Structural mass optimization of the engine frame of the Ariane 5 ESC-B

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ABSTRACT: *This paper reports on the structural mass minimization of the engine frame of the Ariane 5 ESC-B using the COMPACT design space exploration software of CQM. The COMPACT approach consists of four steps. Each of these steps is worked out in detail for the engine frame design problem. It turns out that this systematic design optimization approach quickly leads to insight in engine frame behavior and critical requirements. Moreover, excellent engine frame designs are found.*

Keywords: Structural analysis, simulation-based optimization, robust design, design optimization tool.

1. Introduction

Dutch Space supplies launcher structural systems. A track record stretching back to the early days of the space industry has secured the company's enviable expertise, which has led to close involvement in the Ariane launcher development and production program. Engine frame design often involves finding settings for a, possibly large, number of design parameters that are optimal with respect to several product characteristics, like stiffness and mass specifications. Usually, FE models are intensively used in this trajectory. Since there are many possible design parameter settings and structural analysis are often time consuming, the crucial question becomes how to find the best possible setting with a minimum number of simulations.

CQM is active in the field of simulation-based design optimization and has developed a design optimization methodology and several tools that allow engineers to design in a systematic and integrated manner, enabling an optimum design to be found quickly. This paper reports on the structural mass minimization of the engine frame of the Ariane 5 ESC-B using the COMPACT design space exploration software of CQM. The objective of the study is to find geometry parameter settings (e.g., plate thicknesses) such that stiffness requirements are satisfied and structural mass is minimal.

The COMPACT approach consists of four steps. The first step defines the design parameter space and generates a set of suitably chosen simulation runs. In the second step, the designer executes the proposed simulation runs. The third step involves the application of Response Surface Modeling (RSM) techniques to the obtained simulation results. This step results in a compact model description for each of the simulated characteristics. In the final step, these compact models are used for integral design optimization and robust design using Non-Linear Programming and Monte Carlo techniques, respectively. For a profound description of the techniques that are used in COMPACT, we refer to [6]. Applications in the field of consumer electronics and semiconductor industry can be found in [4] and [2], respectively.

The remainder of this paper is organized as follows. Sections 2 to 5 introduce the design problem of the Ariane 5 ESC-B and apply the four steps of the COMPACT approach. In Section 6, we compare the compact model approach with the SOL 200 solver of MSC.Nastran. Section 7 presents our conclusions.

2. Problem Specification / Parameterization (Step 1)

The engine frame consists among others of a cone, a cone cap, an attachment ring, and cone cap stiffeners; see Figure 1 for a schematic representation. The engine frame should be stiff enough to withstand the forces induced by the 600 kg heavy engine that is attached to it. At the same time the engine frame should weight as little as possible. Required stiffness and minimum mass are specified by the client.

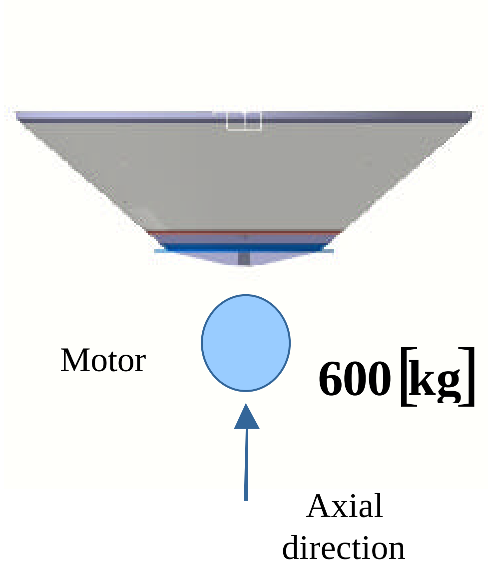

Figure 1: Engine frame.

A simple Finite Element (FE) model has been generated in MSC.NASTRAN with about 2700 nodes and 2800 elements. The cone has been simply supported at the base.

The very first step of our methodology specifies the design optimization problem. We have to decide which design parameters to optimize and which response parameters are used to judge design quality. Furthermore, design restrictions have to be identified. The importance of this phase is often underestimated. In general, wrong parameterization may lead to sub-optimal results and unnecessary many computer simulations.

Design parameter	Lower bound (mm)	Upper bound (mm)
pshell31	12	36
pshell43	15	45
pshell44	3.25	9.75
pshell45	4	12
pshell21	0.855	1.045
prod61	0.05	0.15

Table 1: Design parameter bounds.

In the engine frame design problem 21 design parameters play a role. However, many of them are more or less dependent, because changing one part of a structural subsystem alters all other parts in the same way. After removing these redundancies, 6 design parameters remain: five plate thicknesses and one cross-section thickness. Table 1 gives for each design parameter a lower bound and upper bound. These bounds are set to simulate a realistic variation in the wall thicknesses of the structural elements.

Design quality is assessed by two so-called response parameters being mass and stiffness. The engine frame's weight should be minimal, preferably below 175 kg. For the stiffness of the frame the requirement about the first axial natural frequency is very important in order to prevent dynamic interaction with the engine. The natural frequencies in the lateral direction are less dimensioning. The stiffness condition is satisfied when the first axial frequency is larger than 49 Hz, however preferably it is larger than 50 Hz. Figure 2 summarizes the above.

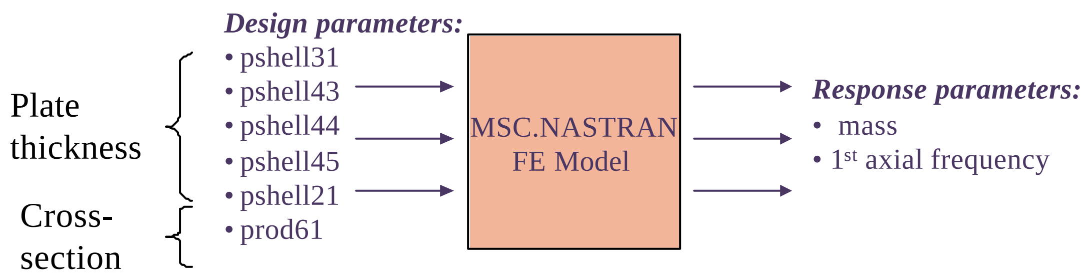

Figure 2: Design and response parameters.

3. Design of Computer Experiments (Step 2)

The second step generates a set of well-chosen design parameter settings or *design points* that lie within the feasible design space, i.e., the part of the six-dimensional space that is defined by the bounds on design parameters; see Table 1.

To be able to construct Response Surface Models (RSM) for all response parameters (Step 3) that predict well for the entire feasible design space, we choose the design points such that as much information as possible is captured from the simulation tool. Intuitively this is the case when the design points are spread throughout the design space as evenly as possible, i.e., the simulation scheme is *space filling*. Hereby we assume that no information about the function underlying the simulation model is available. We propagate the use of space-filling simulation schemes for computer experimentation, not only for providing a suitable basis for Step 3, but also to provide a first exploration of the design space. Besides space-filling schemes for non-box regions, COMPACT provides space-filling simulation schemes for linearly constrained non-box design spaces; see for instance [6]. Finally, COMPACT is able to exploit any existing simulation runs. For more detail we refer to [7].

In the engine frame design problem, the design space is a six-dimensional box shaped area. Before we could generate a scheme for this area, we had to decide how many simulation runs we were going to execute. Experience pointed out that 5-10 times the number of design parameters is a good starting point. Of course, the number of simulation runs that is required to obtain an accurate RSM model depends heavily on the expected non-linearity of the underlying physics. In this case mass and axial frequency are expected to depend only lightly non-linear on the thicknesses. However, since FE runs are not that time-consuming and since we would like to be on the safe side, we generated a simulation scheme of 75 engine frame designs.

Alternatively, we could also have constructed the scheme iteratively by doing a smaller set first and go to Step 3 and return to Step 2 in case the RSM models would turn out to be inaccurate. In general this latter approach is more efficient.

After carrying out those 75 simulations with help of the FE-model, we found that:

1. None of the simulated designs fulfilled both the requirements that the first axial frequency should be at least 50 Hz and that the mass should be below 175 kg.
2. 55 % of the simulated designs satisfied the constraint that the first axial frequency should be at least 50 Hz.
3. 29 % of the simulated designs satisfied the constraint that the mass should be below 175 kg.

Since the used simulation scheme was space-filling we may already conclude from this that our objective, finding an engine with a 1st axial frequency of at least 50 Hz and a weight of at most 175 kg, is quite a challenge. The two best designs so far are shown in Table 2. Both designs satisfy the stiffness condition but are 1-3 kg too heavy.

Design Parameters	pshell31	26.92	26.59
	pshell43	17.03	27.57
	pshell44	5.89	5.18
	pshell45	9.41	9.19
	pshell21	0.86	0.86
	prod61	0.08	0.14
Response Parameters	mass	178.00	176.30
	axial frequency	50.22	49.89

Table 2: Best simulated designs in DoCE.

4. Compact modeling (Step 3)

The third step aims at obtaining good and compact model descriptions for each of the response parameters in terms of the design parameters. These models are based on the results of the simulations proposed in Step 2.

COMPACT builds so-called Response Surface Models (RSM) describing the relationships between design and response parameters. These may be either first or second order polynomial models or Kriging models [5]. Generally speaking, the latter models yield the best approximations when the underlying relationship is highly non-linear.

Because we expect only lightly non-linear physics in this project, we first built linear models for both the 1st axial frequency and the mass. To assess how well the RSM models fit the underlying physics we used two model validation methods: cross-validation and an independent test set. For more background on model validation techniques we refer to [1].

The linear model performed very well for the mass, but was not satisfactory for the first axial frequency. Therefore we also fitted quadratic models for both responses. COMPACT uses a dedicated regression approach that, given a data set, not only fits the regression coefficients, but also optimizes the selection of model terms. Optimal here means that you obtain a RSM with highest prediction accuracy (cross-validation). Benefit of the approach is that for a given data set the best possible regression model is found.

It turned out that for the mass adding one or more interaction or quadratic terms does not improve the model's prediction capabilities. The 1st axial frequency though, could be improved by adding certain interaction and quadratic terms.

From the calculated cross-validation Root Mean Square Error (RMSE) numbers we know that the RSM models for mass and frequency are expected to deviate 0.3 kg and 0.17 Hz on the average, which is very accurate. Moreover, we validated the models on an independent test set of four engine frame designs. Table 3 shows that the predictions for mass and frequency are always very close. It appears that the RSM overestimates the 1st axial frequency.

Validation point	Predicted		Simulated	
	Mass	Freq.	Mass	Freq.
1	176.11	50.27	176.20	49.56
2	175.23	50.12	175.30	49.42
3	174.57	50.08	174.50	49.41
4	175.24	49.95	175.10	49.44

Table 3: Test set validation results for RSM models.

The coefficients for the model terms for the scaled design parameters give an indication about the influence of these terms on the response parameters. Inspection shows that the design parameters pshell31 and pshell44 are most important. These represent thick-machined parts. Figure 3 gives some example plots of the compact models where pshell31 and pshell44 are varied within their bounds.

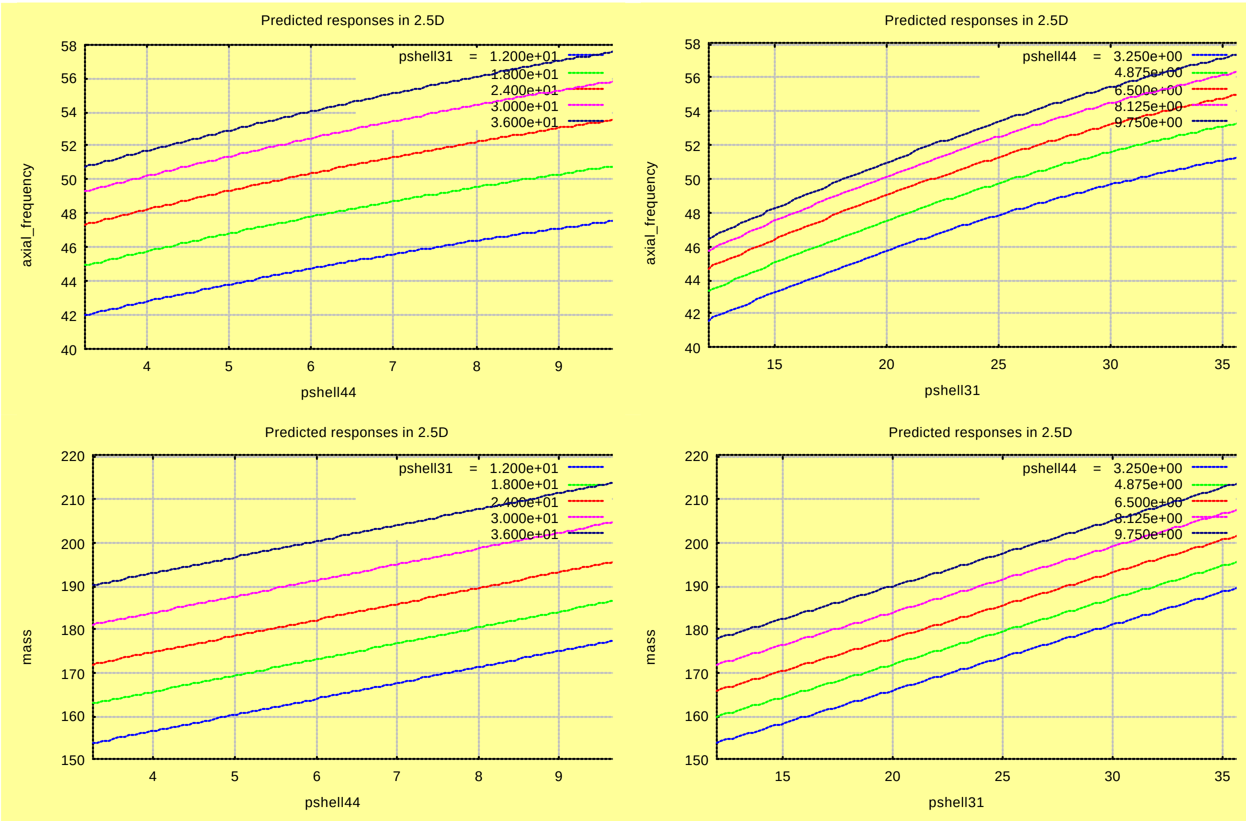

Figure 3. Compact models of mass and axial frequency.

5. Design optimization and robust design (Step 4)

Steps 1-3 result in an RSM for each of the response parameters. Until so far we only used them for prediction purposes; see for instance Figure 3. In the fourth step these RSMs can be used for optimization and robust design, which will be treated next.

Design optimization

Design optimization consists of finding values for the design parameters that satisfy all constraints specified in Step 1 and minimize some chosen objective function. COMPACT facilitates design optimization by using state-of-the-art Mathematical Programming techniques.

There are several ways to choose the objective function and the constraints to formulate the engine frame optimization problem. One option would be to minimize some weighted sum of mass and frequency as follows

$$\begin{array}{ll} \min & M(\mathbf{p}) + w \cdot F(\mathbf{p}) \\ \text{subject to} & L_i \leq p_i \leq U_i \qquad i = 1, \ldots, 6 \end{array}$$

Here w denotes some weight, $\mathbf{p}$ denotes the vector of design parameters, M and F denote the RSMs for mass and frequency, and L_i and U_i denote the lower and upper bound for design parameter p_i. Difficulty with this formulation is the choice of w. A more practical choice is to minimize weight such that the frequency is larger than 50 Hz as follows.

$$\begin{array}{ll} \min & M(\mathbf{p}) \\ \text{subject to} & L_i \leq p_i \leq U_i \quad i = 1, \ldots, 6 \\ & F(\mathbf{p}) \geq 50 \end{array}$$

The possible existence of local minima makes it necessary to apply a global optimization strategy. COMPACT uses a *multi-start* approach, meaning that several local optimizations are started sequentially. Starting points are the set of space-filling points generated in Step 2. Local optimization is done with help of the Non-Linear Programming (NLP) solver CONOPT [3].

COMPACT found two local optima. The global optimum is depicted in Table 4. Note that the predicted mass is almost exactly equal to the simulated mass for that design. The axial frequency was slightly overestimated by the RSM, but remains within 2% of 50 Hz. Hence, an engine frame design satisfying all requirements was found.

pshell31	28.09
pshell43	45.00
pshell44	4.74
pshell45	4.00
pshell21	0.86
prod61	0.15
predicted mass	174.21
predicted frequency	50.00
mass	174.20
axial frequency	49.33

Table 4: Globally optimal design.

However, this optimum is not yet manufacturable. The wall thicknesses of the shells can only be manufactured in multiples of 0.5 mm. One option here is to round the design parameter values of the globally optimal design to the nearest multiple of 0.5 mm. The result is shown in Table 5.

Due to rounding, the limit of 175 kg is not reachable anymore for the specified manufacturing conditions. The value for pshell21 is always set to the lower bound for this parameter. The impact of forcing pshell21 from 0.855 to 0.90 mm while keeping the other design parameters fixed to their continuous optimal values, is an increase of the mass with 4 kg. That is quite a lot.

pshell31	28.00
pshell43	45.00
pshell44	4.50
pshell45	4.00
pshell21	0.90
prod61	0.15
predicted mass	177.14
predicted frequency	50.08
simulated mass	177.10
simulated frequency	49.60

Table 5: Rounded optimum.

In general, rounding a continuous optimum is dangerous and may lead to sub-optimal results. In this project we use our insight that pshell21 is dominant to find a good integer optimal design. We force pshell21 to 0.9 by adding the constraint that pshell21 should be higher or equal to 0.9 and solve the corresponding optimization problem

$$\begin{aligned} \min \quad & M(\mathbf{p}) \\ \text{subject to} \quad & L_i \le p_i \le U_i \quad i = 1,\ldots,6 \\ & F(\mathbf{p}) \ge 50 \\ & p_{\text{shell21}} \ge 0.9 \end{aligned}$$

Rounding down pshell44 and varying pshell31 in discrete steps yields the interesting designs in Table 6. Of course it might also be beneficial to investigate the possibilities for manufacturing components such that pshell21 can remain 0.855 mm. For the remainder of this study we concentrate on the first two designs.

pshell31	27.00	28.00	29.00
pshell43	45.00	45.00	45.00
pshell44	4.00	4.00	4.00
pshell45	4.00	4.00	4.00
pshell21	0.90	0.90	0.90
prod61	0.15	0.15	0.15
predicted mass	173.75	175.27	176.79
predicted frequency	49.27	49.63	49.99

Table 6: Rounded optima for three settings of pshell31.

Robust design
COMPACT provides Monte Carlo sampling techniques applied to RSMs to analyze the robustness of a certain design to random errors in the design parameters. For every design parameter a suitable probability distribution can be chosen. Histograms plots can be generated for individual responses and the objective function.

For the ESC-B project we are interested in the impact of production tolerances on weight and stiffness requirements. Due to the production process, there is a difference in production tolerance for small and thick-machined plates. Plates with a thickness smaller than 2 mm have a production tolerance of ±0.05 mm; above that the production tolerances is ±0.1 mm. We investigate the influence of production tolerances for the first two designs in Table 6. We performed a Monte Carlo on the compact models analysis by applying a normal distribution for each thickness with $3s$ equal to the corresponding production tolerance. Figure 4 shows histogram plots for both mass an frequency. For mass an upper specification limit of 175 kg was chosen, for the axial frequency we have a lower spec of 49 Hz. From these plots we see that for the optimal design, production tolerances lead to spread in mass of ±4kg and spread in frequency of ±0.5Hz. From Table 6 we learned that nominally, the first design is optimal, since it has the lowest weight and the stiffness requirements are met. However, looking at the robustness results in Figure 4, the stiffness results of the second design is preferable.

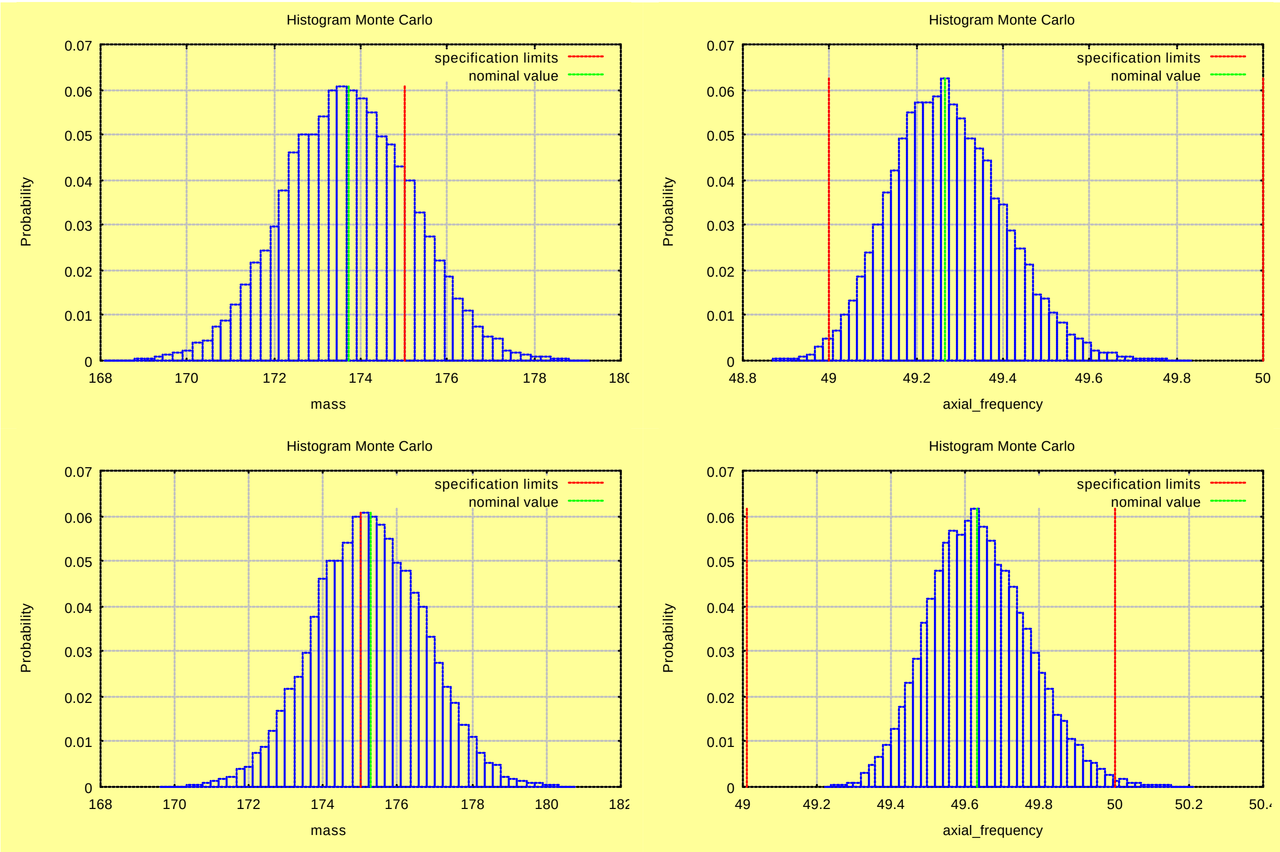

Figure 4. Histogram plots of mass and axial frequency.

6. Compact model approach vs sequential approach

As a comparison, a sequential optimization has also been carried out with help of the MSC.NASTRAN SOL 200 solver. The solution found by SOL 200 was rounded which resulted in an engine frame design with a mass of 178.3 kg and an axial frequency of 50 Hz. From our earlier results we know that this design is not optimal. On the other hand, SOL 200 used only a few simulations to find it. After carrying out several optimizations from different starting points we concluded that is quite some starting point dependence in the sense that the quality of the solution found depends on the starting point of the optimization.

The sequential solver seems to converge rather quickly to a solution, however at the risk of obtaining sub-optimal results. So to be safe you would need to start the optimization from several different starting points. This increases the number of simulations and introduces the problem which design points should be chosen as starting points for these sequential optimization runs.

Besides that COMPACT found a better design, major advantage of the COMPACT approach is the obtained RSM models. They give global insight in engine frame behavior and critical requirements. Moreover, with help of these models, any change in objective function and constraints can be quickly evaluated without the need for additional simulation runs. SOL 200 will have to start all over again as soon as the objective or one of the requirements changes. Finally, as shown, these RSM models can be used for robust design using Monte Carlo methods.

Although the MSC.Nastran runs were not that time-consuming, the manual work to adapt the FE model to a specific frame geometry is quite substantial. For that reason we also investigated the impact of reducing the number of simulation runs on final RSM model quality. We randomly removed 45 of the 75 initial designs and fitted new models with COMPACT on the remaining 30 designs. The 45 designs that we left out were used as an independent test set. For the mass again a linear model performed best, with an RMSE of 0.65 kg on this test set. For the first axial frequency a quadratic model containing only relevant terms performed best, with an RMSE of 0.47 Hz on the test set. These results indicate that the models based on only 30 designs, although less accurate than those based on 75 designs, are still quite satisfactory.

7. Conclusions

It turns out that this systematic design optimization approach quickly leads to insight in engine frame behavior and critical requirements. Moreover, excellent, robust engine frame designs are found. As a reference we optimized the same engine frame using MSC.Nastran SOL 200. Major advantage of COMPACT over SOL 200 is that once the RSM models are built, redesigns can be done quickly and effectively without the need for extra time-consuming computer simulations .

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