Abstract（論文の内容の要旨）

Title of Dissertation（論文題目）

Successive Search-Based Multi-Objective Optimization and its Application to Multidisciplinary Conceptual Design of Reusable Launch Vehicles（逐次探索による多目的最適化および宇宙往還機の複合領域概念設計への応用）

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Body（本文）

Huge improvements in cost, operability, and reliability are required for space transportation systems in order to promote the commercial use of outer space, and reusable launch vehicles (RLVs) are expected to satisfy these requirements. Among some possible concepts of RLVs, the present study focuses on horizontal takeoff two-stage-to-orbit (TSTO) RLVs with airbreathing engines. An essential research activity for realizing such RLVs is to perform their conceptual design studies early so as to clarify system-level goals and associated technical issues. It is desired to investigate conceptual design solutions while considering substantial uncertainties in mission requirements and future technological developments. In this dissertation, multi-objective, multidisciplinary design optimization (MDO) of TSTO RLVs with airbreathing engines is conducted in order to obtain promising conceptual design options and to reveal tradeoff relations between mission requirements, technological constraints, and the resulting vehicle scale. To this end, research efforts are devoted to three subjects below.

First, a novel multi-objective optimization method that can solve multi-objective optimal control problems efficiently is developed. In order to handle parameter interactions and equality constraints that are inherent in optimal control problems, the proposed method successively searches a Pareto optimal solution using a gradient-based optimizer. Since gradient-based optimization methods cannot solve a multi-objective problem directly, the original problem is transformed into a relevant single-objective one by means of min-max goal programming, and it gives a Pareto optimal solution. As the obtained solution depends on the parameters specified in the goal programming, the proposed algorithm successively determines the parameters so that the resulting solution will be located near the farthest point from the solutions obtained so far in the objective space. Existing solutions on the Pareto front are mapped into a lower dimensional Euclidean space using dimensionality reduction techniques. Then, the farthest point in this Euclidean space can be searched via a Voronoi diagram. Next, the found point is mapped back to the original objective space, and it gives the farthest point

from the existing solutions in terms of the geodesic distance along the Pareto front. By successively employing min-max goal programming, the gradient-based optimization method, and the farther-point sampling on the Pareto front, a set of Pareto optimal solutions with a good diversity is finally obtained. Performances of the present method and a multi-objective genetic algorithm (MOGA) were compared by conducting numerical experiments with a test optimal control problem. The result revealed that the proposed technique outperforms the MOGA with regard to optimality, constraint residual, and diversity of the obtained solutions. Another advantage of the developed method is that it can provide as many solutions as needed independently of the solution quality, which is desirable in practical usages. In addition, the applicability to a more complex and practical problem is demonstrated.

Second, in order to incorporate thermal protection system (TPS) analysis into MDO frameworks of RLVs, a numerical method for conducting simultaneous design optimization of flight trajectory and TPS is developed. The design optimization problem is formulated as a transient heat-constrained optimal control problem, where ODE-expressed vehicle dynamics and PDE-expressed thermal behavior are coupled. So as to solve the formulated problem efficiently, the discretization of the PDE in the spatial coordinate using a Legendre pseudospectral method with a special treatment of boundary conditions is proposed. The boundary condition at the TPS surface is described by convective aerodynamic heating and thermal radiation, and that at the TPS backface is defined as the adiabatic condition. Using the developed method, pseudospectral discretization that automatically satisfies these boundary conditions is obtained. The discretized PDE becomes a set of ODEs, and they are solved using a conventional optimal control method along with the ODE-expressed vehicle dynamics. Superior convergence of the proposed technique to previous methods is validated through solving a test problem.

Finally, multi-objective MDO studies of two kinds of TSTO RLVs with different airbreathing engines [pre-cooled turbojet (PCTJ) engines and rocket-based combined-cycle (RBCC) engines] are performed employing the techniques developed above. Numerical frameworks consisting of vehicle geometry definition, mass property estimation, aerodynamic computation, airframe-propulsion integrated analysis, TPS analysis, and flight trajectory calculation, are constructed. In the TPS analysis, the required thickness of insulation tiles is calculated with the aforementioned method. Then, MDO problems are formulated as augmented multi-objective optimal control problems, where variables and constraints concerning vehicle design are appended to continuous-time optimal control problems of the vehicle in the forms of static variables and static constraints, respectively. As a consequence, concurrent design optimization of vehicle and flight trajectory is achieved. Design objectives are maximization of a payload mass to a low Earth orbit, minimization of the vehicle gross mass, and minimization of the horizontal takeoff velocity. The takeoff velocity is selected as a design criterion, because it is a major technological constraint in the design of booster vehicles. By solving the formulated problems using the proposed multi-objective optimizer, Pareto optimal solutions with a good diversity are successfully obtained, which elucidate the tradeoff sensitivity among the objectives. After some inspections are given on selected representative solutions, generic knowledge is extracted from all the obtained solutions via data mining techniques. Scatter plot matrices visualize the relationships between pairs of vehicle design variables and objective values. Proper orthogonal decomposition reveals correlation between optimal flight control and vehicle design. By performing multi-objective MDO of RLVs, this dissertation provides some insight into the influences of the mission requirement and the technological constraint on the resulting optimal design of RLVs. The discovered knowledge will serve as guidelines for conducting more detailed design studies or for creating novel RLV concepts.