Multi-Objective Design Exploration and Aeroelastic Analysis forNext-Generation Regional Jet Development

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論文内容要約

According to the recent jet fleet forecast, in the regional jet segment (60 – 99-seat class), the fleet size will rise from 1881 in 2012 to 3866 in 2032, and there will be demand for 3145 airplanes. The regional jet market is attractive to airframe manufacturers but there are many competitors in this class: CRJ700/900/1000 (Bombardier), ERJ170/190 (Embraer), ARJ21 (China's COMAC), and Superjet100 (Russian's Sukhoi). To compete for market share, new regional jets must meet strong demands on environmental friendliness, such as low fuel burn, low noise, and low emission.

In March 2008, Mitsubishi Heavy Industries, Ltd. (MHI) officially launched the Mitsubishi Regional Jet (MRJ), a next-generation regional jetliner, and Mitsubishi Aircraft Corporation was established by MHI to conduct MRJ's development and its business. The MRJ is the next generation regional jet designed by combining cutting-edge technologies in aerodynamic design, noise analysis, composite materials, and engines. With more than 20% higher fuel efficiency than conventional jets of the same class and a significant reduction in noise and emission gas, the MRJ excels both in operational economic efficiency and environmental friendly.

The development of MRJ, which is the first commercial jetliner in Japan, in addition to being the first Japanese passenger aircraft since the YS-11 produced 40 years ago. Therefore, an industrial-academic- government cooperation in Japan has been actively used to develop the cutting-edge technologies towards success of the MRJ project.

In the MRJ project, MHI and Tohoku University have developed the multidisciplinary design optimization (MDO) system and the multi-objective design exploration (MODE) approach was successfully applied to wing design and engine-wing integration. In these applications, both aerodynamic performance, such as aerodynamic drag under cruising conditions, and structural weight were optimized with constraints of strength and flutter requirements, and useful knowledge regarding aerodynamic and structural wing design was successfully extracted. However, these previous MODE applications left room for further improvements in the following.

- Need to introduce detailed buckling evaluation using a realistic aircraft structure model
- Need to introduce more accurate but efficient aeroelastic analysis in transonic region
- Need to introduce aeroelastic analysis with structural nonlinearity due to control surface free-play

The objective of the present thesis is to establish the MODE method and advanced aeroelastic analysis methods for next-generation regional jet development. These methods are for the previous MODE improvements and should be applicable to the design process of a real aircraft. To achieve this goal, MODE focusing on structural design with buckling evaluation and aeroelastic reduced-order models (ROMs) for wing flutter and control surface limit cycle oscillation (LCO) have been proposed.

First, a MODE was performed for structural design of a regional jet horizontal tail. In this study, combination between the stringer-pitch and the rib-pitch was optimized based on detailed buckling evaluation and MSC/NASTRAN static analysis using a realistic aircraft structural model. The resulting Kriging model provided several solutions with improvements, in both the structural weight and the number of structural components, compared with the baseline design. Furthermore, visual data mining for the design space was performed using self-organizing map (SOM). SOM divided the design space into clusters with specific design features. With regard to the stringer-pitch, the particular pitch size was effective to reduce both the inboard and outboard weights. On the other hand, smaller and larger rib-pitch were effective to reduce the inboard and outboard weights, respectively. The present MODE application not only provided the optimal solutions, but also redefined the design problem itself from the fixed-rib-pitch problem into a rib-pitch variable problem for further improved design solution. The design knowledge acquired from the present application was utilized in the Mitsubishi Regional Jet (MRJ) horizontal tail design.

Next, a CFD-based aeroelastic ROM for a regional jet wing was proposed and validated by the experimental data as the second study. In this study, the unsteady aerodynamic state-space model was generated from aerodynamic responses to step excitation of individual mode using the eigensystem realization algorithm (ERA) system identification technique and connected to the structural dynamic state-space models within the MATLAB/SIMULINK environment to simulate combined static and dynamic aeroelastic responses. The present ROM was first validated for its capability to simulate aeroelastic responses of the AGARD 445.6 wing, not including the static aeroelastic effect, and showed excellent prediction of the aeroelastic responses compared to those computed directly using the full-order aeroelastic model of the Tohoku University Aerodynamic Simulation (TAS) code. The ROM was then validated using the transonic wind tunnel testing (WTT) data of a wing-pylon-nacelle (WPN) model. The step amplitudes for generating the unsteady aerodynamic ERA model were chosen from the static aeroelastic solutions in the dynamic pressure range of interest and the initial generalized aerodynamic forces (GAFs) were computed directly from the restart of the steady rigid solution to simulate the static aeroelastic effects. Although the present ROM showed some discrepancies in the unsteady component of the aeroelastic responses at higher dynamic pressures, possibly due to insufficient step excitation amplitude of the first mode, the ROM provided good prediction of the combined static and dynamic aeroelastic responses and good agreement with the TAS solution on flutter speed, at which damping trend of the time histories of modal displacement shifts from stable to unstable. The present ROM can reduce the computation costs in simulating the aeroelastic responses of the wing and WPN configuration, including static aeroelastic effects, by more than one order of magnitude compared to the CFD-based full-order aeroelastic model. The present aeroelastic ROM appeared promising in enabling practical use of CFD-based flutter prediction in actual aircraft design.

In the next study, a CFD-based aeroelastic analysis method was proposed to simulate control surface LCO induced by free-play gap. The present method is based on the aeroelastic ROM proposed above and extended to treat structural nonlinearity due to the control surface free-play by generating the additional feedback line of generalized residual forces in the MATLAB/SIMULINK model. To reduce the problem size and computation time, the fictitious mass (FM) modal approach was used, which can afford the possible local change of stiffness. The present method was first validated for its capability to simulate aeroelastic responses of a regional jet horizontal tail (HT) model without free-play, and showed good prediction of flutter characteristics measured in the transonic flutter WTT. The present method was applied to the HT model with the elevator free-play gaps. Although there were some differences between computed and measured LCO ranges, the present method well predicted the nonlinear LCO behavior in its amplitude and frequency measured in the test and showed potential for accurate prediction of control surface LCO due to its free-play gap. The discrepancy in computed and measured LCO ranges is possibly due to inaccurate prediction of the static hinge moment and additional study is underway to fully understand the source of the discrepancy, focusing on CFD mesh quality, flow viscosity, and static aeroelastic deformation.

The methods developed in this study contributed to the development of a next-generation regional jet aircraft. The achievements described in this thesis will open the possibility of MODE approach and aeroelastic analysis for further detailed aircraft design and certification activities. For the future work, the prediction accuracy of static hinge moment by the present CFD should be further investigated with considering its effects on LCO characteristics. Moreover, the aeroelastic ROM methods proposed in Chapter 3 and Chapter 4 have to be validated in the MRJ flight testing towards the type certification activities. MODE approach with further improved aeroelastic analysis will be indispensable for future aircraft.