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Concept Study of S4TD based on Reliability Based Design Optimization

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Abstract
The System integration of Silent Super Sonic Technology Demonstrator (S4TD), is verifying an integrated design method that combines low drag and low sonic boom concepts. This paper proposes a new reliability-based design optimization (RBDO) that includes trajectory optimization, and applies it to determine the size of the S4TD. This paper formulates the RBDO problem as a double loop optimization, and the reliability is estimated using Monte-Carlo simulation. The take-off weight obtained by the proposed RBDO is 6.5% lighter than that of the classical concept design. It is also clarified that RBDO is effective for risk management.

Nomenclature

C_D	=	drag coefficient
C_L	=	lift coefficient
CT	=	throttle
D	=	drag
g	=	gravity acceleration
g_0	=	gravity acceleration at sea level
g_{RC}	=	reliability constraint
gc	=	constraint excepting g_{RC}
J	=	objective function
L	=	lift
M	=	Mach number
m	=	vehicle weight
m_{fuel}	=	fuel weight
m_{TO}	=	take-off weight
$Nengine$	=	number of engine
P_{allow}	=	allowable probability of failure
r	=	distance from the Earth center to center of gravity of vehicle
$\boldsymbol{r}$	=	uncertainties
r_s	=	scale
S	=	reference area
SFC	=	specific fuel consumption
T	=	thrust
$Tmax$	=	maximum thrust
t	=	time
$\boldsymbol{u}$	=	control vector
$\boldsymbol{x}_d$	=	design vector
V	=	velocity
W_{dry}	=	dry weight
α	=	angle of attack
β	=	reliability
γ	=	flight path angle
ρ	=	density of atmosphere

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1. Introduction

Since 1997, the Japan Aerospace Exploration Agency (JAXA) has been conducting a series of research and development projects to realize a next generation supersonic transport with excellent economic and environmental characteristics. The National EXperiment for Supersonic Transport (NEXST) program, carried from 1997 to 2006, aimed at addressing operating economics by improving the lift-to-drag ratio in supersonic cruise. JAXA's innovative drag reduction concepts developed to achieve this goal were validated by the non-powered flight experiment of the NEXST-1 [1], [2] in 2005. The Silent SuperSonic technology (S3) project [3] was then started in 2006 aiming to reduce the sonic boom, addressing environmental aspects, and in 2016, the project's final year, a design method which suppresses sonic boom was successfully demonstrated in the D-SEND#2 flight experiment [4].

Following on from S3, JAXA is now engaged in the System integration for Silent SuperSonic technology (S4) project to develop an integrated design method which combines the low drag design method from NEXST-1 with the low boom design method from D-SEND and includes noise reduction during take-off and landing. The technology reference aircraft shown in Fig. 1 has been defined and its design specifications for passenger capacity, cruise Mach number and flight range will be satisfied while meeting the following four technology goals:

Lift-to-drag ratio in supersonic cruise above 8.0
Reducing over 15% of structure weight
Under 85PLdB for sonic boom loudness
Take-off and landing noise accepts ICAO Chapter 14 [5]

Validation of the integrated design method by using a subscale flight experiment vehicle, the S4 technology demonstrator (S4TD), is also planned. This paper describes a concept study of the S4TD.

Up to now, vehicle concept studies have been traditionally conducted by a deterministic approach. However, development cost and schedule risks have been growing due to increasingly demanding technical requirements and complex and sometimes competing performance requirements, and there is a strong need for a more sophisticated concept design approach to evaluate risk quantitatively and reduce excessive margins. Reliability-based design optimization (RBDO) has been widely conducted from a viewpoint of risk management, and has also been used in multidisciplinary design optimization to design both an aircraft's wing configuration and its structure simultaneously [6]~[9]. RBDO has also been applied to aircraft concept design [10]~[12]. Neufeld *et al.* dealt with the uncertainty models both of the uniformly distributed model and the normal distribution model. Jaeger *et al.* proposed an adaptive normal law strategy in the optimization process. Deremaux *et al.* designed a supersonic business jet using a hybrid approach of MDO and uncertainty, and compared its result with the robust approach and uncertainty management approaches. Fatemi *et al.* [13] attempted to take into account the uncertainty of the trajectory, but only showed the result of deterministic design.

Although a vehicle concept design process should take the flight trajectory into account, this has not yet been accomplished. This paper proposes a new RBDO method to integrate the uncertainties of the design condition and flight trajectory optimization. The scales of two flight demonstration vehicles previously developed by JAXA, the High Speed flight demonstrator phase-II (HSFD-II) [14] and the D-SEND#2, had been determined using a traditional approach based on the single error analysis and the root sum square (RSS). In this paper, the scale of the S4TD is designed by the proposed RBDO method, and the obtained vehicle is compared the scale designed by a traditional approach.

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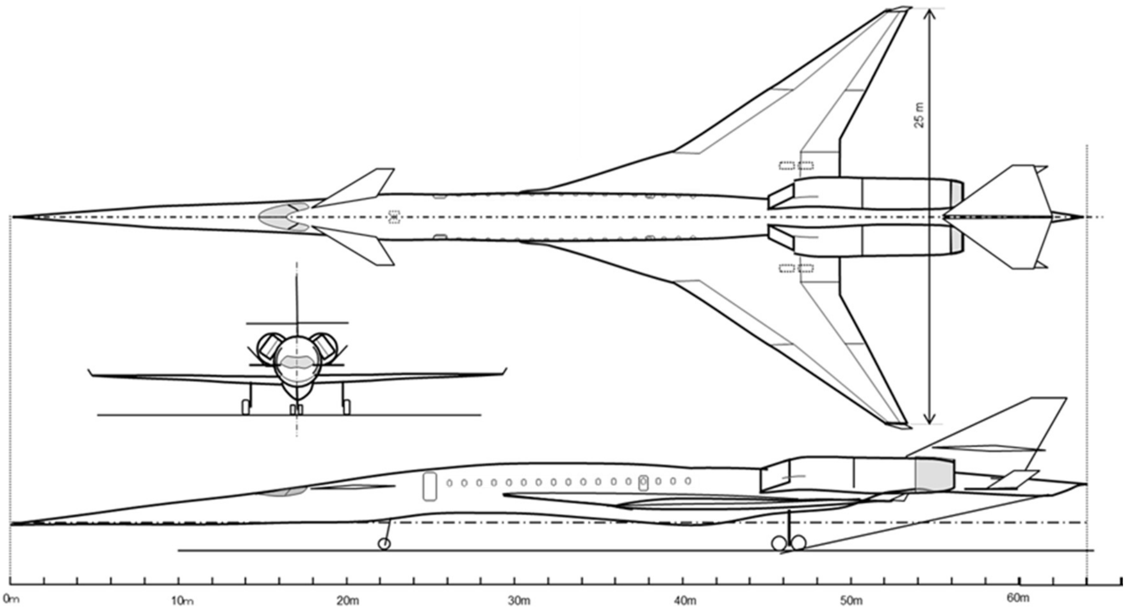

Figure 1: S4 technology reference aircraft

2. Vehicle Descriptions (S4TD)

The S4TD is a sub-scale flight experiment vehicle that will be used to validate the integrated design method for the full-scale S4 aircraft. Fig. 2.1 shows the S4TD configuration, details of which differ from the S4 aircraft (Fig. 1). This paper treats a concept design for the S4TD to determine its scale and climb trajectory, but the vehicle configuration will be left unaltered.

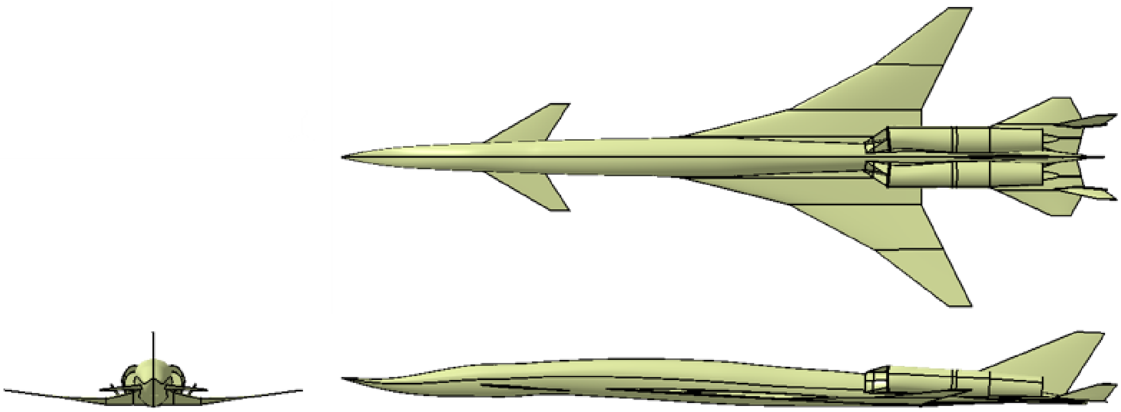

Figure 2.1: S4TD vehicle configuration

2.1 Aerodynamic Characteristics

Fig. 2.2 shows the aerodynamic characteristics of the S4TD predicted by Computational Fluid Dynamics (CFD). The aerodynamic characteristics are functions of Mach number and angle of attack, and are calculated at 1º angle of attack intervals from –2º to +6º, and at M0.6 intervals from M0.4 to M1.6. Values at arbitrary angles of attack and Mach numbers are calculated by 3rd-order spline interpolation of the node data from the CFD calculations. The landing gear and aerodynamic control surfaces are not taken into account at this stage.

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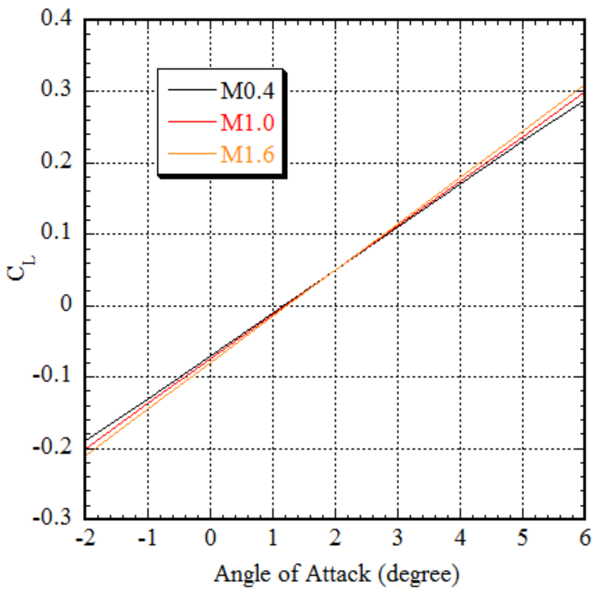

Figure 2.2(a): CL - α

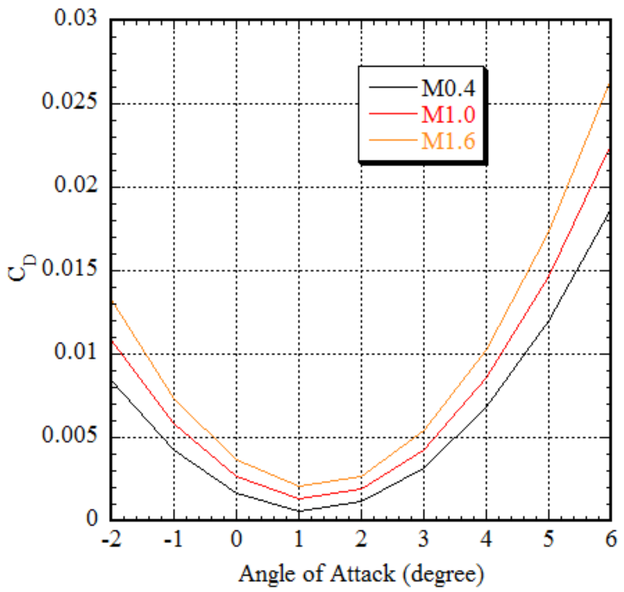

Figure 2.2(b): CD - α

2.2 Propulsion Characteristics

The HF 120 [15] is supposed as engine for the S4TD, and the sea level static thrust is 9320 N. Details of the engine's performance are currently confidential. Two engines are installed, and JET A-1 with density of 800 kg/m^3 is set as the fuel.

2.3 Mass Property

The weight of the vehicle was estimated by Hypersonic Aerospace Sizing Analysis (HASA) [16]. When the weight of a small-scale aircraft is estimated by HASA, it is necessary to modify some of estimated formula, especially the equipment weight. The estimated equipment weight formula was calibrated using the actual equipment weights of other flight experiment vehicles developed by JAXA.

3. Problem Formulation

A generic problem formulation of RBDO is as follows:

$$\textit{minimize } J(\boldsymbol{x_d}, \boldsymbol{r}) \tag{3.1}$$

$$\textit{subject to } g_{RC}(\boldsymbol{x_d}, \boldsymbol{r}) \leqq 0 \tag{3.2}$$

$$g_C(\boldsymbol{x_d}) \leqq 0 \tag{3.3}$$

where x_d is the design vector, r represents uncertainty, g_{RC} is a reliability constraint, and other constraints are represented by g_C.

The mission requirement is set as a cruise Mach number of M1.2 at an altitude of 10 km. This paper designs the climb trajectory from take-off to start of cruise point, but the proposed method can be easily applied to the design of the whole trajectory, and the designed trajectory will be extended to the cruise and descent phases after detailed investigations concerning mission requirements in the near future.

The optimal climb trajectory and the minimum vehicle scale of the S4TD will now be designed to satisfy the reliability requirement (that is, probability of mission success) by a concept study. This concept study is formulated as a double loop optimal problem [17], [18] in which the inner loop optimizes the climb trajectory and the outer loop minimizes the take-off weight of the S4TD while satisfying the reliability requirement. Fig 3.1 presents the concept design procedure.

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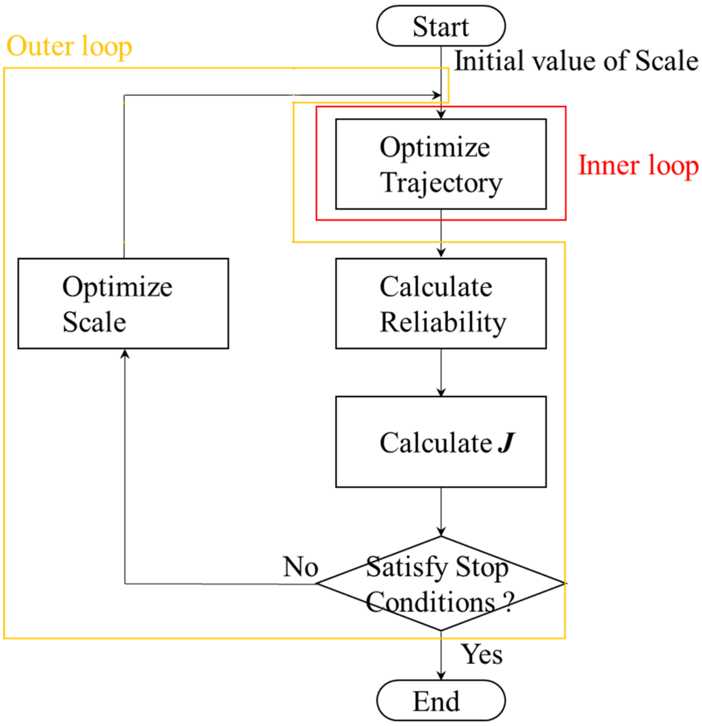

Figure 3.1: Concept design procedure

The design variable of the outer loop is the scale of the S4TD, r_s, and the objective function to be minimized is the take-off weight, m_{TO}. The constraint condition is to maintain the required reliability, which is the rate of successfully establishing the cruise condition within the amount of fuel loaded. The climb trajectory from take-off to the beginning of cruising flight is optimized in the inner loop. The vehicle is modeled as a point mass, and the motion is constrained within the vertical plane. The state variables of vehicle motion are altitude, velocity, flight path angle and fuel weight, and the control vector comprises angle of attack and throttle. Angle of attack is constrained within the range of the existing aerodynamic coefficient data, namely from –2° to +6°. The throttle setting is also constrained in the range 0 (idle thrust) to 1 (the maximum thrust available at the flight condition). The equations of motion are as follows:

$$dr/dt = V\sin\gamma \tag{3.4}$$
$$dV/dt = (\mathrm{T}\cos\alpha - \mathrm{D})/\mathrm{m} - g\sin\gamma \tag{3.5}$$
$$d\gamma/dt = (\mathrm{T}\sin\alpha + \mathrm{L})/(\mathrm{m}\cdot\mathrm{V}) + (V/r - g/V)\cos\gamma \tag{3.6}$$
$$dm_{fuel}/dt = -T\cdot SFC\,/g_0 \tag{3.7}$$
$$\mathrm{T} = Nengine\cdot Tmax\cdot CT \tag{3.8}$$
$$D = \rho V^2 C_D S/2 \tag{3.9}$$
$$L = \rho V^2 C_L S/2 \tag{3.10}$$

The objective function of the inner loop is fuel consumption. The design vector is the time history of the control vector, u, and is optimized to minimize the fuel consumption. The available fuel is limited: up to 80 kg of fuel can be loaded into the fuel tank at the reference scale (= 1.0), and available fuel is modeled as follows:

$$\text{Available Fuel} = 80.0\cdot r_S^3\ [\text{kg}] \tag{3.11}$$

The initial conditions are prescribed as the take-off conditions, and the cruise conditions of altitude, velocity, and flight path angle are set as final constraints. The take-off conditions are altitude of 0 km, velocity of 100 m/s, and flight path angle of 3°. The cruise conditions are altitude of 10 km, velocity of 359.44 m/s (equivalent to M1.2), and flight path angle of 0°. The US Standard atmosphere [19] is used as the environment model.

The reliability is calculated using Monte Carlo Simulation (MCS). Generally, an analytical method, such as the First-Order Reliability Method (FORM) [20] or the Second-Order Reliability Method (SORM) [21], is used to calculate reliability because the calculation cost of MCS is high. However, the derivative of the reliability cannot easily yield in the case of the concept study dealt with in this paper. This research also aims to reduce risk and to

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suppress cost by controlling the mathematical model of the S4TD vehicle from the beginning of the project to the actual flight experiment. Reliability is calculated using MCS in this paper because decisions in the actual flight experiment will also be based on MCS evaluations. Therefore, MCS is performed in the inner loop, which optimizes the climb trajectory for each MCS case. A failure case is defined as a case where an optimal solution cannot be obtained; that is, the S4TD vehicle cannot establish the cruise condition. The reliability, β, is then defined as follows in this paper:

$$\beta = \text{Number of success case} / \text{Number of MCS} \times 100\ [\%] \qquad (3.12)$$

The reliability must be greater than the required success rate. The constraint for the reliability, eq. (3.2), is similarly transformed as follows:

$$g_{RC} = (100 - \beta) - P_{allow} \leqq 0 \qquad (3.13)$$

where P_{allow} is allowable probability of failure.

Each MCS case supposes a random combination of several errors. The error set is fixed during the concept study, and error models for the aerodynamic characteristics, propulsion characteristics, weight property, and environmental model are supposed as uncertainties in this paper. Although all uncertainties are modeled as the normal distribution model, the proposed design method can easily handle the uniformly distributed model. Table 3.1 summarizes the uncertainty models.

Table 3.1: Uncertainty models

Item	**3σ value**
C_L	±20%
C_D	±20%
ρ	see Fig. 3.2
W_{dry}	±10%
T_{max}	±10%
SFC	±10%

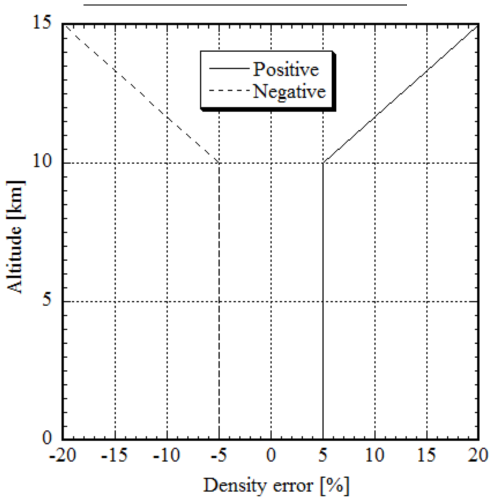

Figure 3.2: Density error model

Mass uncertainty is applied only to the dry weight of the S4TD vehicle, and fuel weight uncertainty is not taken into account. The margin for the fuel load is taken into account by the reliability. Although the take-off weight of

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each inner loop MCS case differs due to the dry weight uncertainty, the vehicle size and the available fuel weight are the same for all cases.

Summarizing the above discussion, Table 3.2 presents the design vector, constraints, and objective function of the inner and outer loops.

Table 3.2: Summarize of design variable, constraints, and objective functions

Item	**Outer**	**Inner**
Design vector	r_s	$\boldsymbol{u}$
Constraint	g_{RC} : eq. (3.13)	g_C : Final constraint Equation of motion (Differential constraints)
Objective function	m_{TO}	Fuel consumption

The outer loop is performed by the downhill simplex method with simulated annealing [22], and the Sequential Conjugate Gradient-Restoration Algorithm [23] is applied as the optimizer of the inner loop.

When the following two conditions are satisfied at the same time or number of the outer loop iterations reaches a defined iteration limit, the concept design procedure is terminated.

The difference of the objective function between successive iterations becomes sufficiently small
The difference of the design vector between successive iterations becomes sufficiently small

4. Results

4.1 Traditional Design Approach

For comparison with the proposed method, the vehicle scale was also determined using a traditional concept design approach, root sum square (RSS), which was often used in JAXA projects. The RSS value is obtained by performing single error analysis. The nominal case (no error) is firstly performed, and then one given uncertainty, whose magnitude is set at the positive or negative three sigma value of its distribution, is input to the system to calculate the difference from the nominal case. This is repeated for all the uncertainties, and the RSS value is obtained using following equation:

$$RSS = [\Sigma\{y(3\sigma) - y_{nml}\}^2]^{1/2} \tag{4.1}$$

$y(3\sigma) \geqq y_{nml}$: for positive evaluation
y_{nml}: performance of the nominal case
$y(3\sigma)$: performance with an uncertainty

Table 4.1 summarizes the results. Finally, the vehicle scale is calculated by summing the nominal value and the RSS value, and is obtained as 0.827.

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Table 4.1: Result of nominal and each error cases

Error Item	Scale	Take-off weight	Deviation [a]
None	0.751	2231.1	
C_L+	0.749	2225.5	-
C_L-	0.770	2284.8	+0.019
C_D+	0.776	2302.0	+0.025
C_D-	0.748	2223.0	-
ρ+	0.758	2250.7	-
ρ-	0.773	2292.8	+0.022
W_{dry}+	0.794	2354.8	+0.043
W_{dry}-	0.722	2152.5	-
T_{max}+	0.728	2169.4	-
T_{max}-	0.772	2291.1	+0.019
SFC+	0.797	2364.7	+0.046
SFC-	0.713	2127.4	-
RSS+	0.076		
Total	0.827	2455.0	

[a]Show only positive deviations

4.2 Results of Proposed RBDM Method

The number of the MCS cases for calculating the reliability was set at 200, and the required reliability was 97%, giving a 3% allowable probability of failure.

The design result of the proposed RBDO is shown in Table 4.2. The CPU time was about 100 minutes in this design case. The take-off weight of the vehicle obtained by the proposed RBDO was 6.5% lighter than that of the classical concept design. The reliability of the vehicle of the classical concept design including the margin was 100%; that is, no failure cases resulted from the MCS. In other words, if a failure rate of 3% is permissible, the take-off weight can be reduced by 6.5%. Of course, if the designer requires reliability of 100%, a vehicle with that reliability can be designed by the proposed RBDO. The proposed RBDO also has the merit of allowing risk to be quantitatively evaluated from the beginning of vehicle development.

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Table 4.2: Comparison of result of proposed RBDO with the result of classical concept design

Item	Classical		Proposed RBDO
	without margin	**include margin**	
Scale	0.751	0.827	0.773
Length (m)	13.7	15.1	14.1
Reference area (m^2)	10.1	12.2	10.7
Take-of weight (kg)	2231.1	2455.0	2294.5
Fuel mass (kg)	33.9	45.2	37.0
Fail (%)		0	3

Furthermore, the six failed cases had important information. Fig 4.1 shows the supposed errors of the failure cases, and the shaded area expresses the region in which errors are small. Points outside the shaded area are therefore significant in their influence on the probability of mission failure. In particular, errors of dry weight and SFC have strong effects on the probability of mission success, and risk management of these two error sources is therefore important.

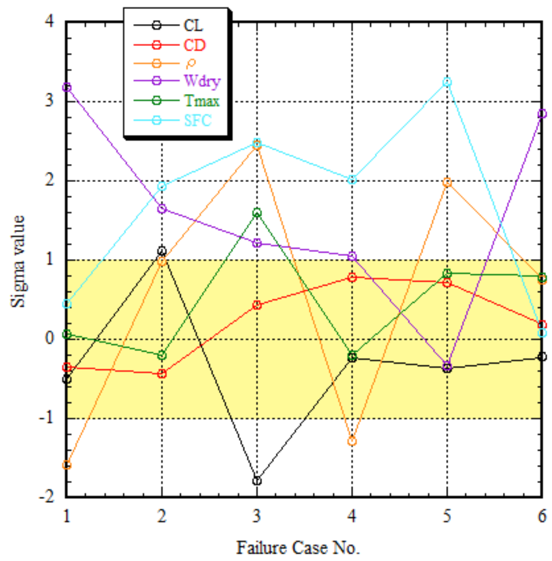

Figure 4.1: Set error of failure cases

5. Conclusions

This paper proposed a new reliability-based design optimization method that includes optimization of flight trajectories. The proposed method brings two significant improvements to concept design: the developer is able to grasp risk quantitatively, and concept design considering quantitative risk can be performed to reduce excessive margin. A concept design of the S4TD was performed using the proposed method with a 97% reliability target. The take-off weight of the obtained vehicle was 6.5% lighter than that of a vehicle designed using a traditional concept design approach. The proposed method also showed another merit, namely that the developer can understand both the error sources and error combinations that have strong effects on the vehicle system at the beginning of the project. Although such information is very important for risk management, it cannot be obtained from the traditional concept design approach.

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