Measurement-based geometric reconstruction for milling turbine blade using free-form deformation

Zhengcai Zhao, Yucan Fu*, Xuan Liu, Jiuhua Xu, Jun Wang, Shujie Mao

College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

Abstract
In aerospace engineering, the combination of hot forming and numerical control milling processes is an effective way to manufacture gas turbine blades nowadays. Due to the shape deviation, it is hard to mill the parts formed by hot forming process to the final nominal shape sometimes. To reduce the rejection rate and save the production cost, a measurement-based approach for geometric reconstruction of final nominal shape using free-form deformation (FFD) is presented in this paper. The original shape was firstly sliced into several cross-sections in its design manner, then each section was modified by FFD based on a set of organized measurement points, and at last the final nominal shape was reconstructed by lofting these modified cross-sections. An iteration process with knot insertion was developed to improve the FFD calculation accuracy. The results were found to be highly encouraging, which validates the feasibility of our proposed geometrical reconstruction method.

1. Introduction

Hot forming processes such as forging, casting and creep forming, are widely used in manufacturing complex structural parts in aerospace application, which can reduce material costs and improve machining efficiency [1–4]. However, they cannot directly meet the high accuracy requirement of some key parts such as gas turbine blades and blisks. Thus, they are often followed by numerical control (NC) milling to ensure the final accuracy of these parts [5–8]. That is, the output of the hot forming process is the input of the NC milling process.

A critical barrier has been encountered in the NC milling of these output parts that they were different from each other because of low forming accuracy. Moreover, some formed parts cannot be milled to the final nominal shape due to large shape deviation. For reducing the rejection rate and saving the production cost, the nominal geometrical shape should be reconstructed [9,10]. In this paper, we investigate the problem of geometrical reconstruction of final nominal CAD model for milling gas turbine blade using free-form deformation.

The main contributions of our work are:

- We consider the geometrical reconstruction of gas turbine blade as a problem of shape modification with multiple measurement points. A least squares minimization approach regarding point-pair displacements was adopted.
- We describe the geometrical shape of gas turbine blade in non-uniform rational B-splines (NURBS) formats. Free-form deformation (FFD) was used to modify the lattice control points to update the NURBS shape. An iteration process of FFD calculation was developed to improve the calculation accuracy by knot insertion.
- The NURBS shape of the gas turbine blade was reconstructed in its original design manner. The NURBS shape was sliced into several cross-sections. Each cross-section was reconstructed first and then the final shape was lofted by these modified cross-sections.

The rest of the paper is organized as follows. In Section 2, some related works on geometrical reconstruction and FFD are described. Section 3 details the geometric reconstruction approach for milling gas turbine blade. Implementation of the proposed approach is given in Section 4. Results of a case study are depicted in Section 5. Finally, conclusions and outlook are presented in Section 6.
three-dimensional (3D) shape are achieved in the scanning and point processing. In the surface reconstruction, a patch or a set of curves is created firstly based on mesh or point cloud data, and then parametric surfaces are fitted into the segments considering the constraints of continuity along the boundaries. Gao et al. [12] digitized the blade to polygon 3D model and loaded this scanned polygon model into the reverse engineering software of Polyworks for the blade tip reconstruction. Lange et al. [13] achieved a three-dimensional point cloud of the measured blade using structured light, then exacted the section outlines from the point cloud, and finally reconstructed the blade model. Yilmaz et al. [14] utilized a 3D non-contact measurement method to digitize the blade and developed an adaptive approach to reconstruct the deposited blade tip surface. Lin et al. [15] scanned the forging blade with a coordinate measuring machine (CMM) and adaptively reconstructed a surface model to solve the disconnection problem between the actual surface of the blade and the theoretical model around the leading edge and tailing edge. Piya et al. [16] and Wilson et al. [17] used the sectional gauss concept to extract Prominent Cross Section (PCS) from an airfoil mesh of a blade and employed the reverse engineering technology to reconstruct the geometry of turbine blades. Gromann and Juttler [18] generated a trivariate B-spline parametrization of turbine blades from measurement data generated by an optical scanner.

It is obviously that previous works firstly required a large point cloud scanned or probed from the turbine blade and then reconstructed the model from these points, which is time-consuming and very labor intensive. Besides, for the same type of turbine blades with different shape deviation, this complicated procedure needs to be repeated again and again. In this study, we attempt to find a more quick and convenient approach which reconstructs the turbine blade model by modifying the nominal CAD model according to a small number of measurement points.

2.2. Free-form deformation

Free-form deformation (FFD) is a well-established technique for editing CAD model, used to deform two- or three-dimensional geometrical entities [19]. This technology was firstly proposed in 1986 by Sederberg and Parry [20], in which surface primitives of any type or degree can be deformed based on trivariate Bernstein polynomials. In 1990, Coquillart [21] extended this technology and proposed a highly interactive and intuitive modeling technique for designers and stylists. Kobayashi and Otsubo [22] proposed a new method of free-form deformation by using triangular mesh in 2003, in which an original shape of polygonal mesh or point-cloud is deformed by a control mesh. Direct manipulation of free-form deformations (DFFD) was first proposed by Hsu et al. [23], which allows a user to control a deformation of an object directly. Th FFD technology has been successfully applied in sheet metal forming [24], 3D printing [25] and auto industry [26].

3. Methodology of reconstructing nominal CAD model

3.1. Problem statement

This paper focuses on a problem of geometric reconstruction of nominal CAD model in NC milling turbine blades, which has been formed to a near net-shape by a hot forming process, i.e., forging, casting and superplastic forming. By undergoing multiple heat cycles, the near net-shape suffered some shape deviation compared to the original design shape, which results in a critical problem in NC milling process. As known, for machining complex surface parts involving turbine blade, computer-aided manufacturing (CAM) technology is necessary for multiple-axis tool path generation. The nominal CAD model is indispensable for tool path generation. Basically, the near net-shape of the blade has a small amount of allowance to be milled. The shape deviation induced in the hot forming process makes it impossible to mill the blade to its final nominal CAD model. Fig. 1 schematically presents the relationship between the actual shape hot forming (HF), nominal shape before and after milling (BM and AM). Ideally, the actual HF shape should be the same with the nominal BM shape if there is no deviations. In fact, the final nominal BM shape cannot be enveloped totally by the actual HF shape, which means that the HF blade cannot be milled to the final nominal AM shape.

3.2. Solving methodology

To solve this problem, one way is to improve the hot forming accuracy and another is to reconstruct the final nominal AM shape. This paper attempts to find a solution by reconstructing the final nominal AM shape. Fig. 2 shows the methodology of geometric reconstruction proposed in this paper. The nominal BM CAD model was first sliced into 2D cross-sections and measurement points were generated from each cross-section. On-machine measurement was used to acquire shape point data of each cross-section. The measurement operation was performed twice with the same planned measurement points. The measured points from the first operation were used to match with nominal CAD shape to find the appropriate position. The second operation with the updated position was performed to build the point-pairs for the calculation of FFD volume. According to the distances between point-pairs, the FFD volume of each cross-section was calculated. To evaluate the FFD calculation accuracy, the deformation error ($d$) was analyzed. If $d$ was greater than the threshold value $e$, the FFD volume was iteratively calculated again. Otherwise, the calculated FFD was applied to each cross-section of final nominal AM shape. Finally, the final nominal AM 3D shape was reconstructed by lofting deformed 2D cross-sections. In this paper, the number and distribution of the measurement points are well planned in order to ensure calculation accuracy. Actually, this approach also can solve the case of incomplete point cloud if the accuracy loss is ignored.
4. Procedure of reconstructing nominal CAD model

4.1. Measurement

The shape of the deformed near net-shape of the turbine blade is the target of the FFD calculation in the geometric reconstruction. The measurement strategy decides the accuracy and the distribution of the points, which has much effect on the calculation accuracy and efficiency of FFD. On-machine measurement (OMM) is a metrological method in which a touch probe sensor or a non-contact sensor replaces the cutting tool in the machine tool spindle to measure the part on the machine tool directly [27]. In this paper, a DMG Ultrasonic Linear 20 machine tool with a Renishaw touch probe was used to measure the turbine blade.

As shown in Fig. 3, the nominal BM CAD model was sliced into seven cross-sections, on which the measurement points were generated. In order to reduce the operating time and save the computational cost in the following algorithms, the rule of generating measurement points is to retain the shape of the cross-section with the least points. Mansour [28] developed an algorithm to reduce the measurement points and time of the blades on coordinate measuring machine (CMM), which was adopted in this paper. Initially, the first four points on one cross-section are approached by a nominal curve using the method of least squares. The polynomial equation is of the form:

\[ Y(i) = Ax^3(i) + Bx^2(i) + Cx(i) + D \]  

The four unknown coefficients \( A, B, C, D \) are calculated by differentiating the sum of squared deviations (S) to each parameter and equaling it to zero.

\[ S = \sum_{i=1}^{n} \left( y(i) - (Ax^3(i) + Bx^2(i) + Cx(i) + D) \right)^2 \]  

\[ \frac{\partial S}{\partial A} = -2 \sum_{i=1}^{n} x^3(i) y(i) - (Ax^3(i) + Bx^2(i) + Cx(i) + D)^2 = 0 \]  

\[ \frac{\partial S}{\partial B} = -2 \sum_{i=1}^{n} x^2(i) y(i) - (Ax^3(i) + Bx^2(i) + Cx(i) + D)^2 = 0 \]  

\[ \frac{\partial S}{\partial C} = -2 \sum_{i=1}^{n} x(i) y(i) - (Ax^3(i) + Bx^2(i) + Cx(i) + D)^2 = 0 \]  

\[ \frac{\partial S}{\partial D} = -2 \sum_{i=1}^{n} y(i) - (Ax^3(i) + Bx^2(i) + Cx(i) + D)^2 = 0 \]  

From Eqs. (3)–(6), the values of the parameters \( A, B, C, D \) are determined. Then the deviations between \( y_{\text{real}}(i) \) and \( y_{\text{cal}}(i) \) are checked if they are within the desired tolerance. If those deviations are satisfied, the next point is added in the initial subset and the above procedure is repeated. Else, the last point is removed and
thus this subset is assigned in this part of the curve. The process continues as before for the rest of the points by selecting following the first four points. For each subset, initially three points are found from the coefficients of the polynomial that approximates these points. With this method, the initial curve can be approached within the desirable tolerance with much fewer points. Fig. 4 presents the calculated result of one cross-section. It can be seen that the original points are dramatically reduced with this method. From the 220 points, only 47 points are required to approximately describe the shape of the cross-section within the deviation of 0.01 mm.

4.2. Registration

To find the appropriate position between the measured points and the nominal CAD shape, the iterative closest point (ICP) method was used in this paper. The ICP algorithm was proposed by Besl and Mckay [29] in 1992, which can find the closest point on a geometric entity, i.e., surface, to the measurement points. This algorithm minimizes at each iteration step the corrective square distance between the measured points and their closest points on the surface, defined by the mean square objective function:

$$f(q) = \frac{1}{N_p} \sum_{i=1}^{N_p} || \bar{x}_i - R(q) \bar{p}_i - \bar{q}_i ||^2$$

where $\bar{q}_i$ is the translation matrix, $\bar{q}_e$ is the rotation matrix, $\bar{p}_i$ is the $i$th measurement point and $\bar{x}_i$ is the $i$th closest point on the surface. In the implemented algorithm, the search for the closest point on the surface was by the multi-dimensional simplex method and the least squares minimization was performed by using the singular value decomposition [30]. When the $\bar{q}_e$ and $\bar{q}_o$ are determined by iterative calculation, the measurement points are moved to closest position to the surface, by which the measurement coordinate is updated. With the updated measurement coordinate, the above OMM operation was repeated. Since there is a one-to-one correspondence relation between the planned points and the measured points. Point-pairs for the following FFD calculation can be built in the measurement process.

4.3. FFD

The CAD model of the turbine blade is represented in the form of Non-Uniform Rational B-Splines (NURBS) surface in this paper. Thus, the cross-section of the blade can be represented as a NURBS spline as follows:

$$L(u, v) = \frac{\sum_{p=0}^{n} \sum_{q=0}^{m} N_{p}(u) N_{q}(v) W_{pq} P_{pq}}{\sum_{p=0}^{n} \sum_{q=0}^{m} N_{p}(u) N_{q}(v) W_{pq}} \quad 0 \leq u, v \leq 1 \quad (8)$$

where $P_{pq}$ is the control points and $W_{pq}$ are control points weights. $N_{p}(u)$ and $N_{q}(v)$ are the NURBS basic functions, which are defined on the knot vectors:

$$U = (0, \ldots, 0, u_{p+1}, \ldots, u_{p-1}, 1, \ldots, 1)$$

$$V = (0, \ldots, 0, v_{q+1}, \ldots, v_{q-1}, 1, \ldots, 1) \quad (9)$$

We intends to deform the shape of the cross-section to align with the measurement points according to the point-pair distances. From Eq. (8), it is known that there are three methods to modify the NURBS spline: (1) redefine the basic functions on new knot vectors; (2) modify the control points weights; (3) adjust the control points. Among these methods, adjusting the control points and modifying their weights are much intuitive and effective methods. However, inversion calculation method is needed to acquire the informations of the control points and the values of the weights according to the shape data of the cross-section, which is time-consuming and computationally expensive.

The FFD algorithm defines a deformation volume represented as a tensor-product combination of three sets of B-Spline functions, in the form of

$$F(u, v, w) = \sum_{i=1}^{L} \sum_{j=1}^{M} \sum_{k=1}^{N} A_{ijk} B_i(u) B_j(v) B_k(w) \quad (10)$$

which defines a mapping $F: (u, v, w) \rightarrow (x, y, z)$ from points with coordinates $(u, v, w)$ in a finite rectangular volume subset $D$ of $R^3$ to points of the cross-section with coordinates $(x, y, z)$ in a volume of subset $E$ of $R^3$. $A_{ijk}$ is the lattice grid points of the volume $D$. 

![Fig. 4. Original and calculated points.](image-url)
the values of which determines the volume \( E, B_i(u), B_j(v) \) and \( B_k(w) \) are the B-Spline basic functions, which are defined on the knot vectors:

\[
U = 0, \cdots, 0, u_{p+1}, \cdots, u_{p-p-1}, 1, \cdots, 1 \\
V = 0, \cdots, 0, v_{q+1}, \cdots, v_{q-q-1}, 1, \cdots, 1 \\
W = 0, \cdots, 0, w_{r+1}, \cdots, w_{r-r-1}, 1, \cdots, 1
\]

Point inversion method is used to find the local parameters \((u, v, w)\) for each point \( p = (x, y, z) \). This yields the initial lattice of \( p = F(u, v, w) \). The deformation of the embedded space in this lattice can be performed by adjusting the lattice grid \( A_{ijk} \), which is formulated as

\[
p' = F(u, v, w) = \sum_{i=1}^{L} \sum_{j=1}^{M} \sum_{k=1}^{N} (A_{ijk} + \delta_{ijk})B_i(u)B_j(v)B_k(w) \\
= \sum_{i=1}^{L} \sum_{j=1}^{M} \sum_{k=1}^{N} A_{ijk}B_i(u)B_j(v)B_k(w) \\
+ \sum_{i=1}^{L} \sum_{j=1}^{M} \sum_{k=1}^{N} \delta_{ijk}B_i(u)B_j(v)B_k(w) \\
= p + \sum_{i=1}^{L} \sum_{j=1}^{M} \sum_{k=1}^{N} \delta_{ijk}B_i(u)B_j(v)B_k(w)
\]

where \( \delta_{ijk} \) is the displacement of \( A_{ijk} \). If \( p' \) is denoted as the measurement point \( q \) and \( p \) is denoted as its closest point on the nominal surface, the cross-section shape can be modified by solving Eq. (12).

![Fig. 5](image-url)
Eq. (12) can be written as
\[
d = \sum_{i=1}^{l} \sum_{j=1}^{M} \sum_{k=1}^{N} \delta_{ijk} B_{i}(u) B_{j}(v) B_{k}(w)
\] (13)
where \(d\) is the distance between point-pair build in the registration process.

Eq. (13) can be formulated as a least-square problem
\[
\sum_{i=1}^{h} \| \delta_{ijk} \|^2 \rightarrow \min.
\] (14)
where \(h\) is the number of the measurement points. This problem can be efficiently solved using an explicit solution proposed by Hu et al. [31].

The Lagrange function can be written as
\[
L = \sum_{i=1}^{d} || \delta_{ijk} ||^2 + \lambda (d - \sum_{i=1}^{l} \sum_{j=1}^{M} \sum_{k=1}^{N} \delta_{ijk} B_{i}(u) B_{j}(v) B_{k}(w))
\] (15)
where \(\lambda = (\lambda_1, \lambda_2, \lambda_3)\) is the Lagrange multiplier.

By setting \(\frac{\partial L}{\partial \lambda_1} = \frac{\partial L}{\partial \lambda_2} = \frac{\partial L}{\partial \lambda_3} = 0\) and \(\frac{\partial L}{\partial \delta_{ijk}} = \frac{\partial L}{\partial \delta_{ijk}} = 0\), the following equation are obtained
\[
\delta_{ijk} B_{i}(u) B_{j}(v) B_{k}(w) = \frac{1}{2} B_{i}(u) B_{j}(v) B_{k}(w)
\] (16)

Combining Eqs. (13) and (16), the explicit solution for solving \(\delta_{ijk}\) is yielded:
\[
\delta_{ijk} = \frac{d B_{i}(u) B_{j}(v) B_{k}(w)}{\sum_{i=1}^{l} \sum_{j=1}^{M} \sum_{k=1}^{N} (B_{i}(u) B_{j}(v) B_{k}(w))^2}
\] (17)

After solving \(\delta_{ijk}\), the deformed FFD volume is achieved. By embedding the nominal shape into the FFD volume, the reconstructed AM shape is obtained.

As shown in Fig. 1, the nominal AM shape is not totally enveloped by the actual HF shape. After analyzing the measurement points, the features of leading edge and trailing edge were

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Fig. 6. FFD results of modifying AM shape.
extracted and it is found that this non-enveloping problem can be classified into three types: (1) shrinkage, (2) twisting and (3) shrinkage and twisting (cp. Fig. 5). In Fig. 5a, the actual HF shape was shrink along the chordwise direction of the blade. Twisting of the cross-section is that the blade was twisted along the spanwise direction, which was shown in Fig. 5b. The third type was depicted in Fig. 5c, in which both the shrinkage and twisting occurred. The third type was most complicated and common in practice.

The FFD results of modifying AM shapes are shown in Fig. 6. In general, all the modified shape are totally enveloped by the actual HF shape, which means all the actual HF shape have the allowance to be removed to reach the AM shape. As shown in Fig. 6a, the nominal AM shape was shorten corresponding to the shrinkage of the HF shape. For the case of twisting, the nominal AM shape was rotated within the contour of the actual HF shape. In Fig. 6c, both the shortening and rotating occurred to modify the nominal AM shape.

4.4. Iterative calculation of FFD

Accuracy is one of most important concerns in machining turbine blade. Hence, it is necessary to ensure the deformation accuracy of calculating FFD volume. As known, the less number of control points in the deformation lattice, the less computing time. However, small number of control points will reduce the flexibility of the FFD volume, resulting in low deformation accuracy. Iteratively refining the FFD volume from a coarse lattice by knot insertion is an effective way to improve the flexibility of FFD volume. We use the iterative refinement method proposed by Sacharov et al. [32]. The challenge is to find where is the largest deviation. The FFD volume is firstly divided into cells and then compare with the target points to locate the cells with large error. The comparison procedure can be formulated as

\[
C = M \cdot L \cdot \frac{1}{k \cdot d} \sum_{i=1}^{d} \sum_{j=1}^{k} \frac{||F_i(\vec{p}_j) - F_j(\vec{p}_i)||_2}{||p_j - p_i||_2^2} \cdot \frac{||p_j - p_i \cdot b_x||}{||p_j - p_i||_2} \quad (18)
\]

where \(L\) is the length of the cell and \(b_x = (1, 0, 0)^T\). \(F_i(\vec{p}_j) = (q_j - F_i(p_j))\) is a residual deviation vector after deformation with \(F_i\). The cells with \(C > \varepsilon\) are refined by inserting a new knot.

5. Results

Our geometrical reconstruction algorithm was implemented by C++ and validated on an example of one certain fan blade. All tests were run on a 64-bit Windows workstation with 2.9 GHz processor and 32 GB memory.

As shown in Fig. 3, seven cross-sections were created from the nominal BM CAD model and the measurement points were generated from these cross-sections by an approximation method in Section 4.1. By setting the threshold value of the calculation deviation as 0.01 mm, the measurement points were generated. The approximation results of seven cross-sections were listed in Table 1. 220 points were firstly selected by equidistance method for all cross-sections. From Table 1, all the cross-sections were approximated less than 50 points within the given deviation.

Based on the calculated measurement points, the HF blade was measured by OMM method. Because of the shape deformation, the positions of the probe center were recorded to ensure the accuracy of the measurement points firstly. Afterward, the normal vector of each measured point was estimated by fitting the least square plane according to the nearest points. Finally, the probe center points were offset by a value of probe radius to achieve the actual points on the HF blade surface. The offset measured points were matched by the ICP method to the nominal BM CAD model to find the best position and build the point-pairs for the FFD calculation. Fig. 7 presents comparison result between measured points and the nominal BM CAD model. The deviation ranges from \(-3.325\) to 2.289 mm. The designed allowance from the nominal BM CAD model to AM CAD model is nearly 1 mm, which means the HF blade does not have the allowance to be milled. The comparison result between measured points and nominal AM CAD model was shown in Fig. 8. The minimum deviation was \(-2.449\) mm, which has exceeded the tolerance range of \(-0.1\) to 0.1 mm. This indicates that it is impossible to mill the HF blade to the AF nominal shape.

To solve this problem, FFD volume was used to reconstruct the AM CAD model. Initially, the B-spline volume of 3-degree with \(4 \times 4 \times 4\) control points was built and the maximum deformation error \(\varepsilon\) was set as 0.01 mm. The development of the deformation...
error with the iteration calculation process was described in Table 2. With the initial lattice, the maximum deformation error was 0.0829 mm. In the second iteration, the lattice was increased to $4 \times 5 \times 5$ control points and the deformation error was reduced to 0.0528 mm. In the third iteration process, the deformation error was satisfied and the lattice was finally added to $7 \times 7 \times 6$ control points. This satisfied FFD volume was applied to the corresponding cross-sections of AM CAD model to modify it. When the cross-sections were modified, the nominal AM CAD model can be reconstructed by lofting modified cross-sections. The reconstructed nominal AM CAD model was shown in Fig. 9. By comparing with the measured points, it is found that based on this reconstructed nominal AM CAD model, the HF blade has the allowance in the range of +0.1705 to +2.869 mm. This means that after geometrical reconstruction, the HF blade has the allowance to be milled to the modified nominal AM shape.

In summary, our method slightly modified the nominal AM model based on the deviation of the actual HF blade. After geometrical reconstruction, a smooth and continuous nominal AM shape was achieved. According to this new shape, the features of the blade involving trailing and leading edges can be milled, which can dramatically reduce the rejection rate and save the production cost. The results of the above case study has validated the feasibility of our proposed method.

6. Conclusions and outlook

This paper presents a new approach for reconstructing final nominal CAD model in milling turbine blade in aerospace engineering, which has been formed as a near-net shape by the hot forming process. Our approach can reconstruct the blade CAD model quickly and conveniently by modifying the nominal CAD model according to a small number of measurement points. This modification problem was formulated as a problem of shape updating with multiple point constraints. The gas turbine blade was described in NURBS formats and FFD volume was employed to modify the lattice control points to update the NURBS shape. The calculation of the lattice control points displacements were formulated as a least squares problem, which was solved using an explicit solution. An iteration process was built to improve the calculation accuracy of FFD volume by inserting knots. The results from a case study of one certain fan blade validates that our approach is feasible and encouraging.

In the future, the machining tolerance should be considered in the process of geometrical reconstruction of the blade, which means that the modification amount of each cross-section should be within the tolerance range of the blade. This can be implemented in the process of FFD volume calculation by adding some boundary conditions according to the range of the machining tolerance. Besides, an evaluation criterion needs to be developed, in which whether the final nominal shape of the blade can be reconstructed within the machining tolerance range with regards to the different deformation amount of the near-net shape formed by the hot forming process. Furthermore, a more general and accurate approach of template-based reconstruction in which the point

<table>
<thead>
<tr>
<th>Iteration no.</th>
<th>Deformation error $\varepsilon$ (mm)</th>
<th>Control points</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>0.0829</td>
<td>$4 \times 4 \times 4$</td>
</tr>
<tr>
<td>2</td>
<td>0.0528</td>
<td>$4 \times 5 \times 5$</td>
</tr>
<tr>
<td>3</td>
<td>0.0072</td>
<td>$7 \times 7 \times 6$</td>
</tr>
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</table>
cloud may be incomplete and the template can be optimized will be studied.

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