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A Pipe Routing Method Considering Vibration for Aero-Engine Using Kriging Model and NSGA-II

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ABSTRACT The computer-aided design optimization and vibration analysis, especially avoiding resonance are fundamental challenge to piping system design of complex products. Conventional pipe design methods commonly focus on either automatic geometry layout or vibration analysis, which usually leads to repeated modifications between both disciplines. In this paper, a multi-objective pipe routing algorithm considering vibration performance for aero-engine is presented based on Kriging model and non-dominated sorting genetic algorithm-II (NSGA-II), where pipe length, smoothness, and natural frequency are taken into account. Pipe node positions are optimized by using NSGA-II subject to several constraints. In order to improve computational efficiency, a Kriging model reflecting the relationship between the pipe node position and natural frequency is constructed, and then is applied instead of computer-aided engineering analysis program to evaluate the individual fitness during evolutionary computations. Several numerical computations are performed on a simplified piping model, and the results show that the constructed Kriging model can guarantee high modeling accuracy and the presented routing algorithm is able to obtain a set of non-dominated solutions of pipe layouts, in particular, the natural frequency of pipes are far from engine excitation frequency, which guarantees to avoid possible resonance.

INDEX TERMS Multi-objective optimization, pipe routing, Kriging model, vibration analysis.

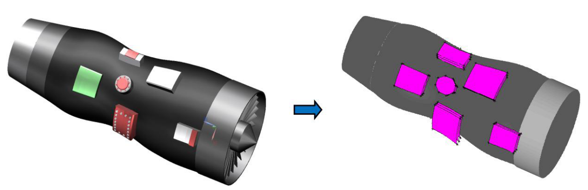
I. INTRODUCTION

As an important channel of energy transmission and medium transmission, pipe system has an important impact on the safety, reliability and cost of mechanical equipment. In the process of mechanical equipment work, mechanical vibration often causes vibration failure of the pipe system and then affects normal operation of equipment. Thus, computer aided design (CAD) optimization and vibration analysis especially avoiding resonance of pipe system are very important for complex product developments. As a classic multi-objective optimization problem, pipe layout design not only involves many optimization objectives, but also needs to consider the space and engineering constraints, which makes pipe layout design be a fundamental challenge to complex product developments.

In order to realize the automation and intelligence design of pipe layout, some automatic routing algorithms have been developed during the past decades, most of which can be classified into cell-based routing algorithms [1]–[4], heuristic routing algorithms [5], [6], and graph-based routing algorithms [7]–[10]. With the development of artificial intelligence (AI), pipe routing approaches based on intelligent optimization techniques have been widely presented in recent years, such as GA-based, e.g., [2], [4], [11], [12], ACO-based, e.g., [10], [13], and PSO-based routing methods [14]. A commonly used technique of these methods is to aggregate multiple routing objectives into single objective by using linear weighting method. Reference [15] applied maze algorithm, NSGA-II [16] and coevolutionary strategy to solve ship pipe layout problems. Reference [17] applied an improved NSGA-II to solve multi-objective pipe routing problem of aero-engine, where pipe length and angles of bends are taken into account as the optimal objectives. Reference [18] proposed a pipe routing method based on octree modeling and modified max-min ant system optimization algorithm while considering pipe length and number of bends by using linear weighting method, and the natural frequency of pipe is calculated only if need. In addition, some other routing algorithms such as fuzzy logic-based decision support system [19], cell-generation method [20], and Answer Set Programming (ASP)-based [21] are also presented to solve various industrial pipe routing problems.

Even though existing routing algorithms could solve some academic and engineering problems, there are at least two aspects that need to be further studied. 1) Most existing routing algorithms focus on automatic geometry layout and belong to CAD areas, where pipe length and the number of bends are most commonly considered as routing objectives. Even though pipe vibration analysis such as Computer Aided Engineering (CAE) analysis has been widely studied (e.g. [22], [23]), it is basically studied as an independent discipline of CAD optimization. This often causes repeated modifications between CAD and CAE disciplines. 2) Routing algorithms based on intelligent optimization are able to handle multiple routing objectives, however, most of which aggregate multiple objectives into single objective by linear weighting method. In recent years, multi-objective routing has become a frontier and a few studies (e.g. [17]) have been conducted. However, cost-effective pipe routing algorithms that enable automatic generation of Pareto solutions with respect to multiple objectives still remain an open area of research.

In this paper, a multi-objective pipe routing method considering vibration performance for aero-engine is presented based on Kriging model and NSGA-II, where pipe length, smoothness and natural frequency are taken into account. To improve computation efficiency, a Kriging model is constructed and is applied instead of CAE analysis program to evaluate the individual fitness during evolutionary computation. The reminder of this paper is arranged as follow. Section II gives space modeling and problem description; Section III gives overall design of the proposed method; Section IV gives the process of constructing Kriging model; Section V gives the details of pipe routing method, where the fitness computation, constraint processing, and algorithm flow are given; Section VI performs some routing numerical computations on a simplified piping model; Section VII finally concludes this paper.



(a) (b)

FIGURE 1. CAD model and its routing space. (a) CAD model. (b) Routing model in MATLAB.

II. SPACE MODELING AND PROBLEM DESCRIPTION

Without loss of generality, aero-engine jacket contours can be described by rotational surfaces, as shown in Fig.1(a). Prior to pipe route design, geometrical information of routing model needs to be obtained. To this end, the coordinate information of sampling points (x_i, y_i, z_i) on a meridian of rotational surface is extracted by using Siemens NX/GRIP, and the cylindrical coordinates (z_i, ρ_i) of these points can be further obtained, where $\rho_i = \sqrt{x_i^2 + y_i^2}$. Then, the meridians of rotational surfaces can be approximately formulated by the least square method over discrete points. In addition, the edges of aero-engine obstacles can be represented by meridians and parallels instead of the straight lines. Fig.1(b) shows the constructed model in MATLAB.

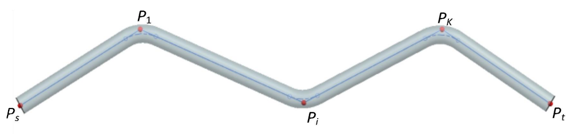


FIGURE 2. Schematic diagram of pipe path.

In general, pipe path can be determined by a series of path nodes. As shown in Fig. 2, the node sequence $\{P_1(x_1, y_1, z_1), \cdots P_i(x_i, y_i, z_i), \cdots, P_K(x_K, y_K, z_K)\}$ determines a pipe path, which can be further optimized by adjusting node coordinates. Thus, these coordinates can be encoded as an individual which can be further optimized by using optimization algorithms such as NSGA-II. The encode can be denoted as follows:

$$p = \{P_s(x_s, y_s, z_s), P_1(x_1, y_1, z_1), \cdots P_i(x_i, y_i, z_i), \cdots, P_K(x_K, y_K, z_K), P_t(x_t, y_t, z_t)\}$$

where $P_i(x_i, y_i, z_i)$ denotes ith node of pipe path; $P_s(x_s, y_s, z_s)$ denotes the starting point; $P_t(x_t, y_t, z_t)$ denotes the ending point; K denotes the number of nodes.

The goal of pipe routing is to seek the optimal layouts with respect to several conflicting and trade-off routing objectives while considering a number of engineering rules in a constrained space. In general, the routing constraints for aero-engine consist of the following ones:

1) Avoid obstacles, where the obstacles refer to accessories, electrical components and restrained regions reserved for operational inspections and maintenance;
2) Bending angle of pipe should be no less than 90 degrees to meet the machinability constraints;
3) Pipes should be paved closer to the inner surface of engines, which tends to increase system reliability and stability.

In addition, the natural frequency of pipe should be adjusted to outside 20% of engine excitation frequency for avoiding possible resonance. In particular, the first order natural frequency has a remarkable influence on pipe vibration performance. With respect to optimization algorithm design, this constraint can be also transformed into an optimization objective. In this paper, the first order natural frequency of pipe is taken into account for example and is further optimized as an objective to avoid resonance.

Thus, aero-engine pipe routing problem is formulated by (1).

$$\begin{aligned} &\textbf{min}\ F(p) = (f_1(p), f_2(p), f_3(p))^T \\ &\textbf{s.t.}\ h(p) = 0, \quad g(p) = 0,\ p \in \Omega \end{aligned} \tag{1}$$

where $f_1(p)$ denotes pipe length;

$f_2(p)$ denotes smoothness of pipe, i.e., bending angle;

$f_3(p)$ denotes the negative of difference value between the first order natural frequency of pipe and the excitation frequency of engine, details of which will be given in section V;

$h(p)$ denotes obstacle-avoidance constraint, where $h(\text{p}) \neq 0$ if the path p overlaps with some obstacles, and $h(\text{p}) = 0$ if p is a collision-free path;

$g(p)$ denotes the constraint of bending angle of p, where $g(\text{p}) \neq 0$ if bending angle of p is less than 90 degrees, and $g(\text{p}) = 0$ if bending angle of p is no less than 90 degrees;

Ω denotes the routing space. As to an aero-engine development, it denotes a rotational surface.

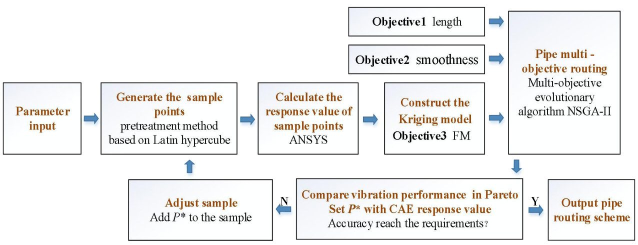


FIGURE 3. **Overall design.**

III. OVERALL DESIGN

Besides pipe length and smoothness, the vibration performance such as the natural frequency also have an important effect on pipe system. In this paper, pipe vibration performance is considered into pipe routing algorithm. To improve computation efficiency, a Kriging model which is commonly used as surrogate model in structure optimization areas is constructed, and then is applied instead of CAE analysis program to evaluate the individual fitness during evolutionary computation. The overall design of the presented method is shown in Fig.3, which mainly contains the following steps.

Step 1: Generate the initial sample points of node position by a preprocessing method based on Latin hypercube, details of which will be given in section IV;

Step 2: Calculate the response value (natural frequency) of sample points using ANSYS software;

Step 3: Construct Kriging model according to the sample points and response values;

Step 4: Perform multi-objective pipe routing optimization using NSGA-II, where pipe length is chosen as objective function 1, smoothness is chosen as objective function 2 and FM (frequency modulation) is chosen as objective function 3, details of which will be given in section V;

Step 5: Compare vibration performance in Pareto Set P^* with CAE response value, if accuracy reach the requirements, then output pipe routing scheme; otherwise add P^* into the set of sample points and go to **step1**.

IV. CONSTRUCTION OF KRIGING MODEL

The construction of the Kriging model is a key step of the proposed routing method, which mainly includes three parts: 1) Preprocessing based on Latin hypercube to improve the distributions of sample points; 2) Calculation of actual response value using CAE software; 3) Construction of the Kriging model.

A. PREPROCESSING BASED ON LATIN HYPERCUBE

Latin hypercube sampling is a commonly used method to generate sample points. However, due to the particularity of the pipe routing problem, there will be a large number of individuals intersecting with the obstacles in the samples by Latin hypercube, which will not only make CAE analysis process meaningless, but also affect the accuracy of Kriging model.

Therefore, this paper uses a preprocessing method to improve distributions of sample points, so that individuals in the sample can avoid obstacles. More specifically, the preprocessing method uses Latin hypercube method to generate initial samples. Then, initial sample is optimized by using the pipe routing method based on NSGA-II, where obstacle-avoidance constraint is considered, and only pipe length f_1 and smoothness f_2 are chosen as objective functions. The maximum number of allowable iterations is set as T_1. Finally, the obtained Pareto solution set P^* is saved as the updated sample data which will be used to construct Kriging model. The preprocessing method works as follows:

Step 1: Set sample population $SP = \phi$ and the maximum number of SP;

Step 2: Generate an initial population $p^1, \ldots, p^N$ using Latin hypercube and set $f_j^i = f_j(p^i)$, for each $i = 1, \ldots, N$ and $j = 1, 2$, where f_j by (3) and (4);

Step 3: Pareto solution set P^* is obtained by multi-objective layout optimization method based on NSGA-II, where the maximum number of allowable iterations is T_1 and objective functions are f_1 and f_2;

Step 4: Remove the individuals intersecting with the obstacles from P^* and then add P^* to SP;

Step 5: Remove the repeated individuals from SP;

Step 6: If the individual number of SP reached the maximum number of SP, then stop and output SP. Otherwise, go to **Step2**.

B. CALCULATION OF RESPONSE VALUE USING CAE ANALYSIS PROGRAM

Considering that Siemens NX software is commonly used in aero-engine pipe design area, this paper uses Siemens NX software to perform CAD modeling. Then the ANSYS software is used to obtain pipe vibration performance. The main steps of pipe CAE analysis are as follows:

Step 1: Solve pipe routing results by the above preprocessing method with MATLAB. Fig.4(a) shows one of the results which is further stored as TXT text file.

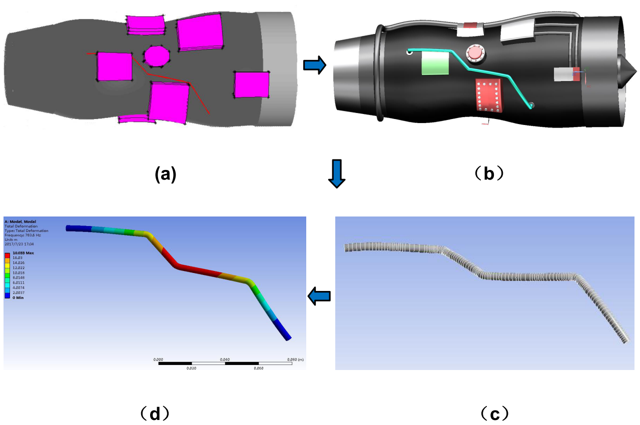


FIGURE 4. **Schematic diagram of CAE analysis. (a) Piping model in MATLAB. (b) Piping model in Siemens NX. (c) Piping model in ANSYS. (d) Calculation result by ANSYS.**

Step 2: Load the TXT text in Siemens NX and build the pipe CAD model using NX/GRIP, as shown in Fig.4(b).

Step 3: Import the pipe CAD model into the ANSYS, as shown in Fig.4(c), and perform the CAE analysis program, i.e., modal analysis. Then the analysis results, e.g., the first-order natural frequency of the pipe, can be obtained shown in Fig.4(d).

C. THE BASIC PRINCIPLE OF KRIGING MODEL

As a commonly used approximate model, Kriging model was first used by [24] in the field of computer experiment design and analysis. The basic principle [25] of the Kriging model can be briefly described as follows:

$$y(x) = F(\beta, x) + Z(x) \tag{2}$$

where $y(x)$ is the unknown polynomial function of x, $F(\beta, x)$ is a known polynomial function of the dimensional-variable x, β is a regression parameter and $Z(x)$ is the realization of a normally distributed stochastic process.

In this paper, the method in [26] is used to optimize the correlation parameter by using the Particle Swarm Optimization (PSO) algorithm. Once the Kriging model is constructed, it can be used to evaluate individual fitness values instead of the CAE analysis program during evolution computations. More details of Kriging model can be found in [24]–[26], which are not described here.

V. MULTI-OBJECTIVE PIPE RROUYING

A. FITNESS COMPUTATION AND CONSTRAINT PROCESSING

Given a sequence of nodes $\{P_1(x_1, y_1, z_1), \cdots P_i(x_i, y_i, z_i), \cdots, P_K(x_K, y_K, z_K)\}$, the routing objectives and constraints mentioned in section II can be formulated respectively as follows:

$$f_1 = l(p) + \delta \cdot h(p) \cdot g(p) \tag{3}$$

$$f_2 = s(p) + \delta \cdot h(p) \cdot g(p) \tag{4}$$

$$f_3 = e(p) + \delta \cdot h(p) \cdot g(p) \tag{5}$$

where l(p) denotes the pipe length, which can be formulated by (6) in Euclidean space.

$$l(p) = \sum_{i=1}^{K-1} \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2 + (z_{i+1} - z_i)^2} \tag{6}$$

s(p) denotes pipe smoothness. For convenience of computation, bending angle is used in this paper, which can be formulated by (7).

$$s(p) = \sum_{i=1}^{K-2} \beta_i = \sum_{i=1}^{K-2} \arccos(a_i \cdot b_i/(|a_i| \cdot |b_i|)) \tag{7}$$

where $a_i = (x_{i+1} - x_i, y_{i+1} - y_i, z_{i+1} - z_i)$, $b_i = (x_{i+2} - x_{i+1}, y_{i+2} - y_{i+1}, z_{i+2} - z_{i+1})$. Note that, β_i is the supplementary angle of ith angle between the path p, which translates the problem of solving the maximum value into the one of solving the minimum value.

e(p) denotes the negative of difference value between pipe natural frequency and aero-engine excitation frequency, which can be formulated by (8).

$$e(p) = -|w_1 - w_e| \tag{8}$$

where w_1 denotes the first order natural frequency of pipe, which can be obtained from the approximation function of the constructed Kriging model; w_e denotes the engine excitation frequency.

$h(p)$ and $g(p)$ denote the "penalty value", which can be formulated by (9) and (10), respectively.

$$h(p) = \begin{cases} 1 & \text{if path } p \text{ overlaps with obstacles} \\ 0 & \text{otherwise} \end{cases} \tag{9}$$

$$g(p) = \begin{cases} 1 & \text{if bending angle of } p \text{ less than 90 degrees} \\ 0 & \text{otherwise} \end{cases} \tag{10}$$

δ denotes a large positive constant.

In addition, as mentioned in section II, pipes need be paved closer to the inner surface of engines. Thus, the presented routing method can be extended to rotational surface by replacing straight lines with geodesic line. Given two points $A(\rho_A, \theta_A, z_A)$ and $B(\rho_B, \theta_B, z_B)$ on a rotational surface, a geodesic line can be approximately formulated in cylindrical coordinate system by (11) [5].

$$\begin{cases} x_i = f_M(z_A + (z_B - z_A) \cdot (\theta_i - \theta_A)/(\theta_B - \theta_A)) \cdot \cos(\theta_i) \\ y_i = f_M(z_A + (z_B - z_A) \cdot (\theta_i - \theta_A)/(\theta_B - \theta_A)) \cdot \sin(\theta_i) \\ z_i = z_A + (z_B - z_A) \cdot (\theta_i - \theta_A)/(\theta_B - \theta_A) \end{cases} \tag{11}$$

where $\rho = f_M(z)$ denotes meridian equation, which can be formulated by the least square method on discrete points extracted from aero-engine jacket contours.

B. FLOWCHART OF THE ROUTING METHOD

The pipe routing system is constructed by customized developments of MATLAB (Matrix Laboratory), Siemens NX and ANSYS, where data are transferred among MATLAB and Siemens NX systems via plain data files. Note that, as mentioned in section II, Kriging model is constructed based on the sample obtained from the preprocessing method, and the individuals thus obtained are feasible solutions that do not intersect with the obstacle. Therefore, it is necessary to perform a similar pre-optimization in initial stage, in order that the individuals in the population are collision-free paths when considering f_3.

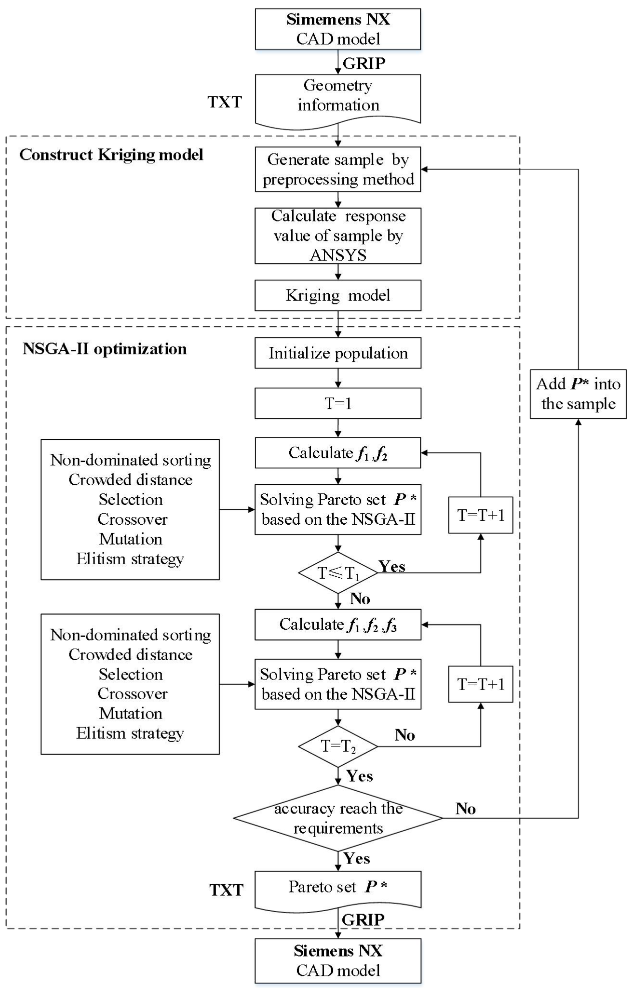


FIGURE 5. Flowchart of the presented pipe routing method.

Thus, the presented pipe routing algorithm based on Kriging model and NSGA-II can be divided into two steps: 1) pre-optimization: when the current number of iterations $T < T_1$, only pipe length f_1 and smoothness f_2 are chosen as objective functions, which complete the pre-optimization; 2) when $T_1 \leq T \leq T_2$, pipe length f_1, smoothness f_2 and FM f_3 are chosen as objective functions. The flowchart of the presented multi-objective pipe routing algorithm is given in Fig.5.

VI. NUMERICAL COMPUTATIONS

To demonstrate the effectiveness of the proposed method, numerical computations on a simplified aero-engine piping model given in Fig.1(a) are performed. The computations are performed on a PC (Intel(R) Core(TM) i5-4460 @3.20GHz, 4 GB RAM). The software used is MATLAB 2010a, Siemens NX 10.0 and ANSYS 15.0.

A. MULTI-OBJECTIVE PIPE ROUTING ON AERO-ENGINE ROTATIONAL SURFACE

The parameters of the routing algorithm are set as follows: the population size $N = 100$, the engine excitation frequency w_e is set as 200Hz for example, the number of iterations $T_1 = 5$, the maximum number of allowable iterations $T_2 = 40$, crossover probability $F_{\rm i} = 0.9$, mutation probability $B_{\rm i} = 0.1$ and the "penalty coefficient" $\delta = 1000$.

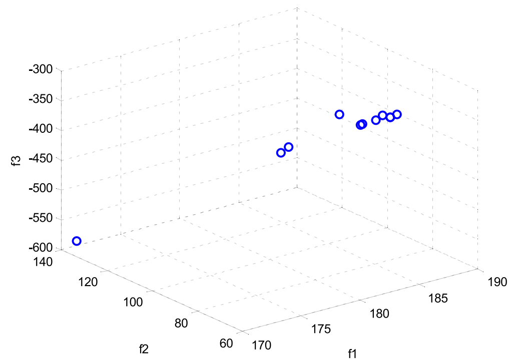


FIGURE 6. Non-dominated solutions in objective space.

TABLE 1. Some non-dominated solutions obtained by NSGA-II.

Pareto set obtained	f_1	f_2	f_3	h	g
Non-dominated solution 1	171	139	-587	0	0
Non-dominated solution 2	186	74	-343	0	0
Non-dominated solution 3	182	105	-440	0	0

The presented routing algorithm runs several times, and a Pareto set containing 10 non-dominated solutions is obtained. Fig.6 gives the distributions of these solutions in objective space. Due to limitation of paper length, Table 1 gives only several typical solutions. Fig.7 and Fig.8 gives pipe layouts and pipe CAE analysis results of these solutions, respectively.

B. RESULT DISCUSSIONS

The above results show that, the presented routing method can obtain a set of several non-dominated solutions with different trade-offs, which offer more options for users to satisfy preference and experience in engineering practice. In particular, the first order natural frequency of these solutions locate outside 20% of engine excitation frequency and are far from

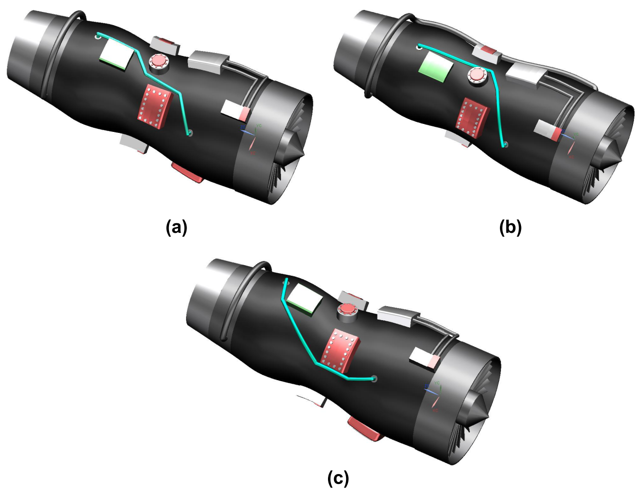


FIGURE 7. Pipe layouts of non-dominated solutions. (a) Non-dominated solution 1. (b) Non-dominated solution 2. (c) Non-dominated solution 3.

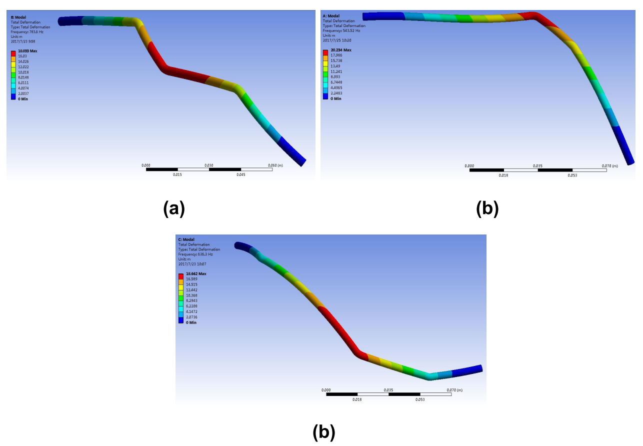


FIGURE 8. CAE analysis results of several typical individuals in the Pareto solution set. (a) CAE analysis results of non-dominated solution 1. (b) CAE analysis results of non-dominated solution 2. (c) CAE analysis results of non-dominated solution 3.

engine excitation frequency, which improves reliability and guarantees to avoids possible resonance.

TABLE 2. Error analysis of calculation results.

Pareto set obtained	f_3	w_e	w_1	w_1'	γ
Non-dominated solution 1	-587	200	787	784	0.38%
Non-dominated solution 2	-343	200	543	544	0.18%
Non-dominated solution 3	-440	200	640	636	0.63%

Table 2 gives the error analysis of calculation results, where w_1 denotes the first order natural frequency of pipe, which are solved by Kriging model, w_e denotes the engine excitation frequency, w_1' denotes the first order natural frequency of pipe by CAE analysis, and γ denotes the relative error between w_1 and w_1'.

As shown in Table 2, the results computed by Kriging model are compared with the ones obtained by ANSYS software, the range of relative error γ is [0.18%, 0.63%]. The error basically meets requirements, which further demonstrates the high accuracy of the constructed Kriging model.

In addition, the presented routing method can significantly improve optimization efficiency. The total running time for constructing the Kriging model is approximately 90 minutes, which includes generating sample using preprocessing method (the preprocessing method takes about 4 seconds each time), calculating the actual response value of sample points by CAE analysis (CAE analysis of one pipe takes about 60 seconds each time) and test of the accuracy of the model. The running time for solving Pareto solutions by using NSGA-II and Kriging model (the population size is 100, the maximum number of allowable iterations is 40) is averagely about 20 seconds. Therefore, the routing optimization method takes about 90.33 min in total. Otherwise, if the CAE analysis is used to calculate the fitness value for each individual during the evolution computations, it will take $(100 \times 40) \times 1\,\text{min} = 4000\,\text{min}$ at least, which is very time-consuming. Obviously, the presented routing method improves the optimization efficiency remarkably because of applying the Kriging model.

VII. CONCLUSIONS

In this paper, a multi-objective pipe routing algorithm considering vibration performance is proposed based on NSGA-II and Kriging model, which is further studied in context of an aero-engine development. The obtained solutions are satisfactory in terms of each objective, which offer more options for users to satisfy preference and experience. In particular, the natural frequency of pipes is far from engine excitation frequency, which guarantees to avoid possible resonance.

In particular, the Kriging model reflecting the relationship between pipe node position and natural frequency is constructed, and the accuracy of which is improved by using a preprocessing method. The proposed multi-objective pipe routing method significantly reduces the calculation cost by applying Kriging model to evaluate the individual fitness values during the optimization process, instead of using a time-consuming CAE analysis program.

The reasons causing pipe vibration of aero-engine are very complex, which include but not limited to engine excitation vibration, fluid fluctuation and possible resonance. In this paper, besides pipe length and smoothness, only the resonance factor is considered. Further study should be on integrating more vibration analysis and optimization into pipe routing algorithms.

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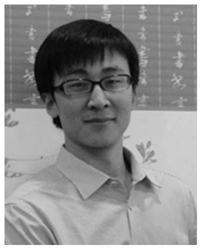

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