

Blade repair analysis process v2.1.0

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Contents

| 1 | Introduction | | |
|---|----------------------|---|----|
| 2 | Input data | | |
| | 2.1 | Sweep scan data | 7 |
| | 2.2 | Tolerances file | 7 |
| | 2.3 | Application settings file | 8 |
| | 2.4 | Probe tip radius | 9 |
| | 2.5 | Nominal curves file | 9 |
| 3 | Data | Data sampling and conversion to 2D forms | |
| 4 | Chordal analysis1 | | 12 |
| 5 | Identifying features | | |
| | 5.1 | Feature identification without using nominals | 13 |
| | 5.2 | Limitations of the approach | 16 |
| | 5.3 | Feature identification using nominals | 16 |
| | 5.4 | Effects of the nominal approach | 19 |
| | 5.5 | Nominal file creation | 20 |
| 6 | Feature analysis | | |
| | 6.1 | Basic feature analysis | 21 |
| | 6.2 | Radius of curvature analysis | 22 |
| | 6.3 | Combined feature analysis | 24 |
| 7 | Analysis output | | 25 |
| 8 | A fin | A final note on the feature analysis | |

6

1 Introduction

The BladeRepairAnalysis.exe application is a small command line application designed to support the MODUS measurement and reporting program for repaired blades. The application accepts sweep scan measurement data of the repaired blades, along with various settings and parameters. It proceeds to analyse repair features in this data, and then outputs details of the repair(s) for reimport into MODUS for reporting.

The software is written to assist in fulfilling the repair analysis set out in the MTU repair instructions. This document references and uses terms from these repair instructions. These repair documents drive the method of analysis, but where possible, the application is configurable for use on other blades that follow the same repair method. As such, parameters such as the number of key sections on a blade are configurable.

2 Input data

The Blade Repair Analysis application is provided with the measurement data to analyse along with settings controlling the analysis via a series of files and command line arguments. These inputs are described below.

2.1 Sweep scan data

The application processes sweep scan measurement data of the full repaired blade. The following assumptions are made about the sweep scan data:

- It is raw uncompensated data (i.e. tip centre).
- It is provided in the coordinate system shown in Fig 1 of the blade repair specification. Namely:
 - The positive Z-axis is the blade centre line, formed by the intersections of planes AC and AB (shown in stage 1 repair doc).
 - The coordinate system origin is at the blisk centre on this blade centre line.
- The density of the sweep scan data is sufficient to capture the detail of the blade edges at the required sample resolution when the data is linearly infilled between the sweep passes.
- The measurements sufficiently cover the length of interest for analysis.

The processing relies on analysis of data from both edges in planes perpendicular to the Z-axis. The data processing range is determined from the chord length limits table (this is described in more detail in the Blade repair analysis user's guide (Renishaw part number H-1000-5448)).

Data is provided via a standard sweep scan ".out" output file from MODUS, which must contain all measurement sweep scans for the blade of interest but no other feature measurements (such as AES side sweeps scans or AES edge scans). The assumptions made when parsing this file are described in more detail in the Blade repair analysis user's guide (Renishaw part number H-1000-5448).

2.2 Tolerances file

The tolerances file gives limits used during the evaluation. This covers:

- The positions of the key areas on the blade (A1, A2, A3, A4).
- The maximum blend depths in these regions (Table 1 in the repair document).
- The minimum blend radii (R_{AC}, R_{AD}) for different blend depths for curvature analysis of features (Table 2 in the repair document).
- The minimum blend radii (R_{AC}, R_{AD}) for curvature analysis of the entire blade edges.
- The chord length limits at key sections along the blade (Table 3 in the repair document).
- The maximum feature AU value for each edge. The blade repair instructions allow for chamfer and fillet repairs to be made on the tips of the blades, however these should not be analysed using the methods described in this document. Any features identified starting beyond the given AU limit will not be reported in the output blend analysis file. This can either be given as one value which is used for both edges, or two values used for the LE and TE respectively.

• The minimum expected edge values. These affect the creation of the reference edge curves and are described in more detail later in the document.

Note that the software is written such that the tolerance table data described above is not defined by a fixed number of intervals. Instead, it will read all lines in a given section, giving flexibility to have different numbers of key ranges on different blades.

The exact format of the file and more detailed discussion is given in the Blade repair analysis user's guide (Renishaw part number H-1000-5448).

2.3 Application settings file

Additional settings controlling the processing and output of the application are given via the application settings file. The effect and meaning of these parameters is covered in more detail later in the document during the data processing and analysis discussions.

This file provides the following:

- The radius to use in the ball filtering when computing the reference edge curves.
- The required section spacing for the MPCS sectioning (i.e. the distance between successive section planes).
- The parameters controlling the MPCS sectioning result, namely:
 - The maximum distance between points in the output section.
 - The minimum distance between points in the output section.
 - The minimum angle (in degrees) formed by successive points in the output section.
 - The maximum projection error.
- A value setting the ordering of leading and trailing edges based on the section analysis.
- The feature cut off depth, used to determine the start and end of features.
- The minimum feature depth, used to discard features identified which are likely to be noise.
- The feature padding length, used to extend the lengths of curves output for identified features to give context to the feature.
- The curvature analysis tolerances used when determining if curvature limits are met (one parameter for feature analysis, one parameter for full curve analysis).
- The point spacing used during the analysis.
- The curve down sampling factor used to reduce the resolution of the output curves compared to the analysis point spacing.
- The output decimal places which sets the precision of floating point number outputs.

The exact format of the file and more detailed discussion is given in the Blade repair analysis user's guide (Renishaw part number H-1000-5448).

2.4 Probe tip radius

The tip radius of the probe used during the measurement is required to perform appropriate tip compensation. Unlike the other settings, which are expected to remain constant between successive runs of the program for a given blade type, this value needs to be set to the correct tip radius for the current measurement. As such, this is supplied as a command line argument into the application, rather than in a settings file, to allow it to be passed directly as a variable from the MODUS program.

2.5 Nominal curves file

The blade repair analysis process has two different analysis options, one of which uses nominal blade edge forms. The analysis method used is determined based on whether a nominal curves file is provided.

The analysis of the blade edges is performed on a 2D representation of the blade edge forms derived from the 3D measurement data. The nominal file contains the 2D representation that would be derived for an expected blade form.

The exact format of the file is described in detail in the Blade repair analysis user's guide (Renishaw part number H-1000-5448). The usage of the curves from this file is described in detail later in this document.

3 Data sampling and conversion to 2D forms

The sweep scan measurement of the blade results in 3D tip centre points describing the surface of the blade. From this data we need to calculate the tip compensated points that determine the chord lengths along the length of the blade.

Subsequently, we need to create a 2D form of the blade edges on which feature identification and analysis can be performed.

The following method is used to derive the data:

 Use MPCS to extract offset sections (i.e. tip corrected) based on the settings given in the application settings file over the range defined by the chord length table. This give a series of "on surface" cross section profiles along the length of the blade. These lie in regularly spaced "XY" planes along the blade axis.



- 2. For each blade section, find the tangent line (as per the blade repair instruction).
- 3. Compute the points in the section that are at the extremes along the direction of the tangent line.
- 4. Project these edge points onto the tangent line.
- 5. The chord length *C* for the section is then simply the distance between the projected extreme points.
- 6. The distances of each projected edge point to the projected point of intersection of the blade axis $(d_{LE} \text{ and } d_{TE})$ are also found*. Note that due to the method of computation d_{LE} and d_{TE} will always sum to the chord length, i.e. $C = d_{LE} + d_{TE}$.

Section tangent line d_{TE} d_{LE}

7. d_{LE} and d_{TE} can then be plotted against Z position to give a 2D representation of the blade edges. The initial points are computed at the section plane spacing, but are linearly infilled to the required point spacing defined in the application settings file ready for the feature analysis. These curves are referred to throughout this document as the **edge actual curves**. When considered as 2D plots, the blade material is then always below the edge actual curve:



* When blade cross sections are taken, the points are ordered such that they run with an anticlockwise winding order in the XY plane, as shown in the diagram below. The section tangent line found will then run on the concave side of the blade section, running in the same direction as the profile on the concave side. The application settings file contains a value which determines whether the edge more positive along this direction is the leading or trailing edge, such that features are labelled against the correct edge name. If this value is set to zero, then the trailing edge is the more positive edge, if 1, then the leading edge is the more positive edge.



4 Chordal analysis

At each sample position the chord length *C* can then be compared against the interpolated chord length limits (CU_{MIN} and CC_{MIN}) defined in the tolerances file. This identifies any areas of the blade below the countable chord length tolerance, and also any violating the minimum chord length.

In addition, the following properties are computed:

- The chord length at each key section requested.
- The location and chord length at the position where $C CC_{MIN}$ has its minimum value. This is the position where the chord length is shortest compared to the lower chord limit (i.e. the position closest to violating the minimum chord length if all chord lengths are valid, or the position of greatest violation if the limit is violated).
- The location and chord length at the position where $C CC_{MIN}$ has its maximum value. This is the position where the chord length is longest compared to the lower limit (i.e. the position where the chord length is farthest from violating the limit, or the position of minimum violation if the entire length is violating).
- The total countable and violating lengths of the blade. This is the total length along the blade where the chord length is less than the given CU_{MIN} and CC_{MIN} curves respectively. This is worked out internally by working out the number of points below these curves, then multiplying this figure by the point spacing (although the first and last evaluated point only count for half). Note that if no point in the chord lengths is deemed violating (i.e. less than the CC_{MIN} value), then the violating length will be zero.

5 Identifying features

The blade repair analysis process aims to identify features present in measured blade edges, and to quantify properties of the features found. In most cases, these features are expected to be blends introduced by a repair to the blade edge. However, since the process does not have any prior knowledge of the repairs that have been made, the methods presented will identify any perceived features in the measured edges. As such the document refers to features rather than blends.

Ideally, features would be identified solely based on deviation of the measured blade edges from an expected nominal form. In practice, this is not possible. Underlying form differences, due either to allowable tolerances at the point of manufacture, or due to erosion of parts once in service, can be significantly greater than the magnitude of the repair features of interest. As such, the underlying form variation masks the features that we are interested in.

Instead, the blade repair analysis process attempts to derive curves representing the underlying form of the specific part measured, with features being identified as deviations to this derived form. Throughout this document, these derived curves are referred to as **reference edge curves**.

The process offers two different approaches to deriving these **reference edge curves**, one referencing a nominal blade form and one not. The underlying principal behind both approaches is the same, and so this document first describes the basic method without reference to nominals, before explaining the extension to utilise the nominal forms.

5.1 Feature identification without using nominals

5.1.1 Filtered edge curve construction

The first step in the reference edge curve construction is to generate **filtered edge curves**. These are the result of applying a rolling ball filter to the **edge actual curves**. This mimics the effect of rolling a ball over the data such that it is always in contact with it, but never passes inside. The effect of the filter is that it always contacts with the peaks of the data, but cannot penetrate narrower troughs:



The filtered curve then follows the original data except where it cannot penetrate. In these regions, the original curve is replaced by points in an arc with radius equal to that of the filter.

The blade edges are expected to be largely smooth, with a large natural radius of curvature. The large ball will therefore be in contact along this length except where there is a repair or other high curvature feature. In these regions, the edge actual curve will deviate from this filtered form as the ball will not be able to penetrate. This means that features can be identified as areas of deviation between the filtered curve and the edge actual curve.

The size of the ball used for filtering needs to be such that:

- It is lower than the natural curvature of the edge (such that when there are no repair features the filtering has no effect on the form).
- It is large enough that it does not penetrate* into the features of interest.

* The ball will still penetrate by a certain distance, influenced by the feature and filter sizes. This is discussed in the next section of the document.

Of additional note is the behaviour of the rolling ball filter at the end of the edge actual curves. The effect of the filter is that the ball "rolls off" the end of the data, meaning that the final point in the set will always be included in the standard filtered result. This effect is not desirable if there are repair features running up to the end of the blade as the feature depth would effectively drop to zero at the end, rather than maintaining its depth. To combat this, "minimum expected edge values" are read from the tolerances file. When computing the filtered result, if the values of the end points of the edge actual curves are less than the given minimum values, they are set to the minimum. This causes the filtered result to "snag" on these points as shown in the following diagram:



Standard rolling ball filter result – the filtered curve runs to the end of the nominal curve.

Filter result using the minimum edge value – the filtered curve snags on the adjusted end point, maintaining the height at the end of the curve.

Values are specified for both the start and end of the leading and trailing edges separately. The values should be chosen such that they do not have influence on edge curves when features are not present, but are a suitable reference height for depth computation if a feature is present.

5.1.2 Candidate feature identification

Features in the blade edges can then be identified by comparing the value of the edge actual curve to the filtered edge curve at each Z position. A feature is considered to have started at the point the edge actual curve deviates by more than the feature cut off depth defined in the application settings file. The feature ends when the deviation drops back below this limit. This limit is designed to allow for small deviations due to local noise in the blade or measurement data.

5.1.3 Feature filtering and reference edge curve computation

The filtered edge curves are a good starting point for definition of the reference edge curves as they follow the gross form of the blade edge without describing sharp local features. However, as mentioned in the section above, there is some penetration of the features by the filtering ball. When considering feature depth as the maximum deviation between any values in the edge actual and reference edge curves at corresponding Z locations within the feature, this penetration has the effect of reducing the perceived feature depth.

To counter this, depth within features is instead computed against a chord formed between the feature start and end position in the filtered edge curve. As such, the depth of each feature identified is found by computing the difference between the edge actual point and the chord at each Z location in the feature:



It should be stressed that this means that the depth is considered in terms of distance along the chord length direction, not in terms of minimum distance between the chord and the edge actual curve.

This method will identify any deviations greater than the feature cut off depth as candidate features, however many of these may still be small and not of interest, existing due to noise rather than being repairs. The application filters out and discards features whose depth is lower than the minimum feature depth given in the application settings file, to reduce the features to only the set of interest.

Note that there is an optional output from the processing to give basic details of all candidate features prior to this filtering. This file may be of interest if a perceived blend is not picked up as it may indicate that it has been discarded based on the minimum depth value given.

Retaining the remaining features, we define the **reference edge curve** as the filtered edge curve where features do not occur, but replace it with the chord over the feature where they do occur (as shown above). This yields a reference edge curve which generally matches the form of the edge actual curve but deviates where features occur. Note that no modifications are made for features which were discarded due to the minimum depth criteria.

The blade repair instructions allow for chamfer and fillet repairs to be made on the tips of the blades which should not be analysed using the methods described in this document. The tolerance file can be used to designate a maximum feature AU value (which can be given either as a single value affecting both edges, or as two values which can be different for each edge). Any features identified starting beyond the given AU limit (for their respective edge) will not be present in the output blend analysis file. However, if they were of sufficient depth, they will still have affected the form of the reference edge curve.

5.2 Limitations of the approach

The approach taken has a direct physical analogy. If a ball were to be rolled along the edge, then a feature would be identified anywhere where the gap between the ball and the edge exceeded the minimum depth parameter (provided also that the start of the feature is less than the maximum feature start value).

However, this does have limitations. The method can only identify areas of concavity in the part which have a sharper radius of curvature than the given ball filter radius (plus an extra error to ensure it exceeds the minimum depth).

This means that there are two types of features that will not be identified:

- If a concave repair was made sufficiently long and smooth, then the filter curve will not deviate sufficiently from the edge actual curve for a feature to be found. As far as the process is concerned, such a feature is indistinguishable from the natural expected form of the blade. Detection can be improved by increasing the radius of the ball filter used, however this is limited by the inherent curvature of the part. If the filter radius is too large, intended form will report as identified features.
- If a nominally convex part of the blade underwent a repair, then it is possible that after the repair the area could become only slightly concave, become flat, or even remain convex. In these scenarios the feature would not be identified as it would not be concave enough to force a feature to be detected. The process however does not have the concept that the area was expected to be convex as it does not know the nominal form.

Additionally, since the process doesn't have any concept of the nominal form, its concept of depth is always to the chord connecting the start and end of the feature – i.e. it assumes that the blade should be locally flat over the identified feature. This means that where it does identify features, it will underestimate depths in convex areas of the blade edge and overestimate depths in concave areas. This is illustrated below:



In each diagram, the black curve represents the edge actual curve, the blue represents the chord over the feature and the green dotted line represents the expected nominal form.

5.3 Feature identification using nominals

As described previously, features would ideally be identified solely based on deviation of the measured blade edges from an expected nominal form. However, underlying form differences, due either to allowable tolerances at the point of manufacture, or due to erosion of parts once in service, can be significantly greater than the magnitude of the repair features of interest. These underlying form differences will result in constant deviation to the expected nominal, or smooth variation in the deviation, and are not indicative of the presence of repair features.

The presence of a repair feature will result in a significant local change in the deviation observed and as such will appear as a feature in the deviation. By applying the methods described previously to a curve representing the deviation to the nominal edge instead of the edge actual itself, we can instead identify the features in the deviations. This is the basis of the feature identification method using nominals and is described in detail below. This method is used if an input nominals file is given to the application.

5.3.1 Converting to delta space

In moving from identifying features in the edge actual curves to identifying features in the deviations to a nominal curve, we move our processing from acting in real space to acting in what we refer to as **delta space**. This differs in that it represents deviations to nominal rather than absolute distances along the chord direction.

By subtracting definitions of the nominal edge curves from the corresponding edge actual curves, we produce **delta space edge actual curves** which are simply plots of the deviation to nominal at each AU value.

The key to the delta space concept is that we see the form of the deviation, not the form of the edge itself. This is demonstrated in the examples below:

| Edge nominal curve (back) and edge actual curve (blue) | Delta space edge actual curve | Notes |
|--|----------------------------------|--|
| | | The actual and nominal perfectly match. The delta curve is constant at zero. |
| | | The actual has worn away from the nominal in a uniform manner across the edge. The delta curve is constant at a negative value. |
| | | The actual has worn away in a linearly increasing manner along the edge. The delta curve is a straight line. |
| | | A repair has been made in the actual form. This creates a sharp concave feature in the delta curve. |

As seen above, where there is a gradual variation in the deviation to the nominal form, this results in the delta space curves either being linear or having only smooth changes, but the underlying blade edge form is no longer represented. Where there are features present, these are observed as clear deviations in the form of the delta space curve which can then be identified.

Note that although the diagrams above indicate that the delta space curves will have negative values, in areas where the actual has more material than the nominal, the value in the delta space curve would be positive. This has no impact on the validity of the delta space processing.

5.3.2 Feature Identification in delta space

Once the data has been converted into delta space, the method proceeds in a similar fashion as before, by running a ball filter over the delta space edge actual curve to produce a **delta space filtered curve**.

The minimum expected edge values used in the standard filtered curve creation are also enforced in delta space. These are simply mapped through by subtracting the nominal curve value at the end points from their corresponding limiting point, giving the same effect at the ends of the curves as the process without a nominal.

Identification of features in the filtered curve happens in essentially the same manner as before. A set of candidate features is first identified wherever the delta space edge actual curve has an error to the delta space filtered curve greater than the feature cut-off parameter.

As before, the candidate features are filtered based on their depth to a chord formed between the points on the delta space filtered curve at the start and end of the feature.

The process then constructs **delta space reference edge curves** in the same manner as before but in delta space (i.e. from the filtered edge curves, but replacing the form with the chords over the identified features of interest).

Note that as with the previously described method, features which begin after the maximum feature start position will not be reported in the output blend analysis file, but will still have affected the construction of the delta space reference edge curves if they have sufficient depth.

5.3.3 What does feature identification in delta space mean?

The chord over features in real space assumed that the nominal form of the blade was linear over the perceived features, and depths were computed relative to this linear interpretation. The chords in delta space represent a linear change in the deviation to nominal over the length of the feature.

By mapping back from delta space to real space, we can see the effective "true" reference edge curves that we have created. This is simply the inverse of the process used to create the delta space curves originally. Each value in delta space is a deviation to the nominal edge. Therefore, by adding the nominal edge value at each point to the corresponding point in delta space, we map back to real space. The diagram below visualises this:



The left-hand side shows the feature when considered in delta space, where a chord is joined to create the delta space reference edge curve. The yellow lines indicate the deviations to nominal, and hence are the same length in both delta space and real space. It can be seen that the form of the nominal over the identified feature is now captured in the reference edge curve.

It is worth noting that the depth at each position in the feature is the same in both delta and real space. As such, the process using nominals always maps back into real space to produce true reference edge curves, and the remainder of the process (i.e. the feature analysis) is performed in exactly the same manner regardless of whether a nominal was used or not.

Note that all curves reported in the mandatory output files are reported in real space rather than delta space. If the delta space curves are of interest, the application can optionally output the delta space edge actual curves and delta space reference edge curves to a separate file.

5.4 Effects of the nominal approach

This approach of using the nominal edges has advantages and disadvantages over the approach without the nominal.

It resolves the problem of not being able to identify features where repairs have been made to a convex area, as even if the repair made was not concave, in delta space the difference will yield a concave area which will be picked up during the filtered edge curve construction.

It also improves the depth computation as the expected edge form is injected into the reference edge curves, rather than assuming a straight line. It is worth stressing again that whenever the blade repair analysis process reports depths using either processing method, these are always depths relative to an inferred expected edge position for the specific blade being measured. This is chosen as considering depth to a nominal is essentially meaningless, as this depth would include the underlying form difference (i.e. from manufacturing variation or erosion) as well as the depth of the repair. As such, by injecting the expected edge form into the reference edge curve, we derive a theoretically better depth value.

In the approach without a nominal, the filter ball radius was limited by the inherent curvature of the blade, which restricted the scope for detecting long, shallow features. Since the underlying form of the blade is removed in delta space, this gives freedom to increase the filter ball radius further, potentially allowing more features to be detected. Note however that the radius is still limited, but this is now based on the form of the underlying deviation of the part from nominal, not on the curvature of the part itself.

The major downside of this new approach is that it is highly dependent on the suitability of the nominal. The nominal provided to the program must sufficiently reflect the expected form in the actual measurements. In delta space, any locally significant form difference has the potential of being identified as a feature, whether they are legitimate repairs or not. For example, if a nominal is derived from CAD and does not describe form present in all of the real parts, all measured parts may report a feature which is not of interest. Constant deviations (or smooth deviations with curvature lower than the filter radius) are acceptable as they will not be picked up by the ball filter.

Also of note is that when the process was performed without a nominal, the ball filter radius had a direct physical interpretation. The filtering in delta space is a much more abstract concept and has no direct physical analogy.

20

5.5 Nominal file creation

As discussed above, the key to successful processing with a nominal input file is a good nominal definition, which reflects the expected form of the parts being analysed.

It is possible to derive this from a nominal CAD model, but this would require converting the 3D CAD geometry into the 2D representation based on chord lengths (as described earlier in the document). A method for doing this is not provided as part of the blade repair package.

The program does provide a mechanism for creating nominals based on a "gold part". The idea is to first find a gold part blade where repairs have not been performed, which is believed to be representative of the form of the other blades. This blade can be measured, and run through the black box application using the method without a nominal. One of the optional outputs of the program is a nominal file containing either the edge actual curves or the reference edge curves from the analysis.

Once this has been done and a nominal file created, the repaired blades of interest can then be measured and analysed, using the nominal file produced from the "gold part". The quality of the analysis though will depend heavily on how well the form of the gold part matches the other blades. To reiterate, any unwanted differences in form in the gold part are liable to be picked up as features in the other blades.

Note that the nominal file written out is based on the analysis settings given (including the spacing and precision at which points are reported). A user may wish to consider running the gold part analysis with different parameters to a standard feature analysis run to achieve the best nominal.

The nominal file does not have to be produced via this method. A user is free to create the nominal via any alternative method (e.g. from CAD) if desired. It is responsibility of the user to ensure that the method of generating the nominal file is suitable to obtain correct analysis from the process.

The exact format and other requirements for the nominal file are described in the Blade repair analysis user's guide (Renishaw part number H-1000-5448).

6 Feature analysis

Having derived the reference edge curves and identified the features of interest, either using the nominal or not, the feature analysis now proceeds in a common manner.

6.1 Basic feature analysis

The following basic feature details are determined:

- Feature Start, Feature End and Full Feature Length:
 - The feature start and end locations were determined as part of the feature identification.
 - The full feature length is simply the difference between the AU values at the start and end locations.
- Countable Feature Length
 - The feature runs between the start and end positions, however not all of this range is necessarily countable (i.e. the chord length drops below the *CU*_{MIN} curve during the length of the feature).
 - The countable length of the feature is the cumulative length of the feature for which the chord length is below the interpolate CU_{MIN} curve.
 - The curves are represented by a series of discrete points at regular intervals along the Z axis based on the point spacing given in the application settings file (note that this is the point spacing *not* the section spacing).
 - Each point in the feature range can therefore individually be identified as countable or not.
 - The countable length is computed as the number of points in the feature that are countable multiplied by the point spacing. However, if countable, the first and last point only contribute half a point spacing to the length computed.
 - As such if the entire feature length is countable, the reported countable length will equal the difference between the feature start and end positions.
 - Note that all features are reported by the application whether countable or not. Features during which the *CU_{MIN}* curve is never violated will report a countable length of zero.
- Maximum Feature Depth
 - As stated before, the depth at any AU value in the feature is simply the difference between the corresponding positions in the reference edge curve and edge actual curve.
 - The maximum depth (*V*) of the feature, and its corresponding position, is simply the point in the feature where this depth has its maximum value.
 - The chord length at this position will also be found.

- Feature Depth Validity
 - The depth limit for any given blend is determined from Table 1 in the repair document.
 - Note that the allowed blend depth varies depending on the region of the blade that the repair lies within. If the repair spans multiple regions (i.e. the transition from one region to the next lies within the start and end positions of the identified feature), the lower allowable depth is used for the analysis of the whole of the repair feature.
- Minimum Feature Chord Tolerance Location
 - In addition, the location where $C CC_{MIN}$ has its minimum value is found.
 - This is the location in the feature where the chord length is closest to violating or most violating the CC_{MIN} chord limit.
 - This is likely to be at the maximum feature depth position but may not always be.
 - The feature depth at this position is also reported.

Along with these values computed for each feature, the application will output a portion of the edge actual curve and the reference edge curve for each feature. This will show a range which encompasses the feature plus an extra distance either side equal to the feature padding length given in the application settings file. This additional length helps to give context to the reported curves.

During this stage of the analysis only the local depth of the feature in isolation is considered when comparing depths against the specified depth limits (i.e. $V \le V_{Max}$). The analysis of combined features (interaction between features on opposite edges of the blade) is covered later in the document to assess $V1 + V2 \le V_{Max}$.

6.2 Radius of curvature analysis

For each identified feature, the internal radius of curvature (R_{AD}) and external radius of curvature (R_{AC}) need to be analysed against the limits given in Table 2. The allowable limits are based on the depth of the feature identified in the previous step.

The table gives the minimum curvature radii allowed in the repair. Since the repair will not have a single constant radius of curvature, it is not possible to quantify the actual radius. Instead, the following method is used to ensure that the minimum curvature is not violated:

- Perform ball filtering on the edge actual curve in the region of the feature from above the curve, with the limiting *R*_{AC} radius to give a **curvature reference curve**.
- Compare the edge actual curve with the curvature reference curve generated between the feature start and end positions.

• If the curves deviate by more than the feature curvature analysis tolerance specified in the applications settings file, the radius of curvature in the edge actual curve is less than the given limit and hence the limit is violated.



• Repeat this process but applying the filter with the limiting R_{AD} radius from the underside of the curve to check against the internal curvature limits.



Note that this analysis yields a pass/fail result for each of the internal and external checks. The location of any violation is not computed, however the edge actual curve and the curvature reference curves are output to allow the violation to be visualised. Again, these are extended either side of the feature range by the feature padding length given in the application settings file. However, the deviation of these curves is only considered between the start and end ranges of the feature of interest. As such, if there is deviation outside of this range (i.e. in the padded region of the curves) it will show visually, but it will not influence the pass/fail result for the feature.

To ensure there is no inappropriate curvature in the blade edge outside of the identified features, the application also performs curvature analysis on the entire blade length. This happens in the same manner as described above. The R_{AD} and R_{AC} tolerances, as well as the curvature analysis tolerance, are distinct from those used for feature analysis. The output blends file will record the Boolean results of these two checks, as well as their corresponding curvature reference curves to allow any violations to be visualised.

Note that when comparing two curves for curvature analysis, as previously, all distances are computed perpendicular to the Z axis. The curvature analysis tolerances are used when assessing curvature as numerical precision during the computation means there is likely to be small differences between the profiles even when the curvature is valid.

6.3 Combined feature analysis

The feature analysis up until now has focussed on the edges in isolation. The final analysis performed is on what will be referred to in this document as **combined features**. Combined features are areas on the blade where identified features on both the leading and trailing edges have an overlapping range between their start and end section heights.



In these regions, there is the further restriction that $V1 + V2 \le V_{Max}$.

The following analysis is performed:

- Identify any combined features by comparing the start and end ranges of each leading edge feature with each trailing edge feature and determining if any overlap.
- For each combined feature identified, find the section height at which V1 + V2 has its maximum value. To be clear, this is identifying a section height where the sum of the depths is maximised. This is not the sum of the maximum depths of the features considered in isolation.
- Compare this against the maximum allowed blend depth. This is found as the minimum for all ranges that either feature is active within, not just where they overlap.

For each combined feature found, a table entry will be given detailing:

- The names of the LE and TE features that form the combined feature.
- The section height of the maximum depth in the combined feature.
- The maximum combined depth for the combined feature, along with the contributions from each edge separately.
- The depth tolerance used to validate the feature depth.

7 Analysis output

Once the analysis has been performed, the analysis details are output in a series of results files that can be read back into MODUS for reporting and visualisation. These contain these results of all the analysis described in this document.

The format of these files is discussed in more detail in the application Blade repair analysis user's guide (Renishaw part number H-1000-5448).

8 A final note on the feature analysis

It is worth highlighting again that the feature analysis described previously in this document is all performed on the 2D representations of the blade edges, and as such is *not* on the full 3D form. Since the 2D curves are of distances along the chord direction, this means that feature depths reported correspond directly to reductions in chord length compared to the perceived edges. Similarly, curvature analysis looks at the change in the edge form in this 2D domain.

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