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STRESS ANALYSIS AND EFFICIENT MODELLING OF A FIR TREE JOINT IN AN AERO ENGINE

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Abstract—one of the major sources of the stress arising in the turbo-machinery blades are the centrifugal and thermal loads acting at any section of the airfoil. Fretting is a phenomenon occurring between two surfaces having relative oscillatory motion of small amplitude fretting damages occurs on the surfaces of contacting components . Accounting for these phenomena stress evaluation of the blade attachment region in the disc has to be performed in order to avoid blade failure. This paper presents a work on geometric models in order to achieve minimum fretting action and stress distribution based on the response surface method and Using design of experiments, central composite design and anova method are opted to obtain optimum geometric parameters these geometric parameters are validated to get the expected results.

Index Terms—Fretting action, response surface method, Design of Experiments, Optimization.

I. INTRODUCTION

The Gas turbine engine design is the most highly advanced design. A good design is one which provides all the strengthand rigidity to meet all its design requirements. The structural components of the gas turbine engine consist of compressor, combustor, turbine, exhaust system and a convergent divergent nozzle. The sectional view of the gas turbine engine as shown in Figure 1.

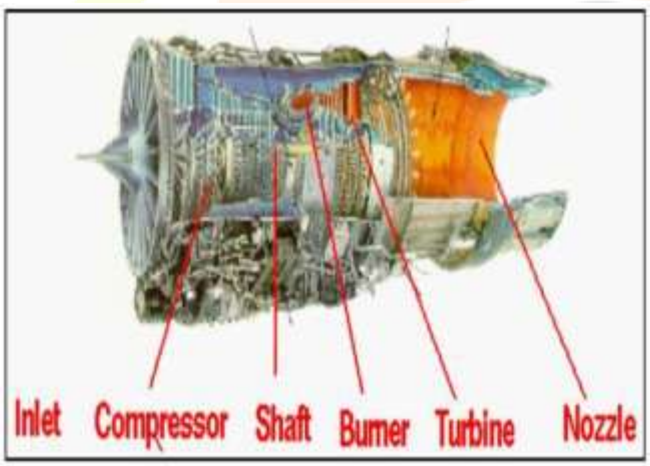


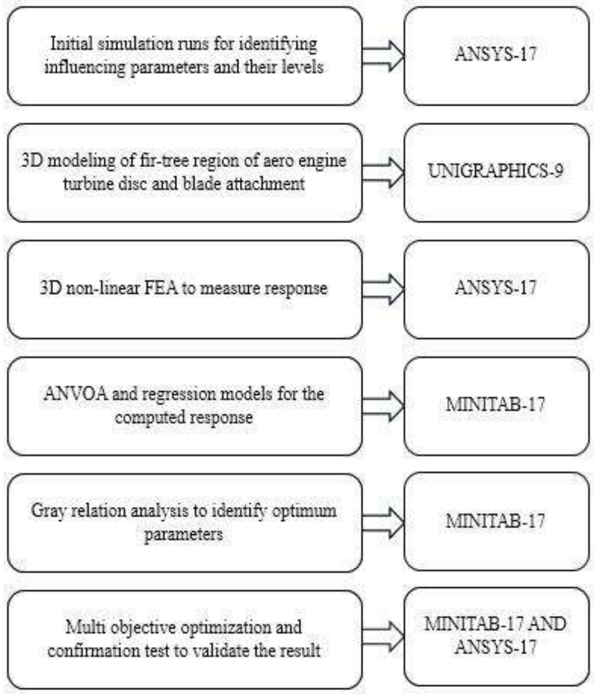
Figure 1. Sectional view of gas turbine engine

The thermodynamic process requires a supply of air under pressure. The purpose of the compressor is to raise the pressure of the air besides a small rise after air intake. A compressor includes a rotor (mobile blades) which imparts motion to a mass of air and a stator (stationary vanes) which transforms the velocity into pressure. In the mobile blades the velocity of the flow increases because of the motion imparted to the air and the pressure increases because of the configuration of the blades (divergence). In the stationary vanes the velocity is transformed into pressure because of the divergent air path, and the flow is straightened. The combustion chamber receives air from the compressor and it mixes with fuel sprayed from nozzles in the front of the chamber. The mixture is burned at high temperatures to generate the maximum possible heat energy. The process of burning is initiated by igniter plugs, it is isolated after startup, and continues until the fuel supply is shut off. In a gas turbine engine, the output of the turbine is used to turn the compressor (which may also have an associated propeller or a fan). The hot air flow leaving the turbine is then accelerated into the atmosphere through an exhaust nozzle to provide thrust or propulsion power. The exhaust system passes the turbine discharge gases at some velocity to atmosphere, and in the required direction, to provide the resultant thrust.

II. LITERATURE SURVEY

The literature review was carried out to understand the background of this project work.
Literature review has been discussed in the previous published paper named as "Review on Stress analysis and efficient modelling of a Fir Tree joint in an aero engine."

III.PROJECT METHODOLOGY



- Initially simulation runs were carried out by considering the fretting parameters to identify most influencing parameters and their levels for the analysis using ANSYS
- In order to minimize the analysis runs, Central composite design was adopted
- Based on CCD design matrix was developed and standard geometrical models for fir-tree region of aero-engine turbine disc and attached blade were designed in UNIGRAPHICS with appropriate dimensions. The dimensions for the model were taken from Meguid et al. [21] and Tiago et al. [43]. Parasolid file of the model was then imported into FE analysis package ANSYS 17.0. `
- 3-D nonlinear structural analysis was carried out using appropriate boundary conditions to measure the responses Such as von-mises stress, maximum principle stress, minimum principle stress, maximum shear stress and contact pressure which were responsible for fretting phenomenon
- Analysis of variance was performed to identify the significant factors for each response. Regression models were prepared for each of the response using
- MINITAB
- Grey Relational Analysis (GRA) was used to achieve the parametric conditions that correspond to the minimal response values
- Multi objective optimization was carried out using response optimizer of RSM in MINITAB 17.0 and a confirmation test was done in ANSYS 17.0 to check the desirability of the solution obtained from the response optimizer Figure 3.1 shows the methodology adopted for the present project work.

IV.RELATED WORK

The fir-tree geometry configuration with its parameters name and detail dimensions fir-tree geometry tabulated as represented in Figure.2

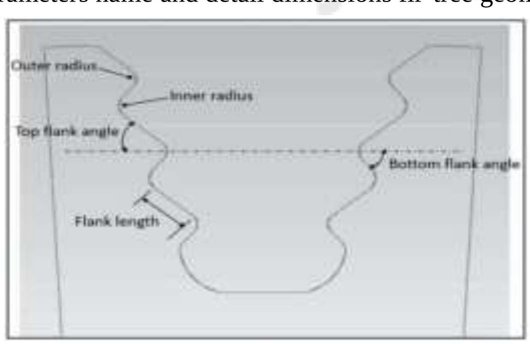


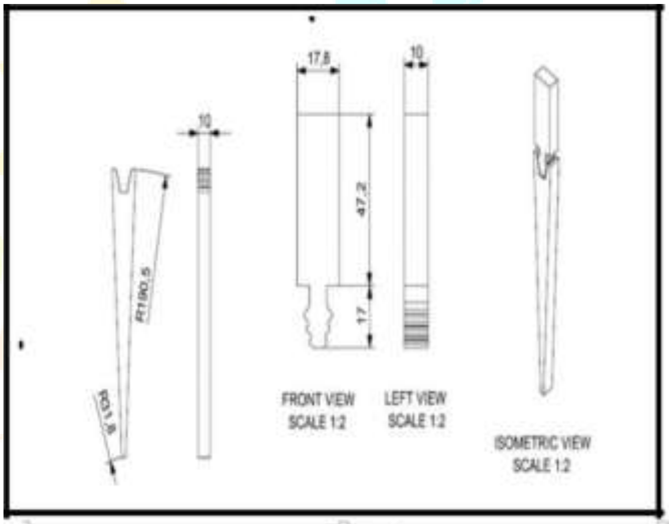
Figure 2.

From the literature analysis and initial runs in ansys it has been found that three major parameters are most affecting the fretting and fatigue life of the component. Those are

Bottom flank angle
Number of teeth
Skew angle.

Fretting phenomenon: When two or more metals are in contact with each other having some amount of relative motion between the metals due to external forces then these components
may suffer from fatigue failure before the desired number of cycles is achieved, this phenomenon is called fretting fatigue. The fretting fatigue damage will increase with increasing followings
With increase in pressure between the two sliding surfaces.
With increase in relative motion between two parts
With increase in number of cycles
When the metals are worn out due to sliding motion, the weight of the components get reducing.

Hence to reduce this drawback, blade disc design geometry has been considered.



Geometrical parameter	Dimensions
Disc inner radius	31.8 mm
Disc outer radius	190.5 mm
Blade height	42.7 mm
Blade width	17.8 mm
Thickness (Disc & Blade)	10 mm
Inner radius	0.68 mm
Outer radius	0.52 mm
Top flank angle	50°
Bottom flank angle	Variable
Number of teeth	Variable
Skew angle	Variable

Table 1.

The modeling of disc and blade was done in UNIGRAPHICS 10.0 based on dimensions given by Meguid et al. [21] and Tiago et al. [43]. The dimensions considered for creating disc are the inner radius 31.75 mm, outer radius 190.5 mm, thickness 10 mm and sector angle 17.5^0. The blade model was created with height of 47.24 mm & 10 mm thickness and then assembled with disc. The Figure 4.1 shows the blade and disc model dimensions In the above table it can been observed that 3 major parameters are considered in order to alter the geometry design and to obtain the optimum geometry to reduce fretting affect on the fir tree joint.

Since there are three parameters involved in the geometry there is probability of many different combinations of geometry exist. Therefore design of experiments method applied to get best possible cases.

For that Minitab 17.0 software has been used where it is found 20 best possible models using Response Surface Method.

The most popular response surface method based on a rotatable central composite design (CCD) with three levels and three factors was applied to investigate the influence of process factors (Bottom flank angle, Skew angle, and Number of teeth) on multiple responses including; von-mises stress, maximum principle stress, minimum principle stress, maximum shear stress and contact pressure.

All design descriptions will be in terms of coded values of the variables. Therefore the total DOE was 20 that means at least 20 experiments/analysis runs need to be conducted to assess the effect of process parameters so FE analysis was carried out in ANSYS based on this standard design matrix to measure the response such as von-mises stress, maximum principle stress, minimum principle stress, maximum shear stress and contact pressure. Original and coded values of the independent variables considered for the present analysis are shown in Table 2. CCD design matrix of the analysis runs were designed based CCD using MINITAB is presented in Table.3

Parameters	Coded values		
	-1	0	1
	Original values		
Bottom flank angle(A)	30	40	50
Skew angle(B)	0	10	20
Number of teeth(C)	3	4	5

Table 2.

The 20 different combinations of fir-tree dimension models were considered for the analysis as tabulated in Table 3.

Model No.	Bottom flank angle (Degree)	Skew angle (Degree)	Number of teeth
1	50	0	3
2	30	0	3
3	40	10	5
4	40	10	4
5	40	10	4
6	50	0	5
7	40	20	4
8	50	20	3
9	30	20	5
10	40	10	4
11	40	10	4
12	40	10	4
13	40	10	4
14	30	0	5
15	40	0	4
16	40	10	3
17	30	10	4
18	50	10	4
19	30	20	3
20	50	20	5

Table 3.

Partition at fir-tree region done using Unigraphics as shown in Figure 3. And 4.

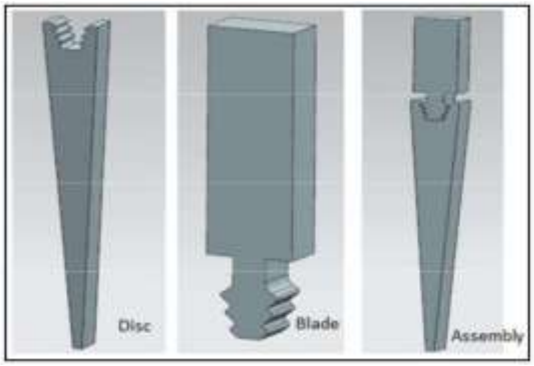


Figure 3.

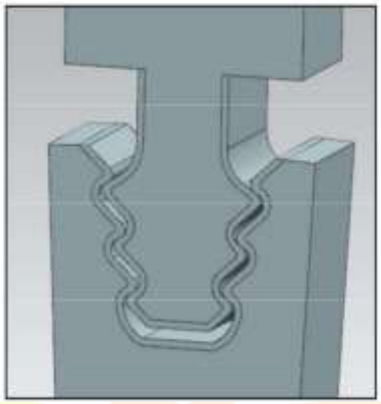


Figure 4.

Measurement of responses

Based on the physical layout of the experimental runs, twenty different fir-tree joint were modeled with all specifications as shown in above table 1. Created models were converted into the parasolid file and imported into ANSYS Workbench 17.0 to conduct the experiments/analysis .The 20 set of experiments/analysis were conducted to measure the response. Such as von-mises stress, maximum principle stress, minimum principle stress, maximum shear stress and contact pressure.

Regression models and statically analysis of fretting fatigue responses:

The computed values of responses were fed into MINITAB 17.0 to analyze the effect of fretting fatigue parameters on the computed response. Using MINITAB 17.0 Regression models for each of the responses were developed using RSM (Response Surface Methodology) to compare and correlate the response and analysis of response surface design was performed to carry out the significant test using F and p distribution.

For Von-mises stress regression equation and R-sq values are obtained from MINITAB-17 software are shown in equation below.

Von-Mises stress = 539 + 43.7*A + 14.37 *B - 314 *C - 0.588 *A*A - 0.006 *B *B+34.1*C*C+0.1601*A*B + 0.275*A*C - 2.135*B*C

R-sq. = 97.21%

In the similar fashion R-Square value is obtained for all the response and values obtained are as follows Max.Principle stress : R-sq= 98.50% Min. Principle stress : R-sq= 65.50%

Max.Shear Stress: R-sq= 83.65%

Contact Pressure: R-sq= 99.29%

The value of R-sq. represents confidence level of regression. Values of 0.9721 for von-mises stress, 0.9850 for maximum principle stress, 0.8365 maximum shear stress and 0.9929 for contact stress are within desirability range [49]. Except minimum stress is for which R-sq. value is .6550 not within desirability rang this because considered parameters (bottom flank angle, skew angle, number of teeth) have less influence on minimum principle stress.

Gray relation analysis (GRA):

The grey theory is an evaluation method based on random improbability of small samples to resolve certain problems of systems that have incomplete information and complex in nature [51]. There are two types of systems namely white system and black system. A white system is system with adequate information while black system is system for which information is completely unknown. The system which lies between these two systems is grey system which has limited information [52]. Grey relational analysis (GRA) is a normalization evaluation method to solve difficult multi-performance characteristics. The various steps in GRA are:

a. Data normalization

b. Derivation of reference sequences

c. Calculation of grey relational coefficient and grey relational grade

d. Average grey relational grades.

GRA system involves certain set of equations which are explained in [52].

Form grey relational analysis it is found that bottom flank angle 50^0, skew angle 0^0 and number of teeth 5 are the optimum levels for the factors.

Optimization response using response optimizer:

Using the obtained CCD models the optimum variable values for the defined goals (in this case, the goal is to set target value for minimum response) were determined using response optimizer. In this project work the target value was taken as the minimum value of the response. For several responses, all goals are combined into an overall desirability function that has to be minimized. Several solutions will be obtained with minimized desirability function (values near to one) that could be arbitrarily selected based on the process requirements. In this study, numerical optimization was carried out for minimum responses using MINITAB-17, and the desirability functions were considered for the optimization. The Figure 5. shows the optimal levels of the factors and their response.

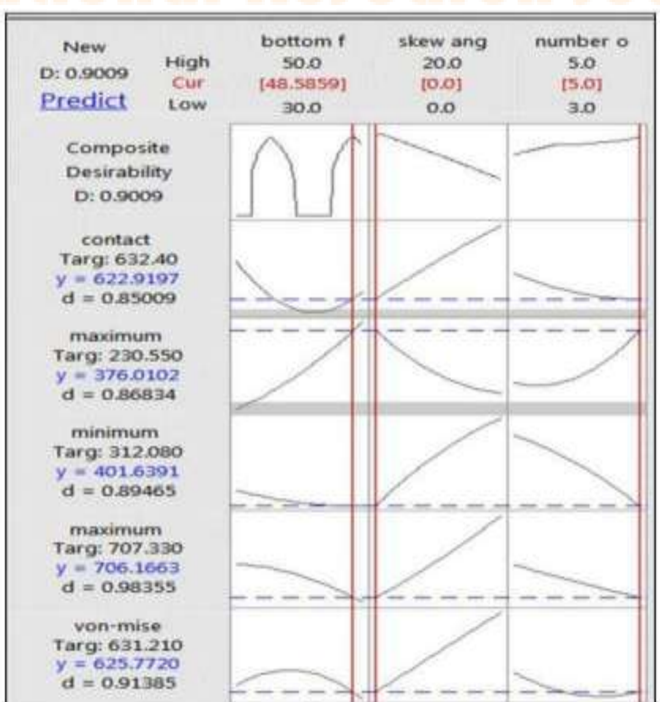


Figure 5. Optimal levels of the factors and their response. From the response optimizer it has been found that bottom flank angle 48.5859, skew angle 0.0 and number of teeth are 5 as it can be seen from the figure 5.

Confirmation test:
To conduct confirmation test new UG model was modeled with optimal values of the parameters i.e. (Bottom flank angle 48.5859^0 skew angle 0^0 and 5 teeth configuration) then model is imported into ANSYS 17.0 and analysis were conducted to get the target

value. Farther these value were compared with values obtained from RMS to check the desirability of the multi objective response optimization.

From the analysis it was observed that response value were almost closure to the response values obtained from the response optimizer of RSM in the MINITAB 17. This confirms the desirability of the RSM. Figure 5.2 (a)-(e) shows the stress/response plots obtained from the ANSYS 17.0. Predicted values of the responses from RMS, calculated values response from confirmation test (ANSYS) and the percentage error are shown in Table 5.15 and graph of predicted values and calculated values (from confirmation test)of response are plotted as shown in Figure 5.3.

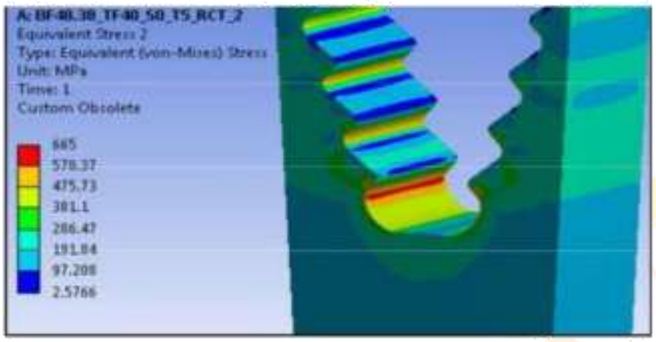


Figure 5.2 (a) Von-mises stress

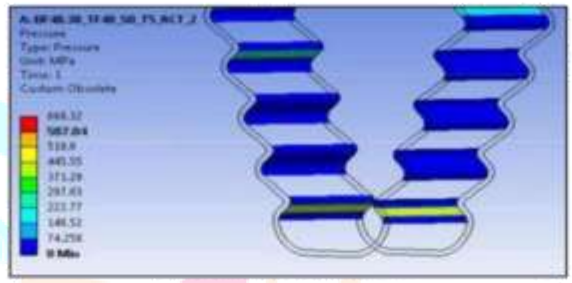


Figure 5.2 (e) contact pressure

Table 5.15 Predicted and calculated value of response and there percentage error.

Response	Predicted values	Calculated	% Error
Von-mises stress	625.77	665	5.8992
Maximum principle stress	706.163	732.05	3.5362
Minimum principle stress	401.6391	419.53	4.2645
Maximum shear stress	376.0101	374.7	0.3496
Contact pressure	622.9197	668.32	5.8902
Average percentage Error			3.9879

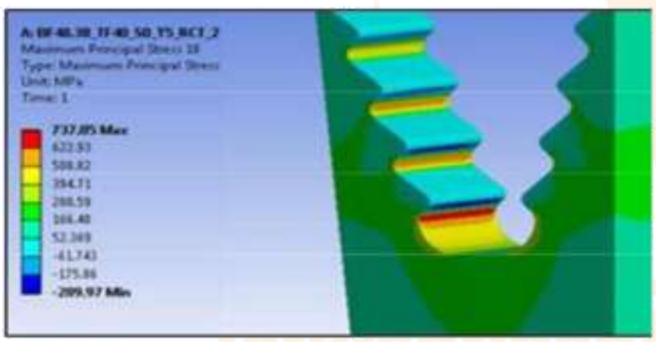


Figure 5.2 (b) Maximum principle stress

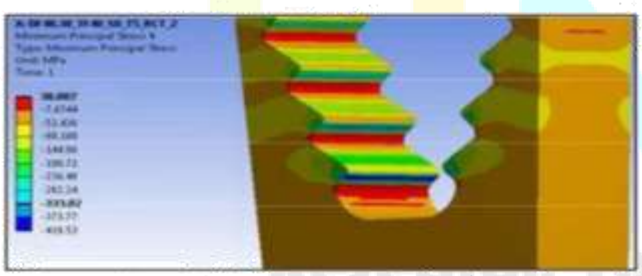


Figure 5.2 (c) Minimum principle stress

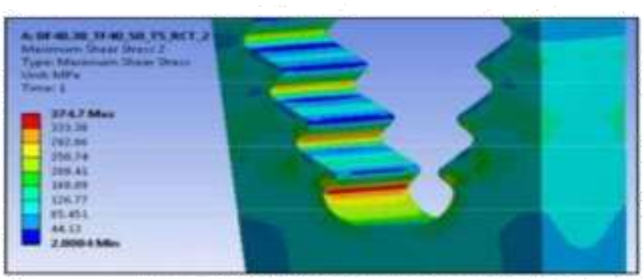


Figure 5.2 (d) Maximum shear stress

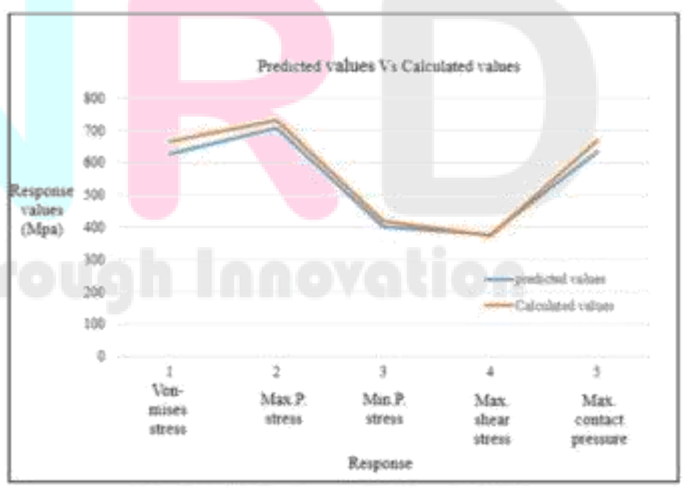


Figure 5.3 Predicted vs calculated target value chart

Validation of the results with available literature:
Since the researchers have considered the photo elastic stress freezing model to validate the FE results, Computed normalized compared with the available literature data as shown in Table 6.

Table 6. Validation of results

Authors	Normalization factor (pω2a2) (KPa)	Eq. stress (MPa) (σ)	Normalized Eq. stress (σ/ pω2a2) (Kpa)
Tiago et al.[43]	12.2	0.760	62.32
Suraj	12.2	0.854	70.06

III. CONCLUSION
The following conclusions can be drawn from the results obtained.

- The maximum stress occurs at the fillet location on the blade due to more load is accumulated at the location.
- From the analysis of variance methodology von-Mises stress, maximum principle stress, minimum principle stress, maximum shear stress and contact pressure are influenced by bottom flank angle, contact angle, skew angle and number of teeth.
- From 3D surface plots it has been observed that as bottom flank angle increases and skew angle decreases, all response values decreases gradually, and observed that all response value is minimum when skew angle is 0^0.
- This study shows the importance of calculating the clearance between the teeth of the blade and disc, for the calculation of thermal expansion of the bodies indicates the smallest possible value of clearance, thus obtaining the lower stress for the geometry to be developed. However this factor was not evaluated in this study.

IV. FUTURE WORK
As turbine blade flank length & depth is very imported dimension in the turbine rotor. The optimized dimension should be made to have minimum stress & displacement at the root of the blade & disc. As turbine blade require cooling to reduce the thermal stresses, the size of the cooling passage is very important. The optimized size should be made to have maximum cooling of the blades but there should not be over cooling as it affects the thermal efficiency.

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