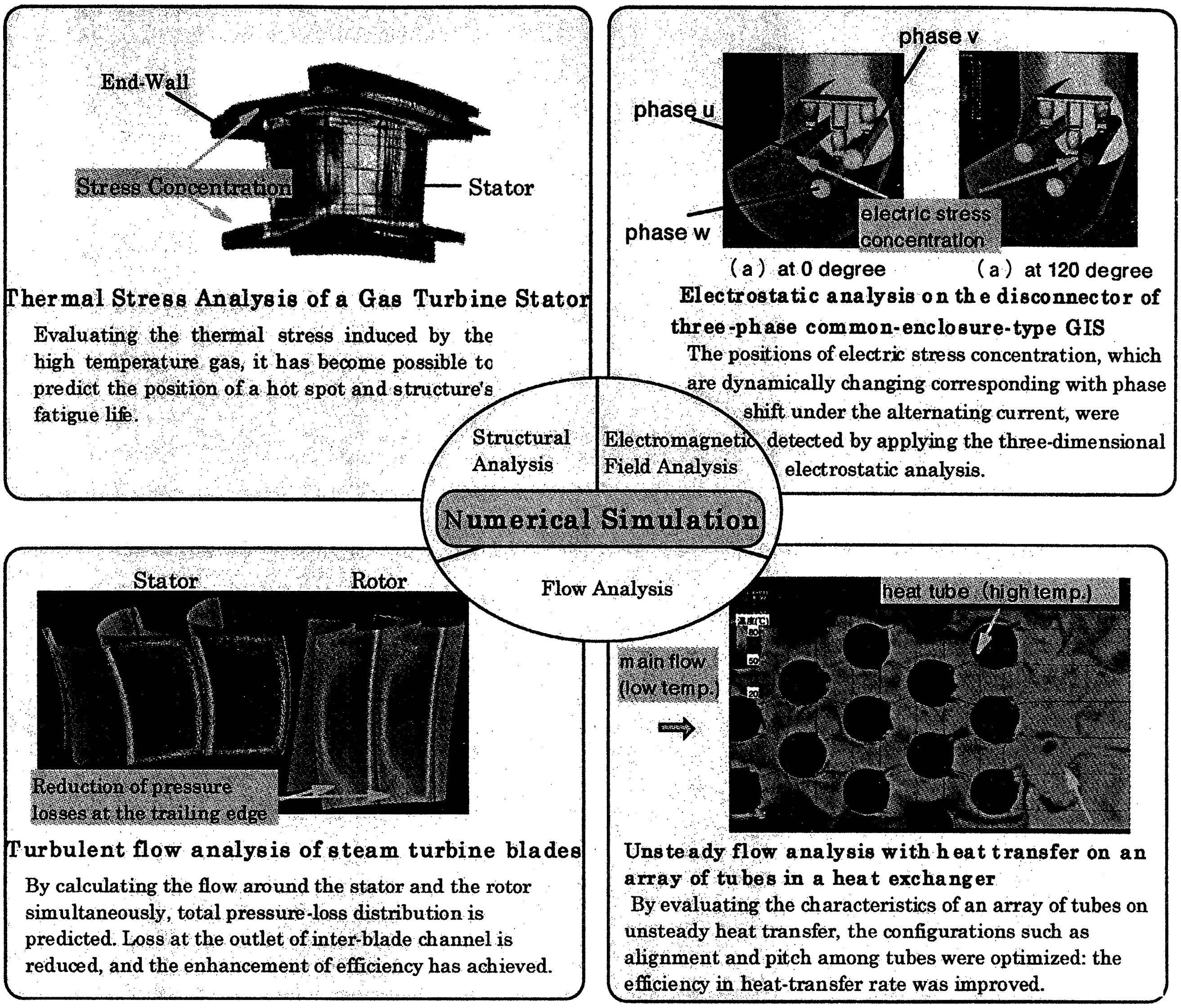
When a small fraction of metal debris happens to be sit in a pipe composing a part of a GIS (Gas Insulated gear System) in a power transmission system, the metal particles, electrically charged by the alternating current of a high-voltage conductor, will float around inside the pipe, which may eventually cause breakdown of electrical insulation. In order to cope with this type of problem, we have developed the three-dimensional simulation method which can trace the movements of particles under electrostatic fields. By using this program, we have predicted a typical behavior of a metal particle in a GIS⊐s bus pipe and have found the best-suited shape and the position of a particle trap.

On the other hand, in the design of a device in a power electronic system, the effect of stray inductance in a circuit cannot be ignored as the improvement of power semiconductor in the voltage/current ratings and the switching speed. We have, thus, developed the combined method; methods in electromagnetic fields and circuits are systematically integrated to take account of the dynamical effects of an electromagnetic field into the analysis of an electric circuit. Figure 7 indicates the calculated results of current distribution on bus bars of a transistor inverter. In our method, three-dimensional electromagnetic field analysis is coupled directly with circuit analysis: Inductance including the effect of unsteady fluctuation of electromagnetic field is evaluated with no approximation. With this program, the circuit's electrical behavior with stray inductance of the bus bars can be analyzed and, as a result, the value of voltage and current on power devices in the circuit can be precisely predicted. This technique is fully used to optimize a configuration of bus bar: to minimize over-voltages on power devices and to balance the electrical load among devices in parallel.

6. Conclusion

In the article we briefly introduced technologies and some examples of their applications in computational engineering developed in Hitachi. In order to extensively utilize these technologies in a process of production, the following two things are essential: Choose appropriate models and solution techniques, considering the typical characteristics of products and Exploit products being aware of the limit of the application and the accuracy.

The importance of computational mechanics in a production of industrial equipment will have been increasing. In Hitachi, since we consider computational mechanics as a central and fundamental technological tool for manufacture, we will continuously develop new computational methods highly effective in a process of production.



Thermal Stress Analysis of a Gas Turbine Stator

Evaluating the thermal stress induced by the high temperature gas, it has become possible to predict the position of a hot spot and structure's fatigue life.

Electrostatic analysis on the disconnector of three-phase common-enclosure-type GIS

The positions of electric stress concentration, which are dynamically changing corresponding with phase shift under the alternating current, were detected by applying the three-dimensional electrostatic analysis.

Turbulent flow analysis of steam turbine blades

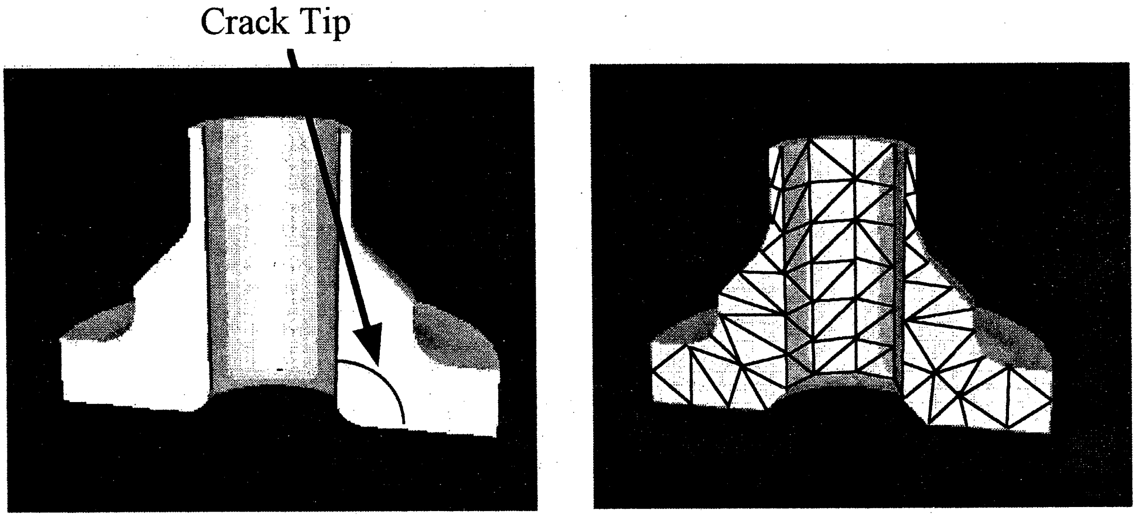
By calculating the flow around the stator and the rotor simultaneously, total pressure-loss distribution is predicted. Loss at the outlet of inter-blade channel is reduced, and the enhancement of efficiency has achieved.

Unsteady flow analysis with heat transfer on an array of tubes in a heat exchanger

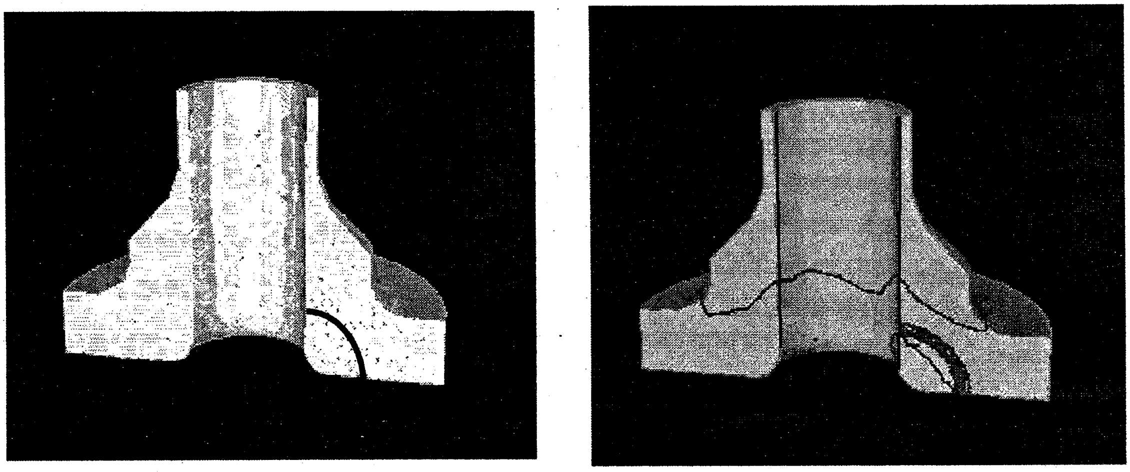
By evaluating the characteristics of an array of tubes on unsteady heat transfer, the configurations such as alignment and pitch among tubes were optimized: the efficiency in heat-transfer rate was improved.

Fig.1 Expanded fields in computational engineering and examples of its applications.

In the production of power plants, numerical simulation provides new methods to find a novel idea: drastic improvement in performance of equipment can be achieved with it. This method also provides a way to reduce development time by demanding much less number of model test. The method of computational mechanics is now becoming the most important infrastructure which supports the development of products.



(a)Model Profile (b)Initial Mesh Subdivision



(c)Adaptively Refined Mesh (d)Principal stress distribution

Fig. 2 Stress Analysis with Adaptive-Mesh Method

Above is an analyzed example of a nozzle with a crack tip near its fixed end. By the adaptive-mesh method, an adequate mesh is automatically generated to express the stress concentration near the crack tip precisely.

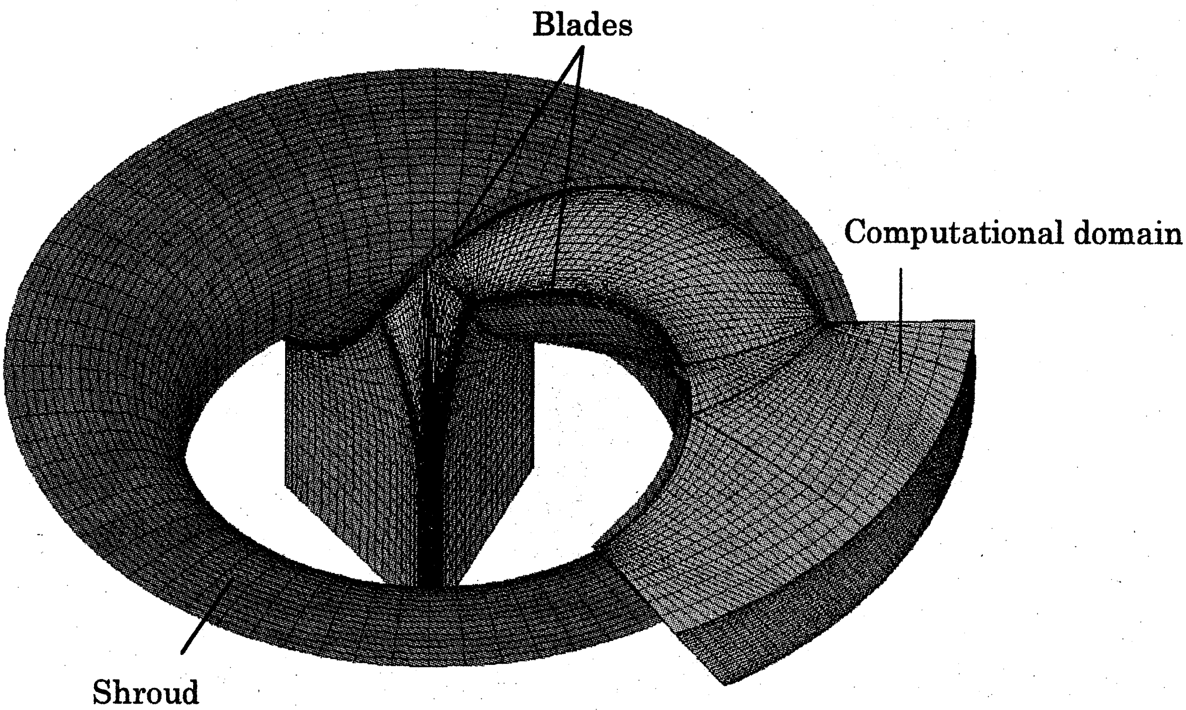
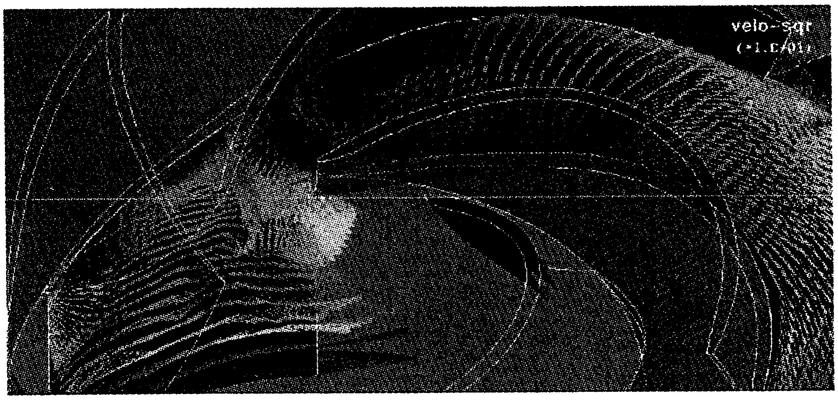
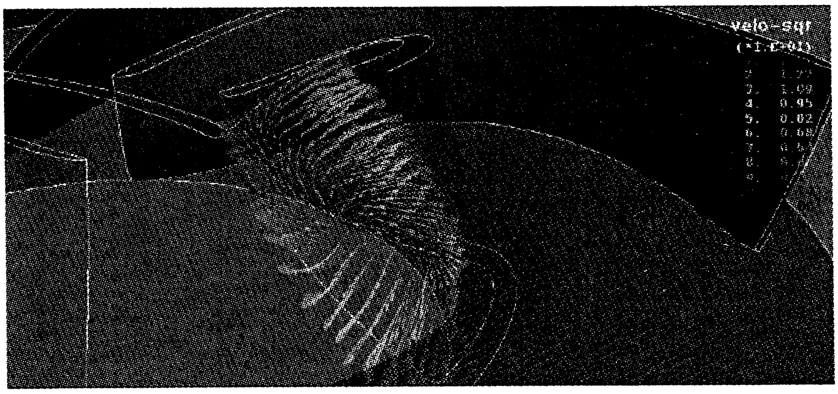


Fig.3 Computational domain of a flow analysis in the pump turbine

A system of three dimensional grids is generated in one of the inter-blades. Grid-generation techniques, such as the grid spacing control method, are indispensable for turbulent flow analysis with high accuracy.



(a)Velocity vectors on the shroud surface



(b)Velocity vectors on the cross sectional surface at the leading edge

Fig.4 Numerical results of a reverse flow in a pump turbine

The reverse flow at the blade-to-blade inlet is observed when flow rate is in the low range. By adapting the design that will help to suppress the reverse flow, the operation range of a turbine can be extended toward the low flow rate region.

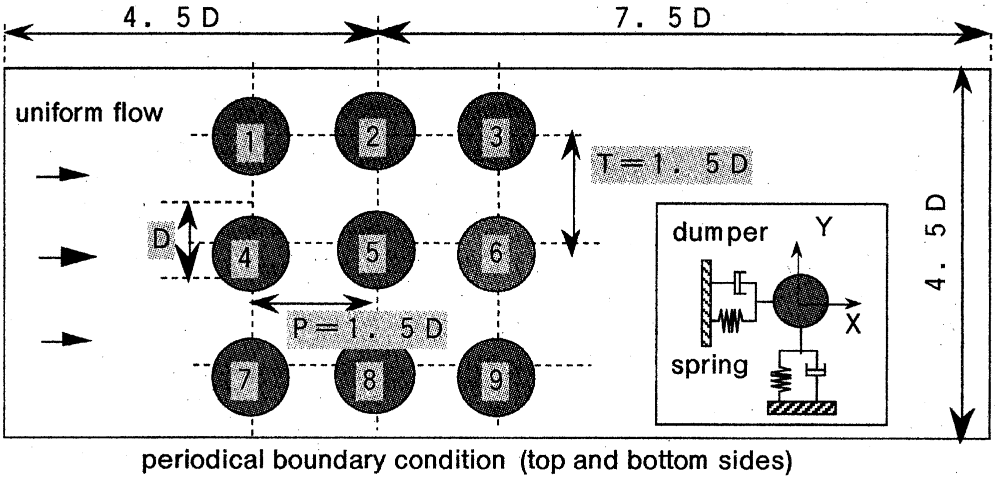


Fig.5 Calculation domain for the flow-induced vibration in a tube array

Calculation domain for a heat exchanger was shown. Each tube has two dimentional degrees of freedom and is assumed to be supported by elastic spring in x and y direction, so that the occurrence of resonance caused by fluid-structure coupling effect can be simulated.

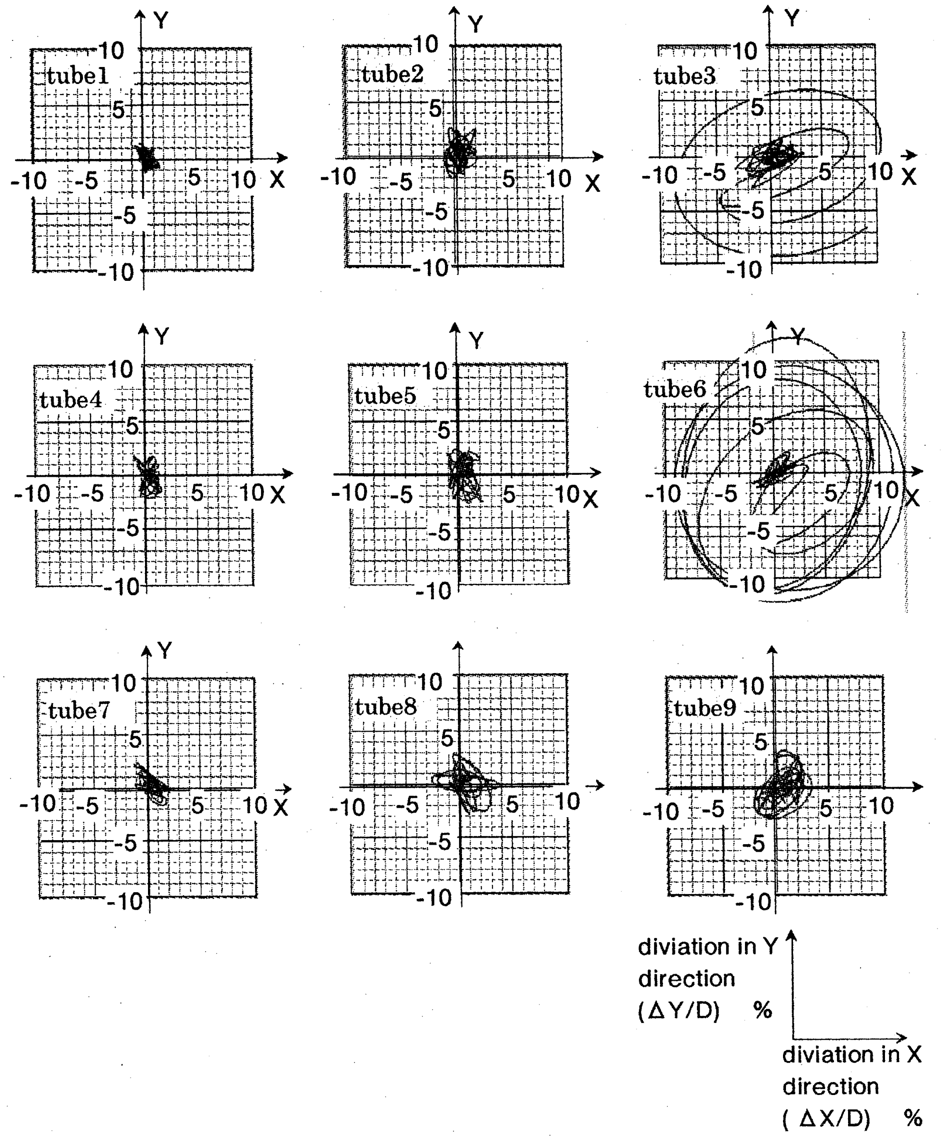


Fig. 6 The orbit of central position of each tube center when the fluid-elastic vibration occurred.

Increasing the inlet velocity, fluid-elastic vibration occurs at a critical velocity. In this example, the vibration began at the last row. The critical velocity, conventionally obtained by experiments, has also been able to be evaluated numerically.

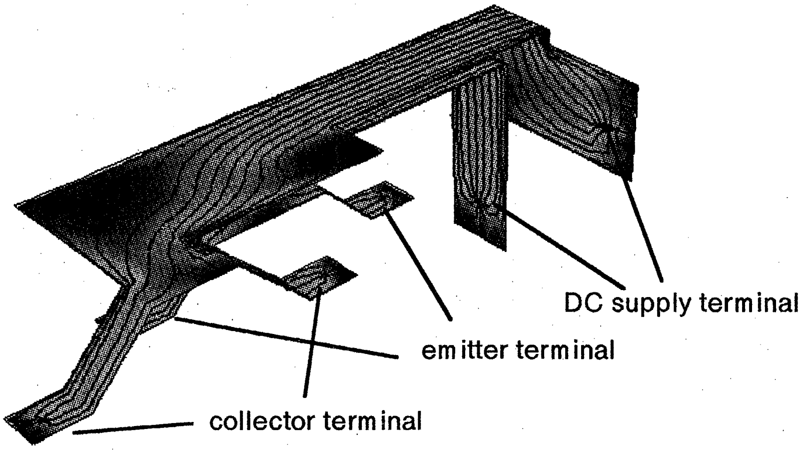


Fig. 7 Current distribution on bus bars

Stray inductance of the bus bars depends on the physical distribution of the electric current changing with the connected circuit's condition. Applying a thin plate model, three-dimensional magnetic field around the bus bars is simulated to determine the stray inductance. The current flow and the density distribution are indicated by solid lines and color gradation respectively.