論文の内容の要旨

論文題目　Finite Element Analysis for Fluid–Structure–Control Interaction Phenomena
（流体構造制御連成現象の有限要素解析）

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Fluid–structure interaction (FSI) phenomenon such as bridge deck flutter or aircraft wing flutter is an interdependent phenomenon between a fluid and a structure that affects their dynamic behavior. Since FSI gives rise to undesired vibration of structures and can even lead to disastrous consequences, the control of FSI phenomenon has been investigated for a long time. Control methods are classified into active and passive control methods. The latter uses a set of actuators and sensors in conjunction with a feedback loop. Although active control needs external resource such as electricity, it is easy to design various control laws and to adjust them. Therefore, active control has a potential to adapt the dynamic change of the surrounding fluid environment and the condition of the structure. Since this adaptivity is a strong advantage of active control, which passive control does not have, this thesis focuses on active control.

In general, the first step in control studies is to create a low-dimensional and simple model which can capture important characteristics of a controlled phenomenon. In control studies for FSI problems, it is conventional to use an aeroelastic model based on the lifting surface theories as a simple mathematical FSI model. This aeroelastic model takes many assumptions such as small deformation, harmonic vibration, truncation of high order modes, irrotational and inviscid flow, and simple geometry. Therefore, it cannot capture complicated behavior such as large deformation-induced geometrical nonlinearity, nonlinear flow due to the large deformation, boundary layer effect, flow separation, and so on. It is well known that nonlinearities in the structure and the aerodynamics can cause self-sustained oscillations of limited amplitude that remain constant in time, known as limit-cycle oscillation (LCO). Hence, the aeroelastic model cannot handle LCO too. As an example of problems which the conventional aeroelastic model is difficult to apply to, there is a flutter control problem for an unmanned aerial vehicle (UAV) with high-altitude and long-endurance (HALE) flights. Because HALE flights require very efficient aerodynamic, high-aspect-ratio wings with a low structural weight have been widely investigated. Such a wing often exhibits LCO, which may be beyond small deformation. Although the destructive vibration should be suppressed, some researchers have worked on energy harvesting from the LCO while a certain magnitude of vibration is allowed. Since the scavenged energy covers the energy consumed by active control, the energy harvesting contributes to the efficient flight. Because active vibration control and energy harvesting interfere each other, this is a balancing problem between active control and energy harvesting. Unlike normal control problems, the objective of which is to suppress vibration as much as possible, the balancing problem requires quantitative evaluation of the amplitude of LCO. Hence, the conventional aeroelastic model cannot be employed for this problem.

In the conventional approach, many simplifications make it impossible to consider various kinds of complexity. Whereas, in this thesis, by coupling detailed computational structural dynamics and computational fluid dynamics with active control systems, a high-fidelity fluid–structure–control interaction (FSCI) analysis method is developed. Since the developed method handles a large number of degrees of freedom (DOFs), it can capture various types of nonlinear behavior and enables to numerically evaluate complicated control problems including the aforementioned balancing problem. On the other hand, the large-scale model engenders two downsides. The first is a large amount of the computation time. However, thanks to the improvement of computer performance and parallel computing techniques, a high-fidelity and large-scale FSCI simulation is getting feasible. The second is unsuitability for control design. Since small-DOF models are usually demanded to design control laws, some dimensional reduction techniques need to be applied to the high-fidelity FSCI model. In this thesis, however, the control design is out of the scope. The purpose of this thesis is to develop a FSCI analysis method which enables highly accurate numerical evaluation of control laws which are given in advance.

Although some studies on high-fidelity FSCI analysis have been recently reported, the existing studies neglect the dynamics of actuators and sensors. In active control for FSI problems, light weight and small devices are desired in order to keep the lightness of the controlled structure. In this case, there might be a strong interaction between the dynamics of actuators and sensors and that of the structure. Moreover, the existing studies do not provide proper numerical examples to show the usefulness of FSCI analysis. Unlike the existing studies, this thesis takes account into the finite element model of piezoelectric materials as actuators and sensors. Also, it demonstrates a complicated control problem which the conventional modeling cannot cope with.

In Chapter 2, ignoring the dynamics of actuators and sensors, a high-fidelity FSCI analysis method was developed. Firstly, a partitioned iterative method based FSI analysis system was explained. In the partitioned iterative method, the mesh update, fluid analysis and structural analysis are conducted sequentially and iteratively. Secondly, an active control system was implemented into the FSI analysis system. In the structural analysis, control forces were added into the right-hand side vector as the external forces. The control forces were determined from the structural state such as acceleration, velocity, displacement and so on. In this chapter, two algorithms for the FSCI analysis were proposed. The first algorithm is to place the routine which determines the control forces into the FSI loop. The second is to place it outside the FSI loop. These two algorithms were compared by the stability analysis using amplification factor. Then, it was concluded that the first algorithm should be employed because the second has a possibility to excite high-order vibration modes.

In Chapter 3, the FSCI analysis developed in Chapter 2 was verified by a flutter control problem. In this problem, a flat plate is placed in a uniform flow. When the mainstream velocity exceeds the flutter velocity, the flutter occurs. Active control is introduced to improve the flutter velocity. This problem is classical, and the conventional approach based on the lifting surface theories has been often used to derive the aero-servo-elastic mathematical model, which is needed to design control laws. In this chapter, it was examined whether the FSCI simulation shows the characteristics of the control laws, which can be roughly predicted during the control design stage. Firstly, based on the Schwartz's method, which is a two-dimensional unsteady lifting surface theory, the aero-servo-elastic mathematical model was constructed. Then, the model was transformed to the state-space representation, and the output feedback control was designed by the root-locus method. Secondly, the flutter problem with the control law was simulated by the developed FSCI analysis. Then, the quantitatively reasonable results were obtained in terms of the improvement of the flutter velocity.

In Chapter 4, the dynamics of actuators and sensors were considered. This thesis focuses on piezoelectric materials, which have good conversion property between mechanical and electric energy. Moreover, they have excellent properties such as light weight, easy fabrication, and so on. Therefore, piezoelectric materials have been widely used as both actuators and sensors. There have been many numerical and experimental studies on active vibration control by piezoelectric materials. In this chapter, two finite element models of piezoelectric materials were explained. The first type is the finite element model based on standard solid elements. However, a solid element needs a lot of elements to discretize thin structures. Structures exposed to FSI and the integrated actuators and sensors are usually thin. Therefore, the more efficient finite element model is desired. The second is the finite element model based on solid shell elements. Solid shell elements have both characteristics of solid and shell elements. The domain is discretized like solid elements, but the high-aspect-ratio elements are allowed thank to the aspect of shell elements. Besides, solid shell elements can skip complicated laminate theories because solid shell elements allow for the modeling of each single layer with one separate element. Because the modeling of composite structures is inevitable in active vibration control studies, solid shell elements are expected to be suitable. After the introduction of the finite element models of piezoelectric materials, the models were implemented into the FSCI analysis developed in Chapter 2. The behavior of piezoelectric materials is an electro–mechanical coupling phenomenon. Since there is no interaction between fluid and electric field, the implementation was realized by simply replacing the structural analysis in the previous FSCI analysis into electrostatic–structure interaction analysis. For the actuation mechanism, instead of prescribing the control forces, the piezoelectric actuators were driven by the applied voltage, which was treated as the electric essential boundary condition. Also, in the routine of the control laws, the applied voltage was determined from the voltage measured by the piezoelectric sensors.

In Chapter 5, the FSCI analysis with piezoelectric materials developed in Chapter 4 was qualitatively verified by the following three analyses. The first is the analysis of a piezoelectric bimorph actuator in non-flowing fluid. The second is the analysis of vortex-induced vibration (VIV) of a cantilevered beam embedded with two piezoelectric sensors. The third is the analysis of active control of the VIV, which occurs in the second analysis. In the third analysis, one of the piezoelectric materials in the second analysis was operated as an actuator, and the direct velocity output feedback control was designed. From these three analyses, it was confirmed that piezoelectric sensors and actuators were modeled properly, and that the interaction between fluid and structure and the effect of the feedback control system were reproduced reasonably in the simulations.

The numerical examples in Chapter 3 and 5 were small deformation problems, and their complexities are not heavy. In Chapter 6, the usefulness of the developed FSCI analysis was shown by solving the aforementioned balancing problem between active vibration control and piezoelectric energy harvesting. An energy harvester was modeled by a closed circuit with a resistor and a piezoelectric material. The model was implemented into the FSCI analysis system. In the numerical example, a cantilevered beam embedded with many piezoelectric materials was placed in a uniform flow. Firstly, the materials were used in the open-circuit condition. Then, it was confirmed that LCO with large amplitude appeared when the mainstream velocity was a certain value. Secondly, the materials were used as actuators, sensors, and energy harvesters. The relation among the generated energy by the harvesters, consumed energy by active control, and the amplitude reduction was investigated. The change of the structural displacement induced the transition of the LCO state. As a result, the energy pumped into the structure from the surrounding fluid was also changed, which sometimes overshadowed the shunt damping effect and the active control damping effect.

In summary, this thesis developed the FSCI analysis method to investigate highly nonlinear and complicated control problems. The general case which ignores the dynamics of actuators and sensors and the special case which has the finite element model of piezoelectric materials were provided together with the verifications. Then, for the sake of demonstrating the usefulness of the FSCI analysis, the balancing problem between active vibration control of LCO and energy harvesting was analyzed. The numerical example showed that even in such a complicated FSCI problem, the FSCI analysis enables us to numerically evaluate given control laws.