Possibility Based Design Optimization of a Light Aircraft using Database Driven Approach

Maxim Tyan[1]*, Nhu Van Nguyen[1], Jae-Woo Lee[1]
건국대학교[1]

Abstract

Aircraft conceptual design usually uses low to medium fidelity analysis to determine the basic configuration of an aircraft. Optimum solution is bounded by at least one of the constraints in most cases. This solution has risk to fail at later stage when analyzed with more sophisticated analysis tools. This research uses pre-constructed database to estimate the analysis prediction errors associated with simplified analysis methods. A possibility based design optimization framework is developed to utilize the newly proposed piecewise-linear fuzzy membership functions that compensate the discrepancies caused by simplified analysis. The proposed approach for aircraft design produces the optimum aircraft configurations that are less likely to fall into infeasible region when analyzed using higher fidelity analysis at later design stages.

1. Introduction

Aircraft design is a complex problem consisting of several phases: conceptual, preliminary and detail design stages. Design optimization algorithms are widely implemented at conceptual design stage to find the best possible aircraft concept. Reliability of this approach highly depends on contributing analysis methods. Design tools used at this level are usually semi-empirical and low to medium fidelity methods calibrated with statistical databases and handbooks. There exists family of the methods that enable the consideration of uncertainties in design problems. Design optimization under uncertainties extends traditional deterministic optimization by predicting the behavior of uncertain variables and parameters on a final design. There exist three main algorithms to account for uncertainty in design optimization: Reliability Based Design Optimization (RBDO), Possibility Based Design Optimization (PBDO) and Robust Design Optimization (RDO). Both RBDO and PBDO minimize the likelihood of the constraints violation that may be caused by uncertainty of variables or parameters. RBDO treats uncertainty as a random variable and requires probability distribution function (PDF) to resolve the problem. PBDO represents uncertainty as a fixed interval when probability distribution is unknown. RDO forces to minimize the expected variance of the objective function due to uncertainty. Design with uncertainty has its roots in structural design; however, the number of applications in aerospace field is also high. Neufeld et.al has implemented multidisciplinary RBDO for passenger jet aircraft and PBDO for light aircraft design. Nguyen et.al performed design of a high altitude long endurance UAV using RDO and electric UAV using PBDO algorithm. The method for generation of fuzzy membership functions proposed in this paper uses limited set of data to estimate the accuracy of analysis methods. The open domain data is stored in a database and then used to estimate the accuracy dedicated analysis. The piecewise linear membership function (PLF) is then constructed using the predicted error values. The approach makes it possible to construct fuzzy membership functions that describe the level of membership in more details than conventional triangular function. Target possibility index α_{t} in this case directly corresponds to amount of database entries used to construct uncertain interval.

2. Methodology

The process starts with constructing the database. The data is collected from reliable sources such as catalogues, official manuals and websites of the product manufacturers. The database is composed of two parts:

1. The first part contains the data used as an input for analysis X_{in}, for example aircraft geometry, engine model, payload, fuel mass, etc.
2. The second part contains the data that can be predicted by the dedicated analysis tool Y_{db}, for example total mass of an aircraft, maximum range, etc.

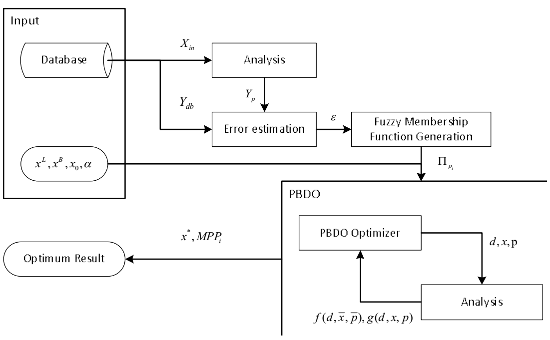

Fig. 1 The process of database supported PBDO

After the database is constructed, each item stored in database is processed using dedicated analysis. The analysis takes X_{in} from the database as an input and predicts the values of required parameters as Y_{p} (predicted data). Prediction error ε is estimated at next stage by comparing the predicted value of with database entry Y_{db} for all parameters stored in the database.

$$\varepsilon = \frac{Y_{\mathrm{p}}}{Y_{\mathrm{db}}} - 1 \tag{1}$$

Prediction error should be calculated for every item and every parameter we want to estimate the accuracy. Then the fuzzy membership function is generated for each parameter using the proposed linear-piecewise function (PLF). The details about PLF are shown in Section 3.1. The analysis method is then modified to replace with corrected term:

$$Y_{\mathrm{c}} = \frac{\mathrm{Y}_{\mathrm{p}}}{1+\varepsilon} \tag{2}$$

Here the error ε is uncertain and represented as uncertain interval. Uncertain error for each parameter has its own membership function constructed based on results of analysis benchmarking. PBDO solver is implemented to find the optimum point that will produce feasible result with any possible combinations of ε for each parameter. Optimization can be performed at single value or at a sequence of α_t.

The piecewise-linear function (PLF) is proposed in this paper to construct fuzzy membership function that describes the analysis prediction error term. PLF function is more accurate and flexible comparing to conventional triangular membership function. The PLF degenerates into triangular function in case of uniform distribution of samples or if amount of samples is 2 or 3. PLF fuzzy is composed of right and left parts each defined by set of linearly interpolated node points.

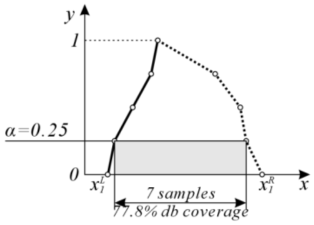

Fig. 2
Piecewise-linear fuzzy membership function

3. Light Aircraft Design

The data about 15 general aviation aircrafts of very light aircraft (VLA) category has been collected. VLA is a class of light aircraft with maximum takeoff mass less than 750 kg. The data is divided into two groups as explained in section 2.

The main analysis tool used in this research is in-house code named Aircraft Design Synthesis Program (ADSP). ADSP consists of two main parts that can run independently or sequentially: preliminary sizing (loop 1), conceptual design synthesis (loop 2). Both loops have been validated to predict performance characteristics of general aviation aircraft, unmanned aerial vehicles and regional jet aircraft. Existing aircraft is used as a baseline configuration and ADSP loop 2 as analysis tool.

The analysis framework has been benchmarked using the database entries for several parameters that are used for aircraft design optimization. The parameters used in this study are: aircraft empty weight, stall speed, takeoff distance, landing distance, rate of climb and maximum range. Figure 3 shows the PLF membership functions of each parameter.

The objective of light aircraft PBDO is maximizing the range. Mission profile with takeoff, climb to cruise altitude of 2000 meters, cruise, descending to sea level and landing is used to estimate maximum range and endurance. Optimization formulation for this problem is:

Maximize:

$$Range(d,\overline{p})$$

Subject to:

$$\Pi(g_i(d,p)>0) \le \alpha_t, i=1,...,13$$

The problem has been successfully solved using deterministic and proposed methods. Detailed results will be shown at conference presentation.

4. Conclusions

Light aircraft conceptual design problem has been successfully solved to demonstrate the proposed algorithm. Results of design with uncertainty are more conservative with wide uncertain intervals (high database coverage). The proposed methodology makes it possible to use small amount of data to efficiently calibrate the analysis tools and increase designer' s confidence that the optimum result will remain feasible when more accurate analysis methods are implemented at later design stages.

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