Robust and optimal strain gauge positions for blade vibration testing

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Abstract: The maximal dynamic stresses on turbo machinery blades used for predicting end of life due to high cycle fatigue (HCF) are obtained from the correlation between an FE modal analysis and dynamic strain measurements. Still today it is rather common to use sets of strain gauges to measure the dynamic strains.

A particular challenge in preparation of blade vibration measurement is the selection of locations and directions for strain gauges to be mounted, for capturing dynamic blade behavior of various mode-families.

The paper presents an automatic selection strategy of an optimum gauge placement using greedy hill climbing and tabu search, considering following criteria:

- *gauge performance,*
- *distinguishability of neighboring modes,*
- *accuracy regarding positioning robustness,*
- *measurement robustness regarding possible gauge failure and*
- *installation constraint regarding gauge size and available space.*

The proposed automatic procedure is implemented in Python and can be applied for any Abaqus FE-modal analysis using any meshing techniques and element types. The placement of strain gauges and measured strains are written in a new Abaqus odb. The strain distribution within the actual gauge size is used as an quality indicator regarding the strain gradient. Thanks to this new developed tool, it is possible to obtain optimum gauge performance under additional robustness criteria with a minimized total design process cost regarding HCF.

Keywords: strain gauge, high cycle fatigue, blade vibration, automatic pre- and post-processing, Abaqus scripting language, Python, optimization, hill climbing, tabu search

1. Introduction

High Cycle Fatigue (HCF) is one of the major factor, that can cause blade failure in turbomachinery. In the design process, modal, forced response and fluid structure interaction (FSI) analyses are carried out in order to prevent HCF damage. However, the actual blade dynamics behavior cannot be fully predicted due to uncertainties e.g. aerodynamic damping. A blade vibration measurement is required for certifying the blade life regarding HCF.

The blade dynamic behavior can be observed by a non-intrusive method using tip timing or an intrusive method using strain gauges. Both methods are used for blade vibration testing at ABB Turbo Systems. A big advantage of using strain gauges is to have a real time data processing using FFT.

The particular challenging in preparing blade vibration measurement is the selection of the gauge positions and directions to capture all modes of interest. This paper presents an automatic selection strategy based on a pre-existing method used in ABB Turbo Systems (Szwedowicz, 2012). The application of the pre-existing automatic tool is limited to a “rectangular” blade surface meshed by a structured meshing technique using hex elements. The use of the pre-existing tool can be then counterproductive due to the effort needed for the particular requirement, although it increases the quality of the HCF design process.

Given a blade geometry of a certain complexity e.g. a turbine blade with damping wire or limited accessibility for mounting high-temperature strain gauge using flame spray (cf. Figure 1) the requirement of the pre-existing tool cannot be fulfilled with acceptable effort. The position and orientation of strain gauges have to be then manually determined. This leads sometimes to dissatisfying results.

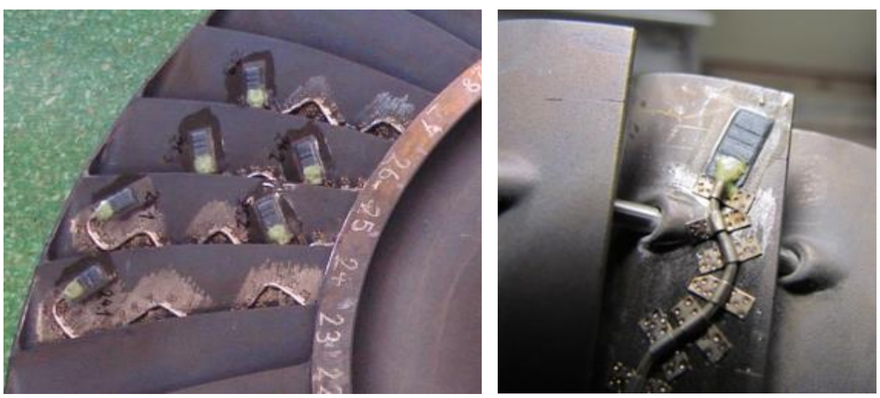

Figure 1. High-temperature strain gauge installation for blade vibration measurement

For these reasons, a new approach has been proposed to determine the optimum placement of strain gauges considering following criteria:

• gauge performance,
• distinguishability of neighboring modes,
• accuracy regarding positioning robustness,
• measurement robustness regarding possible gauge damage and
• installation constraint regarding strain gauge size.

2. Optimum gauge position for a mixed flow turbine blade vibration measurement

To illustrate the developed approach, an Abaqus modal analysis of a mixed flow turbine wheel is carried out. The cyclic symmetry model was meshed with tetrahedral elements using free mesh technique. A good model quality can be still achieved with very fine tetrahedral elements using free meshing technique, which is much less time consuming. The modelling effort is significantly reduced compared to the modelling using structured technique. Due to the high-temperature operating, flame-sprayed resistance strain gauges are used for the blade vibration measurement. The applicable regions are limited to the installation constraint regarding accessibility of flame spray. The set of strain gauges can be placed on the highlighted regions (two small regions on the suction side and one small region on the pressure side), cf. Figure 2. The highlighted regions are defined as sets or surfaces within the Abaqus odb.

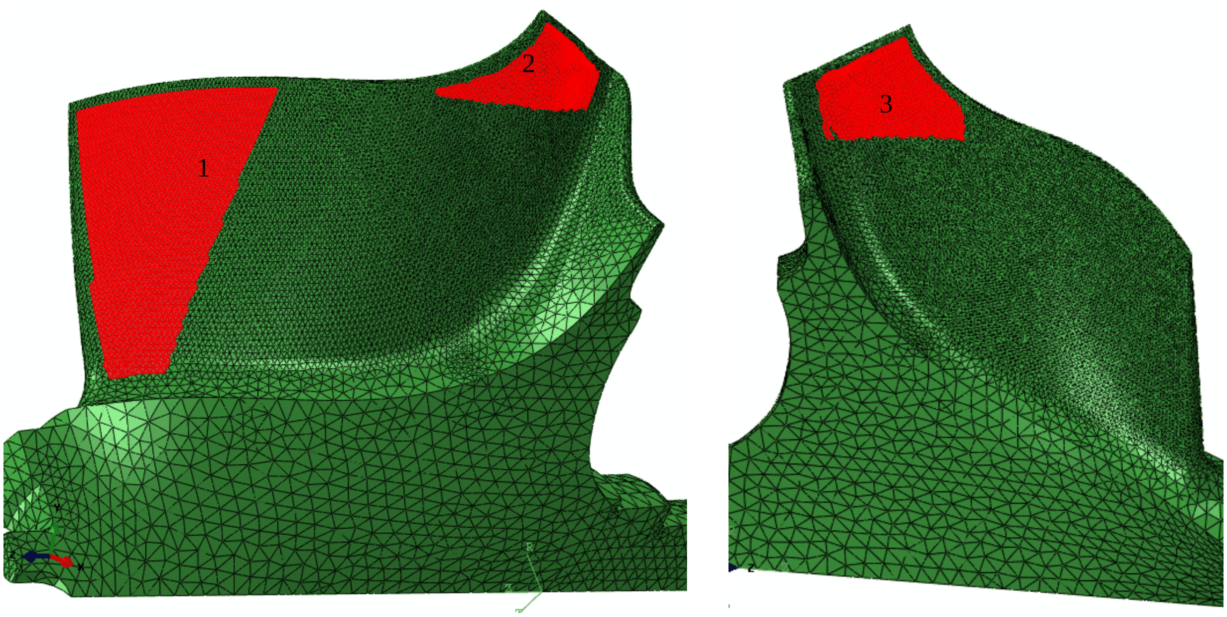

Figure 2. Applicable high-temperature strain gauge regions

The optimum placement of 4 strain gauges for capturing dynamic strains of 22 mode-families of nodal diameter 2- 5 (number of vibration modes of interest = 82), with natural frequencies below f_{max}, are requested for blade vibration measurement, cf. the blue highlighted area in Figure 3. Despite up to 10 telemetry channels available for the blade vibration measurement, only a small number of gauge placements are determined to have at least two redundant signals of different blades for capturing amplitude magnification. If the natural frequencies of neighboring mode-families are close to each other, there is a certain risk that the measured modes cannot be clearly distinguished by using the frequency level. In this case the measured strains at the same blade are used to distinguish the neighboring modes. In the given example , the circled mode combinations in Figure 3 have to be distinguished using a suitable mode identification criterion based on the dynamic strains.

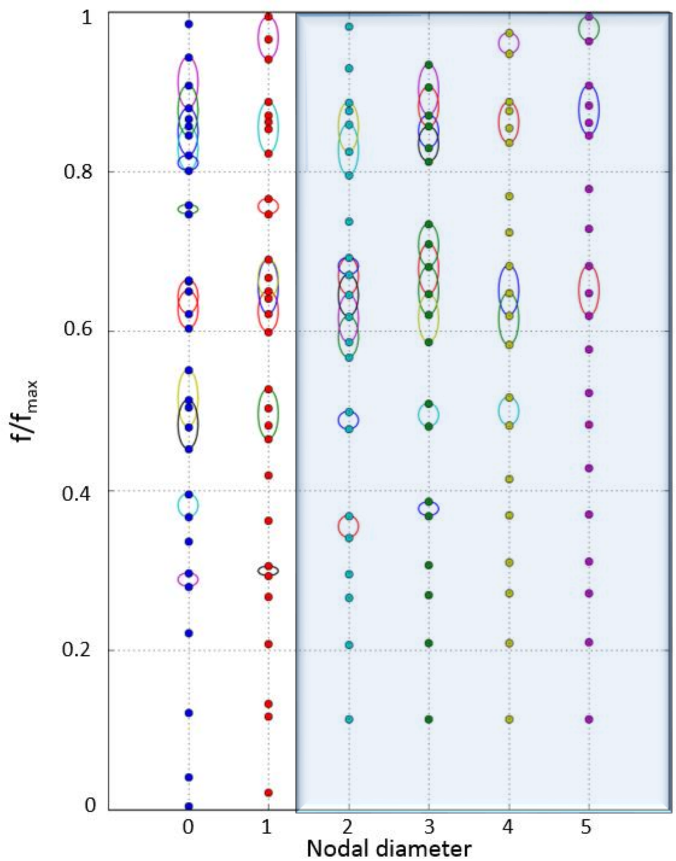

Figure 3. Dispersion diagram and the critical mode-combinations to be distinguished

3. Automatic selection strategy of optimum gauge position

The new automated selection approach is implemented in Python. Python is the standard programming language for Abaqus products and can be used to extend the functionalities that are not directly available in Abaqus (Simulia, 2014). As the required functionality for strain gauge application is missing, Python is used here.

The optimum gauge performance criterion considered here relates to transmission coefficient, which is estimated by the relation between the maximum Mises stress and the potential strain of the underlying material during the vibration. Therefore, the optimum gauge performance is associated to the dynamic strain. The dynamic strain data from Abaqus can be exported by using “Pickle” method. The further data preprocessing can be carried out outside Abaqus.

3.1 Data Preprocessing

Compared to the pre-exiting tool, which can be used only for the structured mesh and a rectangular-like application region, data preprocessing needs to be changed significantly. The flow of data preprocessing is shown in Figure 4. Contrary to the pre-existing method, the new proposed strategy considers all nodes on the highlighted surface in Figure 2 as a center of a strain gauge. Thus, the new tool can be applied for any shape of surfaces or sets of application regions.

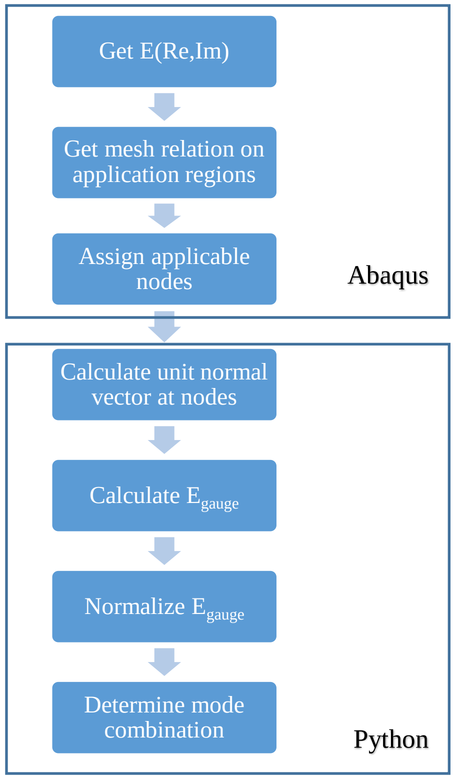

Figure 4. Data preprocessing flow

As a first step, the real and imaginary part of the nodal strain component are obtained from the cyclic symmetry FE modal analysis. The average nodal complex strain tensor $\boldsymbol{E}^{c}(\mathrm{k})$ in the spatial Cartesian system of FE model is expressed by

$$\boldsymbol{E}^{c}(\mathrm{k}) = \begin{pmatrix} \varepsilon_{xx}^{re} + i \cdot \varepsilon_{xx}^{im} & \varepsilon_{yx}^{re} + i \cdot \varepsilon_{yx}^{im} & \varepsilon_{zx}^{re} + i \cdot \varepsilon_{zx}^{im} \\ \varepsilon_{xy}^{re} + i \cdot \varepsilon_{xy}^{im} & \varepsilon_{yy}^{re} + i \cdot \varepsilon_{yy}^{im} & \varepsilon_{zy}^{re} + i \cdot \varepsilon_{zy}^{im} \\ \varepsilon_{xz}^{re} + i \cdot \varepsilon_{xz}^{im} & \varepsilon_{yz}^{re} + i \cdot \varepsilon_{yz}^{im} & \varepsilon_{zz}^{re} + i \cdot \varepsilon_{zz}^{im} \end{pmatrix},$$

where k is a node on an applicable blade region. The application region can be then reconstructed using the existing mesh information from Abaqus e.g. nodal coordinates, element connectivity. Considering the installation constraint regarding gauge size, the boundary lines of the application regions are determined by finding the boundary nodes and elements from the mesh relation derived from Abaqus e.g. quadratic order elements at boundary always have at least one middle node, that belongs to one single element in application surface. Nodes lying in the gap between the boundary and the offset of a half of gauge foil are not considered for mounting. In this given example, the nodes highlighted in red cannot be used for the instrumentation, c.f. Figure 5.

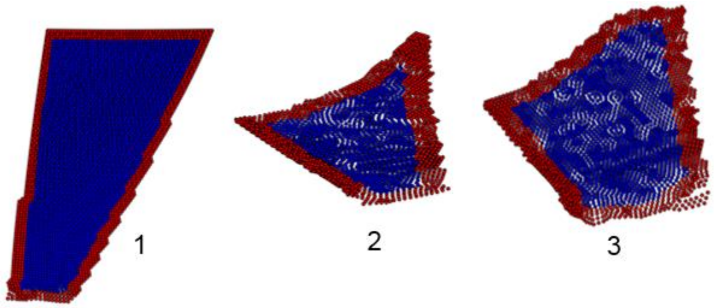

Figure 5. Region assignment for possible gauge-installed region

The nodal strains derived from Abaqus are in the global Cartesian coordinate system. To calculate the dynamic strain in gauge directions, the normal vector at each node derived from a weighted average of the adjacent faces is required. Figure 6 shows the validation of the calculated node normal of different mesh type. The validation can be carried out by using Python to create a normal at each applicable nodes, which can be compared with the adjacent element normal queried from Abaqus.

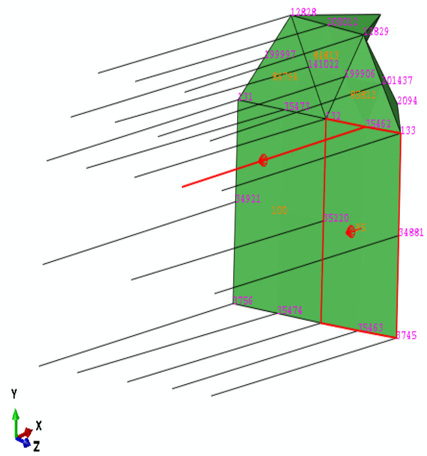

Figure 6. Element face normal and node normal

The complex dynamic nodal strains $\varepsilon_m^c(k,\varphi)$ along unit directional vectors $\vec{r}(\varphi)$ about a node normal axis can be then calculated by the equation below.

$$\varepsilon_m^c(k,\varphi) = \left[r_x(\varphi), r_y(\varphi), r_z(\varphi)\right] \cdot \boldsymbol{E}^c(\mathrm{k}) \cdot \left[r_x(\varphi), r_y(\varphi), r_z(\varphi)\right]^{\boldsymbol{T}}$$

Figure 7 illustrates the measured nodal strain for all possible gauge orientation. It shows, that the value of dynamic strain is depending on the orientation of strain gauges, i.e. the mode vibration can be well detected from certain gauge directions.

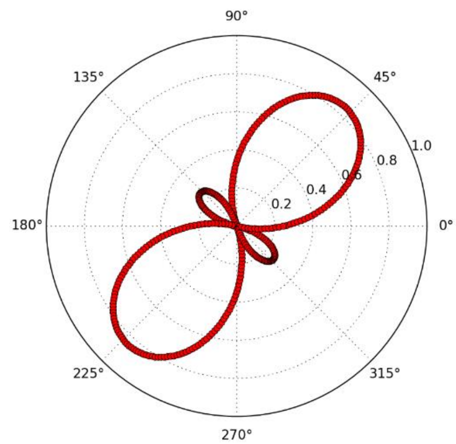

Figure 7. Measured strains along unit vectors of each φ about a nodal normal axis

The expected strain to be measured $\varepsilon_m(k, \varphi)$ at node k in direction φ is then the absolute value. It is common that all vibration modes have different maximum response, which can cause a different trade-off among mode families. To prevent the complex weighting, the nodal dynamic strains normalized by the maximum dynamic strain of each mode are used for the optimization.

3.2 Optimization

A number of candidates is dependent on the number of applicable nodes and the number of direction vectors $\vec{\boldsymbol{r}}(\boldsymbol{\varphi})$ about a node normal axis. For the given example 11357 nodes lying on the highlighted surface, can be used for instrumentation. Each node has 18 measuring axes ($\boldsymbol{\varphi} = \mathbf{0}°, \mathbf{10}°, \cdots, \mathbf{170}°$). The total number of candidate combinations using 4 strain gauges is

$$\binom{\mathbf{11357} \times \mathbf{18}}{\mathbf{4}} = \frac{(\mathbf{204426})!}{\mathbf{4}!\,\mathbf{204422}!} == \mathbf{7.2764} \cdot \mathbf{10^{19}}$$

Due to such a big number of candidates greedy hill climbing technique is used for finding an optimum gauge placement. The algorithm has a tendency to converge to local optima. Therefore, multiple run with different random start value are carried out. Moreover, to improve the performance the algorithm is extended with tabu search (Glover, 1999).

By the preprocessing described in the previous section, each candidate $\boldsymbol{i} \in \{\mathbf{1} \dots \boldsymbol{N}\}$ is associated with a normalized strain sensitivity $\boldsymbol{A_{i,j}} \in [\mathbf{0}, \mathbf{1}]$, referred to as *mode coverage* in the following, for each mode $\boldsymbol{j} \in \{\mathbf{1} \dots \boldsymbol{M}\}$, where $\boldsymbol{N}$ is the number of candidates and $\boldsymbol{M}$ is the number of vibration modes. The coverage of one candidate for one mode is subject to some uncertainty, since there are simulation inaccuracies, and in the experiment, the placement of the strain gauges may be inexact.

Hence, the coverage values $\boldsymbol{A_{i,j}}$ are replaced by robust counterparts by taking the minimum over some segment r_{pos} around $\boldsymbol{x_i}$, cf. Figure 8:

$$\widetilde{\boldsymbol{A}}_{\boldsymbol{i,j}} = \min_{\boldsymbol{k}:\, \|\boldsymbol{x_i}-\boldsymbol{x_k}\| \le \boldsymbol{r_{pos}}} \boldsymbol{A_{k,j}}$$

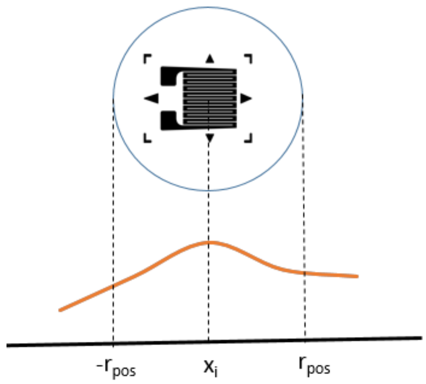

Figure 8. Position robustness

Then the basic problem to be solved translates to selecting a subset of number of strain gauges $\boldsymbol{n}$ from the candidate set while achieving the best and robust overall coverage, where the basic definition of overall robust coverage (objective function $\boldsymbol{f}$ to be maximized) is given by the least covered mode:

$$\max_{I \subset \{1 \ldots N\}, |I|=n} f(I), \text{ where}$$

$$f(I) = \min_{1 \le j \le M} \max_{i \in I} \tilde{A}_{\boldsymbol{i,j}}.$$

Strain gauges that are physically too close together cannot be placed on the same blade, this gives rise to a constraint. A candidate i can be selected only if there is no other candidate within some radius r on the same blade. Depending on the setup of the blade vibration measurement, there are $n_b \ge 1$ blades available for strain gauge placement. Denoting the center position of a candidate i by x_i, candidate i can be selected only if

$$|\{k \in I \setminus \{i\}: \|x_i - x_k\| \le r\}| \le n_b - 1.$$

In order to solve the real problem, mode distinguishability and measurement robustness regarding possible gauge damage need to be respected, giving raise to complexity of the optimization problem.

3.3 Post processing

After the optimization, the placement of strain gauges with the actual size can be visualized in Abaqus viewer. The nodal dynamic strain in gauge orientation is used to calculate a transmission factor. If the strain distribution along the gauge segment is constant or linear, no error is induced. Apart from that the average strain over the gauge length has to be performed in order to correct a transmission factor, which is calculated by using the nodal dynamic strain at the gauge center (Dally, 2005). The possible error due to strain gradient can be obtained from the strain distribution within gauge size, cf. Figure 9.

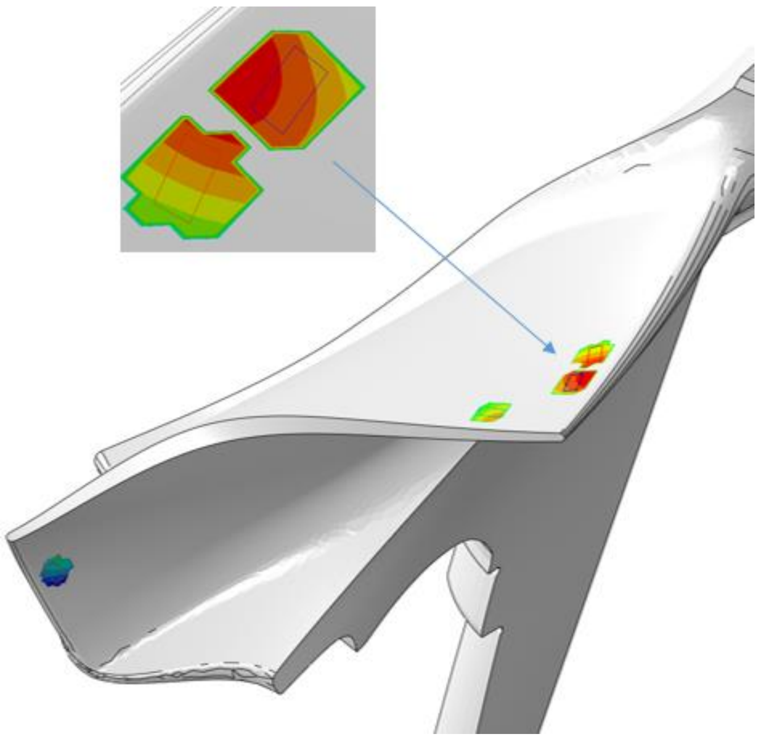

Figure 9. Strain gauge placement and strain distribution within gauge size

4. Result

In this section the results of the variants of the optimization problem are presented. It must be realized that the selection of the optimum placement of strain gauges generally involves compromises because of typically conflicting objectives.

4.1 Robust mode coverage

Starting with the optimization of the basic problem, only the strain sensitivity (robust mode coverage) of vibration modes of interest are taken into account. Finding the optimum mode coverage seems to be a straightforward task, since the same objective function values were achieved by using 20 different random start values, c.f. Figure 10. The optimum solution is found within 2 minutes.

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solution found, value = 0.6704, elapsed = 51.2379s, #feval first = 1881456, best = 1881456, total = 8051361
solution found, value = 0.6704, elapsed = 51.2948s, #feval first = 1881456, best = 1881456, total = 8051361
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solution found, value = 0.6704, elapsed = 20.0992s, #feval first = 2130513, best = 2130513, total = 2653882
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solution found, value = 0.6704, elapsed = 18.4969s, #feval first = 2250135, best = 2250135, total = 2773506
solution found, value = 0.6704, elapsed = 19.7600s, #feval first = 2250135, best = 2250135, total = 2773506
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solution found, value = 0.6704, elapsed = 19.4062s, #feval first = 2250135, best = 2250135, total = 2773506
tabu search result = 0.670406
best selection = [ 13528  26303  55961 104770]
elapsed = 97.07802701
Opt4dms1_noMAC_wavg0
Min(mode coverage) = 0.670405, Average(mode coverage) = 0.860181512195.
Min(2. best mode coverage) = 0.07224.
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Figure 10. Optimization of mode coverage of the given example

The objective function value returns the minimal mode coverage of all interested vibration mode. The best possible objective function value is 1.0, if the strain gradient is 0. With this problem setup the minimum overall mode coverage obtained from the optimization is 0.67 ($f_{3.2}$) and the average mode coverage is 0.87, cf. Figure 11.

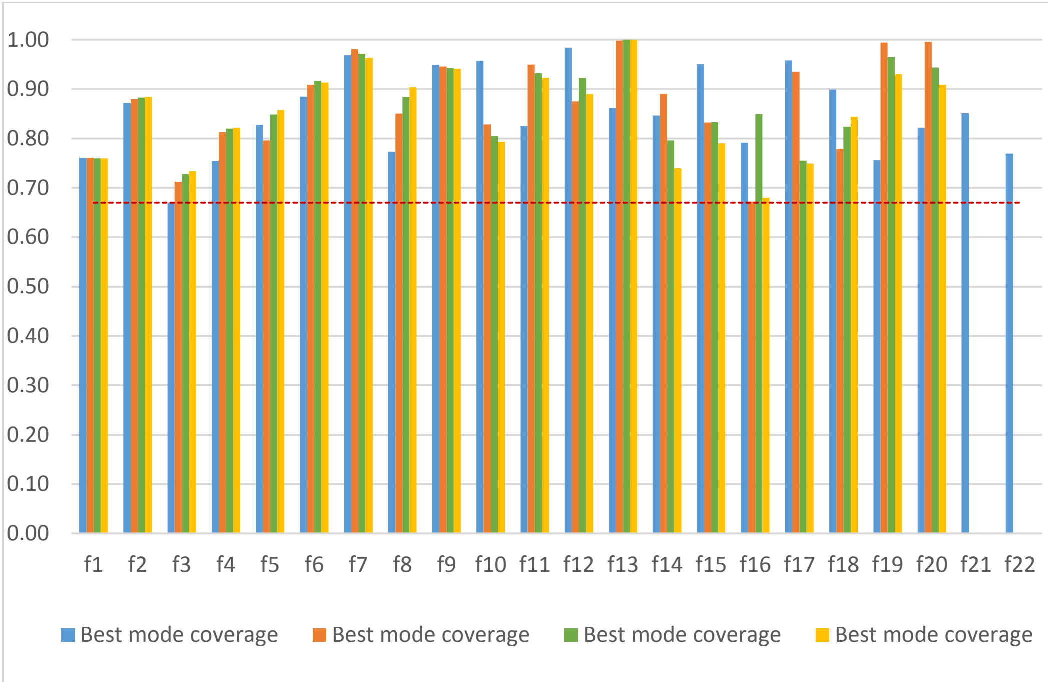

Figure 11. Mode coverages using 4 strain gauges considering one gauge per mode

4.1.1 Strain gauge failure robustness

Depending on the test operation turbocharger blade can rotate at a rotational speed of 60000 rpm up above. Due to such a huge load strain gauges may be damaged during the test operation and cannot deliver the measurement signal. In order to protect against these failures, one may request good coverage of at least two or even more strain gauges per mode. Figure 12 shows the mode coverage of the extended basic problem that requires at least two strain gauges per modes. The optimization focuses on the second best mode coverage. Therefore, the best mode coverage fall off in quality. The minimum of best mode coverage of the best coverage is 0.35 ($f_{4.2}$) and the minimum of second best mode coverage is 0.34. The average of best mode coverage is 0.555 and the second best coverage is 0.546. The normalized strain of the best and the second best mode coverage have almost the same level. Therefore, a trade-off parameter between the best mode coverage and second best mode coverage is introduced for improving the best mode coverage.

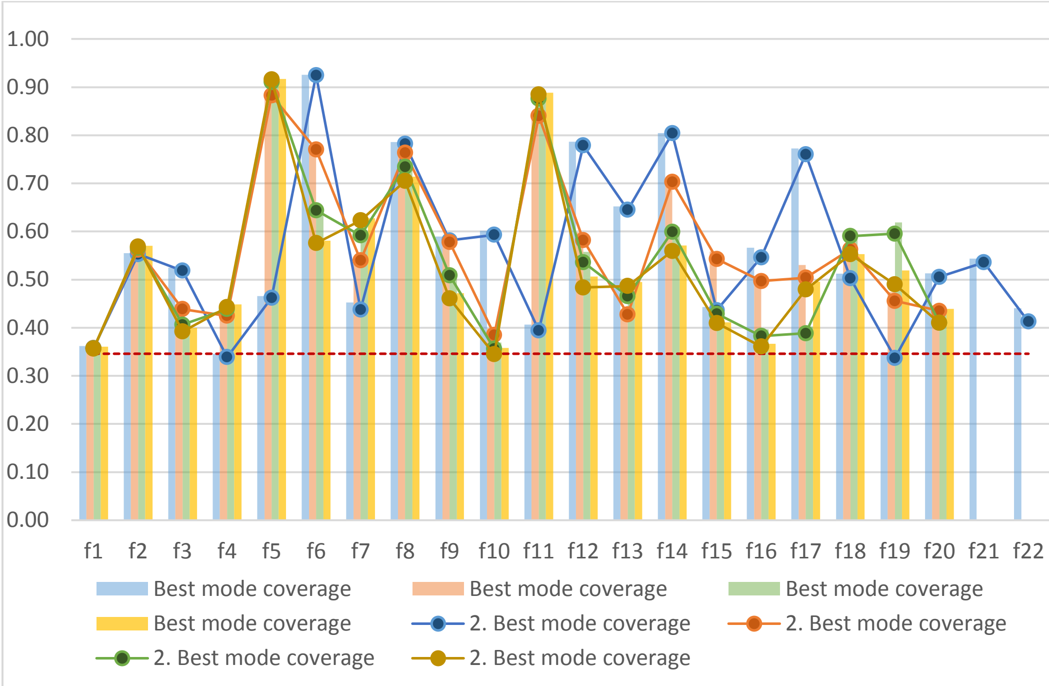

Figure 12. Mode coverage of the best and the second best strain gauges without weighting

The weighting between the best and second best mode coverage has to be suitable selected in order to get an acceptable trade-off for a robustness regarding gauge damage without a big loss of mode coverage. The algorithm can now focus on the best mode coverage as desired. The second best mode coverage still have an acceptable level. Figure 13 shows the enhancement of the best mode coverage compared to Figure 12. The second best signal coverage of 3 vibration modes have instead a poor quality.

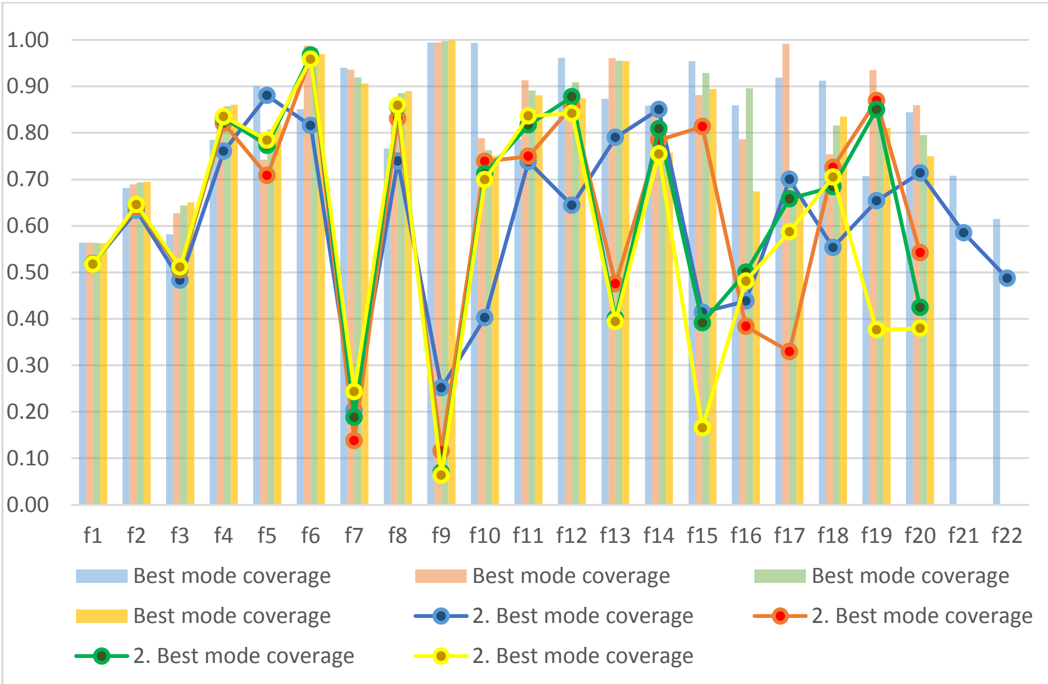

Figure 13. Mode coverage of the best and the second best strain gauges using a proper weighting between the best and the second best mode coverage

4.1.2 Distinguishability of neighboring modes

If modes are very close in frequencies, it is important to be able to distinguish them by a pair of strain gauges, where one of them has a good coverage of the first and bad coverage of the second mode, and the opposite for the other strain gauge. This is considered in the problem setup in two alternative ways: strong and soft neighborhood distinguishability criteria. With the strong neighborhood distinguish criterion, each coverage is directly penalized with the neighboring coverages. Thus, a strain gauge for one mode is always selected because it covers the mode well and not the neighbors. With the soft criterion in contrast, a strain gauge for one mode may be selected just for good coverage, while another strain gauge may be responsible for distinguishability to a neighbor.

Figure 14 shows the proposed optimum placement using strong neighborhood distinguishability criterion. For the given example we are going to look at the nodal diameter 4 in detail. Each neighboring mode combination can be well captured from at least one specific strain gauge. The first combination consists of mode families 7 and 8. Strain gauge 3 and 4 are responsible for mode families 7. Strain gauge 2 can capture the mode families 8 well. The Neighboring modes can be well distinguished. However, due to the very strong criterion the minimum mode coverage drops now to 0.3 ($f_{1,4}$). The average mode coverage is 0.76. The optimization result shows that the mode coverage can be suffer from the strong neighborhood criterion.

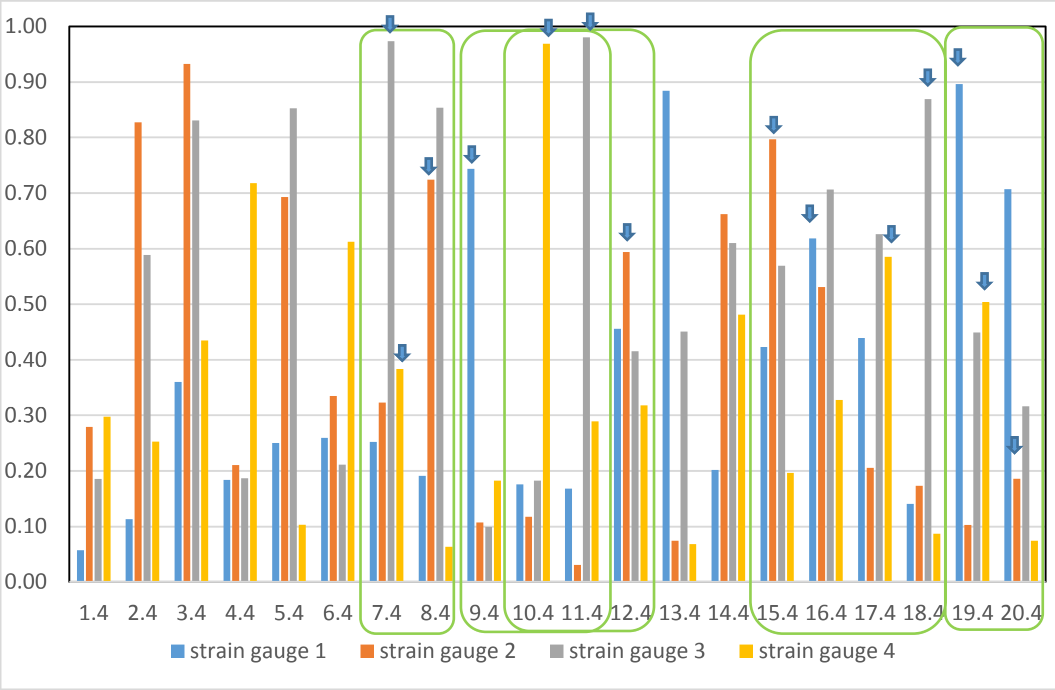

Figure 14. Optimization result using strong neighborhood criterion

The soft neighborhood criterion is aimed at a compromise in neighborhood distinguishability in return of an increase in mode coverage. The result obtained from the optimization is shown in Figure 15.The most neighboring mode can also be well distinguished. Only the mode families 15-18 cannot be as clearly distinguished as the result obtained from the strong neighborhood criterion. The minimum mode coverage is now 0.45 and the average coverage is 0.79.

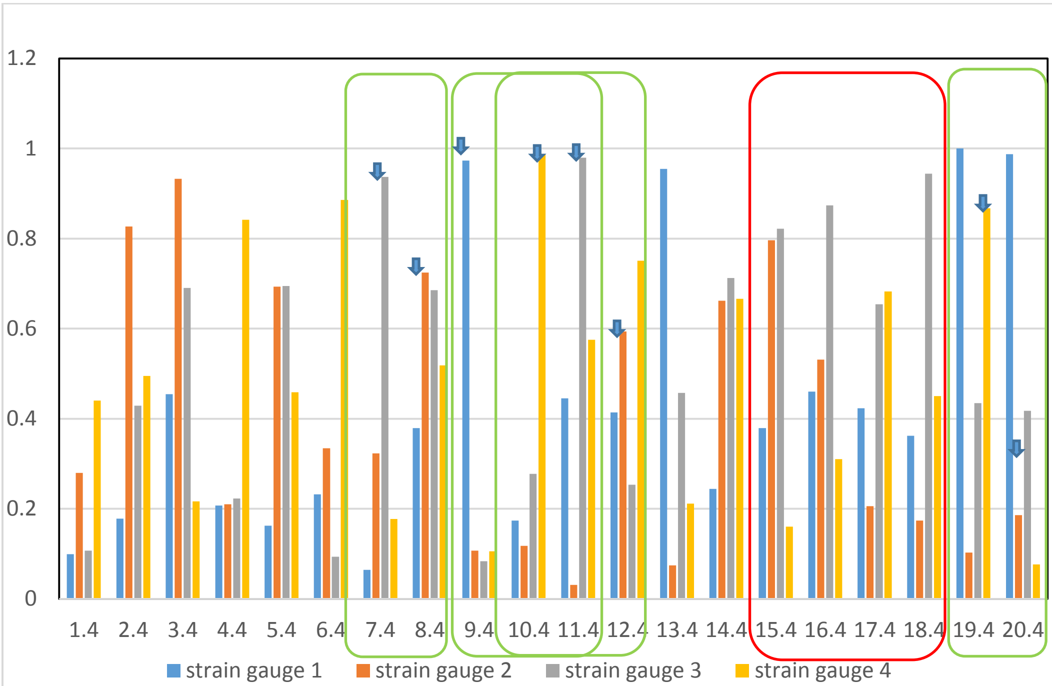

Figure 15. Optimization result using smooth neighborhood criterion

5. Conclusions

The automatic procedure for the optimum and robust placement of strain gauges related to blade vibration measurement has been developed based on the pre-existing tool used in ABB Turbo Systems. The automatic selection method is implemented in Python and can be now applied for any blades using Abaqus FE-modal analysis. The placement of strain gauges and expected strain to be measured are written in a new Abaqus odb. The strain distribution within the actual gauge size is used as an quality indicator regarding the strain gradient.

Thanks to this new developed tool, it is possible to obtain optimum gauge performance under additional robustness criteria with a minimized total design process cost regarding HCF.

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