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Design for Inspection - Evaluating the Inspectability of Aerospace Components in the Early Stages of Design

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Abstract

One important part of the manufacturing process of aerospace components is making inspections using Fluorescent Penetrant Inspection (FPI). This mandatory inspection represents a non-negligible part of the manufacturing and service cost. It is therefore important to make the geometry of the components suitable for inspection i.e. practicing Design for Inspection (DFI). This has been studied at an aerospace company with the aim of bringing DFI to the early stages of product development process. In this paper, a tool is proposed for the evaluation of inspectability in the early design stages. The tool is applied on CAD-models of the components automatically ranking the inspectability of design proposals using a novel inspectability index. Thus, inspectability can be considered together with other performance and manufacturing aspects forming a powerful decision support. The tool has been run and evaluated together with manufacturing staff at the aerospace company with promising results.

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Keywords: Inspection; Welding; CAD; multi-diciplinary; Inspectability index; Design for inspection; DFI

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1. Introduction

The multidisciplinary nature of design requires that design suggestions are analyzed from several different aspects simultaneously. If the various analyses are performed in sequence, there is a risk that the whole process needs to be done all over again should the proposed design fail in one or several aspects. To make multidisciplinary analysis possible, different types of digital models of the design suggestions are created. These allow a multitude of life - cycle aspects to be taken into consideration. Examples include computational models such as FEA and CFD, analytical expression, empiric formula and rules. By using digital models, the structural strength and stiffness of the proposed design can be analyzed along with for example the hydro and aerodynamic performance as well as addressing other life-cycles aspects such as manufacturing and sustainability.

An example involving digital models used in a multidisciplinary environment has been studied in the research behind this paper. A manufacturer of components for aero engines makes multi-disciplinary evaluations of design suggestions in the early stages of design using digital models and including several life-cycle aspects. By evaluating design proposals from several aspects simultaneously, time consuming rework is avoided. Examples of multidisciplinary considerations is that the aerodynamic and structural performance is evaluated at the same time as the manufacturability and sustainability of the proposed designs. When the company has developed a new conceptual design, parametric CAD-models of the proposed concept that can be geometrically and topologically changed are created. By selecting several parameters and changing them in a preplanned way hundreds of geometrically different models are created. From these, digital models are automatically created and analyzed. This will show how each of the design variants perform from various aspects, allowing a mapping of the design space. The large number of variants require that the digital models are fast and reliable and that they can indicate the performance from each of the disciplines accurately.

While developing predictive models for manufacturability [1] it was found that the inspection of welds is a crucial manufacturing operation that must be considered to avoid ending up with having to design complicated instruments and procedures to perform the mandatory inspections. An example when this is especially critical is when scaling down an existing aero engine for use in another range of smaller aircraft.

It was found that, already in the early stages of design based on the aforementioned CAD-models, it should be checked that the surfaces for inspection are accessible with standard instruments and that a clear line of sight to assess the result can be obtained ensuring sufficiently good conditions for performing a successful Fluorescent Penetrant Inspection (FPI). Here, a digital model of the inspection procedure is needed to determine if it can be successfully performed on the suggested design is needed. A method has been proposed and included in an automated tool previously [2]. It has since then been evaluated with manufacturing staff leading to several changes that are elaborated in this paper. It was highlighted at the evaluation that the probability of detection (POD) is not a suitable indicator of inspectability. Instead, a simplified indicator is presented in this paper.

2. Literature

One of the major challenges in multidisciplinary design studies is finding indicators that represent the performance of the design for each of the life-cycle aspects. As an example, the structural behavior of a design can be represented using a limited number of parameters such as the maximum Von Mises stress or the expected stiffness expressed as deflection/applied force. Thus, it can easily be determined which of several design proposals that perform best on each parameter and to weigh them together by studying e.g. the pareto front [3]. This is also known as multiobjective simulation. These parameters can be called indicators since their purpose is to distinctively indicate the performance.

Recently, more elusive life-cycle aspects are being brought into the multidisciplinary environment. Examples include sustainability and manufacturability. Just as in the case of the structural properties, these aspects need to be condensed into a few indicators to make it possible to quickly understand the behavior of the product. Finding such indicators is a major challenge. Progress have been made in the case of sustainability and especially on the ecological sustainability where life cycle assessment (LCA) now is a widely-used method of determining the environmental load of a product during its life-cycle allowing it to be expressed in e.g. the amount of CO2 emitted during the products life cycle. Thus, the expected amount of CO2 emitted provides an indicator of the performance. Recently, effort has been made to include additional sustainability aspects and condense them into suitable indicators

[4, 5]. There are also suggestions on how human factors such as ergonomics in production when developing products [6].

The manufacturability aspects on design has been extensively researched [7-10]. The term manufacturability is broad but from an overview perspective it concerns finding the lowest manufacturing cost for a particular product. Calculating the manufacturing cost require a close study of the manufacturing process in detail such as in machining and the variation of for example surface roughness [11]. The tolerancing is e.g. factor with major influence and should be considered when evaluating the manufacturability [12].

In early stages of design, the information available will perhaps not suffice to successfully apply a cost model. Instead, the manufacturability part of the design can be analyzed by employing Design for Manufacturing (DFM) and Design for Assembly (DFA). These are recommendations specific to each manufacturing process on how to design to avoid pitt-falls and how to make the design suitable for the intended manufacturing process. General recommendations are readily found in hand-books [13, 14]. However, these needs to be complemented with specific rules and recommendations for each manufacturing process, such as [15] showing how a checklist can be used to avoid designs with poor manufacturability.

This paper is focused on "Design for Inspection" (DFI). Like DFM it features recommendations on how to design the product so that inspection of it facilitated. In DFI this depends largely on what method of inspection that is intended. Consequently, no general method of assessing the "level of inspectability" for a part exist. However, recommendations are found in literature concerning e.g. how to design infrastructure for visual inspection to avoid deterioration with potentially catastrophic results to go unchecked [16, 17].

3. Results

There is an array of inspections methods in use at the manufacturer. These include visual, x-ray, ultrasound, and tomography inspection. However, FPI emerged as crucial because it is necessary to access from both sides using both borescope and implements for acetone application. It was consequently identified as necessary to include in the manufacturability evaluation. FPI is performed in several steps:

1. Soak or spray the whole part with florescent fluid
2. Wash off excess fluid with water
3. Inspect for cracks
4. The detected cracks are verified by applying a small amount of acetone and wiping once with a brush. If the crack reappears it is a confirmed crack which is documented.

As seen above, the inspection is done two steps where the first step involves making a screening of the cracks and in the following step the indicated cracks are confirmed. The workshop need to show an ability to find all cracks with a statistically documented capability. This is certified through a standardized test where the workshop performs the inspection with a certain probability of detection (POD). A percentage of cracks with lengths exceeding a certain minimum length must be detected. Multiple samples are completed to control the variation in POD.

To make a digital model of this procedure, a parameter is needed that can indicate the inspectability directly from the CAD-models. It must make a quick and accurate prediction allowing hundreds of CAD-models to be analyzed in a short time. For this purpose, the ratio L/R has been proposed [2]. This ratio is here called "inpectability index" (Ii). R is the radius at the place of inspection i.e. the radius of the largest circle that can be inscribed at the place of inspection without colliding with the surrounding geometry. The place of inspection being a point along the weld. The distance from the entrance to the place of inspection is represented as the distance L. To illustrate, the figure 1 below show an imaginary welded structure with two welds, 1 and 2. The structure is a cone, open only in the right end so all welds must be inspected from the right side.

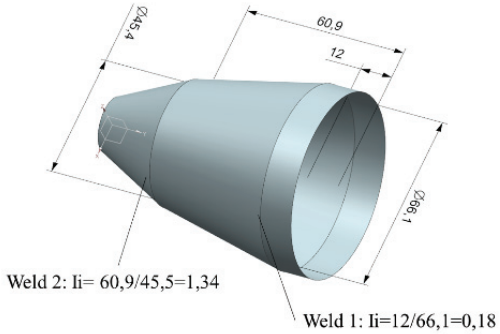


Fig. 1. Imaginary welded structure

For weld 1, the distance from the entrance to the weld (L) is 12mm. The radius at the weld is 66,1mm. Thus, the Ii for weld 1 is Ii=L/R=12/66,1=0,18. The Ii for weld 2 is L/R=60,9/45,5=1,34. Ii can be used as an indicator of the difficulty to inspect the welds. A small R located far from the entrance (large L) means a high value of Ii and consequently poor inspectability. Low values of Ii means good inspectability. There is a maximum permissible value of Ii denoted a. Exceeding a means that it inspection is not possible. Thus, the condition for inspection to be possible is that:

$$Ii \leq a \quad (1)$$

In addition to the Ii, absolute limits for L and R are needed. This is because condition (1) can be fulfilled without the part being inspectable in the following two cases:

1. R and L are very small.
2. R and L are very large.

In first case, there is too little space available to view the place of inspection regardless of a small L and in the second case the weld is out of reach due to a too large L. The model is therefore amended with thresholds for R and L.

$$R \geqslant R_{min} \quad (2)$$
$$L \leqslant L_{max} \quad (3)$$

Where R_{min} is the minimum acceptable value of R and L_{max} is the maximum acceptable value of L. This will also handle the numerical instability when R-> 0.

The values of a, R_{min} and L_{max} depend on the types of products and the inspection procedures. They must be determined for every individual product type.

3.1. Interpreting the inspectability index.

According to (1) the part is inspectable for all Ii smaller than a. However, this does not take into account that the inspection get more difficult when Ii is approaching a. It was thought that POD [2] instead of Ii could be used in this range, letting the POD deteriorate when approaching the limit a. However, since the workshop is certified at a POD required by aviation standards it should be regarded as fixed. Instead, a range of Ii where inspection is possible but presents more difficulty is introduced. Such range is shown in figure 2.

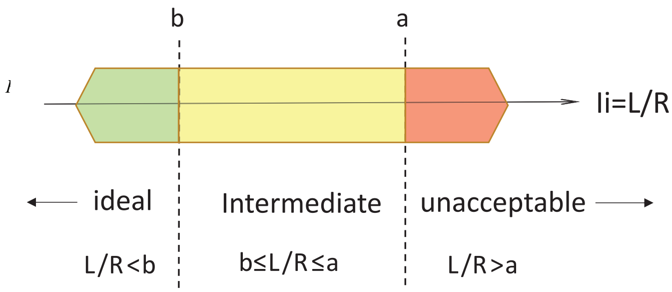


Fig. 2. Categorization of Ii

An additional value b is introduced for values of Ii that are sufficiently low and therefore representing ideal conditions allowing inspection to be performed with the standard procedure. This is shown in leftmost green color range. The yellow range will require precaution, perhaps using specialized inspection tools. If the Ii exceeds value a, inspection is not possible (red range).

Categorizing Ii like this will highlight anticipated difficulties in inspection allowing the design team to consult the manufacturing staff on the possibilities of performing inspection of the yellow range design suggestions. Red range design suggestions need to be reworked or abandoned. This color coding is presumed to allow the design team to quickly gain a perception of the inspectability for a multitude of design variants.

3.2. Testing the proposed tool

The figure 3 below shows a fictitious static turbine frame. It is a component to direct the gas-flow through the engine and to transfer loads. The variant shown in figure 3, has 10 hollow sheet metal vanes with several welds that must be inspected on their insides. The cavity inside the vanes can only be accessed from the entry point shown in the figure.

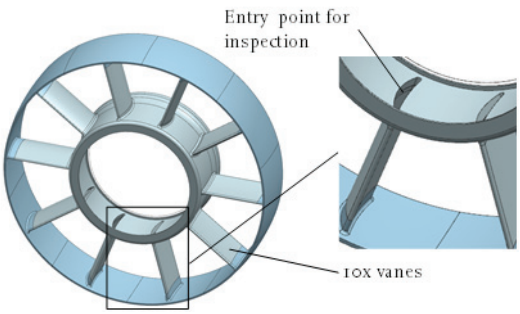
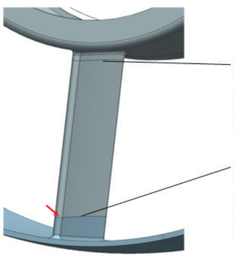


Fig. 3. Static turbine frame

When generating the design suggestions among others, the parameters of the vane profile are varied. These include, the radii of the leading and trailing edges the corda length, the thickness of the profile and the thickness of the sheet. Varying these parameters has an impact on the aerodynamical and structural performance of the engine. This is studied by making automated structural and aerodynamical calculations on each of the design suggestions. To assess the inspectability, the values or R and L are determined at various positions along the weld and the largest Ii for each weld is extracted. The Ii has been calculated for one design variant shown in the below figure 4.



Weld 1	Rmin	Lmax	Ii
EDGE W1: 1	8	5	0,63
EDGE W1: 2	8	5	0,63
EDGE W1: 3	8	5	0,63
EDGE W1: 4	2	5	2,50
		Li max	2,50
Weld 2	Rmin	Lmax	Ii
EDGE W2: 1	8	70	8,75
EDGE W2: 2	8	70	8,75
EDGE W2: 3	8	70	8,75
EDGE W2: 4	2	70	35,00
		Li max	35,00

Fig. 4. Evaluating welds

The inspectability for the weld 1 falls in the green category because it is located close to the point of entry. Weld 2 is indicated as intermediate. The inspection must take place 70mm down into the vane and the space available is only 2mm. This position is indicated by the arrow in figure 4. This need to be highlighted with production before progressing the design suggestion.

The result of the inspectability evaluation is to be evaluated together with other performance parameters such as the aerodynamical pressure loss trough the component and its safety factor against buckling. This will enable insightful multidisciplinary decisions on which of the geometric variants that constitutes the best trade-off between the conflicting requirements.

4. Discussion

The quantification of how well a part lends itself for inspection i.e. the degree of inspectability has not previously been explored. An assumption can be made is that companies regard it as a checklist item in the requirements specification - "Must be possible to inspect using x method". If so "easy inspection" is not currently considered as a value adding feature. This paper has highlighted that, in some cases such as in aerospace components, the available space on the inside is limited and the importance of successful inspection is paramount, it should be taken into consideration earlier in the design process. This is further accentuated by the fact that inspection make up a non-negligible part of the manufacturing and operating cost. It should therefore be subject to trade-off against other performance parameters. As an example, it is perhaps worth accepting a somewhat increased pressure loss through the engine if that will give an improved inspectability. The importance is further underpinned by the assumed stepwise behavior of the inspectability index, not passing the assumed thresholds becomes important.

There has not yet been any thorough validation of the proposed tool. Manufacturing staff have been interviewed on their view on the tool after being by showed the intended functions using a demonstrator. More validation on actual CAD-models are needed. These must be related to the inspection process by assigning values to a, b, R_{min} and L_{max} and testing the accuracy of the predictions of the tool.

It has been shown how the tool is used on the final component. However, aviation regulations prescribe that FPI should be made also for subassemblies such as the vane before it is welded into the complete frame. It will then be another case open in both ends. The inspection tool should be possible to apply also to these sub-assemblies. Another area of application is when planning overhaul inspections of the aircraft when it is in service. The tool can then be used to find out how much the disassembly is needed to obtain a certain degree of inspectability.

5. Conclusion

This paper has highlighted the importance of DFI in early stages of design in aerospace components were inspection make up a large part of manufacturing and operating cost. Inspectability should therefore be regarded as value adding and be maximized or traded-off against other performance criteria. A tool has been presented to quickly assess the inspectability for FPI for the integration in multidisciplinary design space explorations for visualizing the trade-offs that can be made.

In future work the tool must be validated to relate the values of a, b, R_{min} and L_{max} to actual FPI and to evaluate CAD-model of existing and future aerospace components.

Acknowledgements

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