# Experimental model validation of an aero-engine casing assembly

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**ABSTRACT**

This work presents an experimental model validation of an aero-engine casing assembly. The objective is to show how to perform an experimental model validation of a casing assembly with bolted flanges. One of the major challenges was given by the unknown geometrical dimensions and material properties of the structure at the outset. This goal could be reached by using modal updating so as to identify the best geometrical and material parameters for the model. Experimental testing was a key contributor in this process, since the test data were used to benchmark the updating process. The updating process highlighted that the model could not be correctly updated until the joints were included. Therefore, the FE model required to be upgraded, by inclusions of joint flexibility, before it could be updated. This paper will present both the upgrading-updating process and the experimental testing carried out on the casing assembly.

**KEYWORDS:** Upgrading, updating, experimental model validation

## 1 INTRODUCTION

This research work was developed using an aero-engine casing assembly the finite model of which was not available at the beginning. The hardware was used in past researches [1] where the model was developed and supported by the project sponsor. Unfortunately, this information was not available in this present research. So, the objective and challenge was to exploit the potential of the model updating to experimentally validate a FE model. Ewins et al [2] suggested that any FE model is good as much as it includes the correct physics which enables the right calculation of the dynamic responses. Ewins also suggests that a model must be upgraded if physical elements are not yet taken into account for the calculation of the dynamic response. So, any FE model can be updated as much as possible but it will inevitably fail to simulate the correct dynamics until all important flexible elements are not included, for instance joints. Therefore, under these circumstances, a model should be upgraded and then updated. For example, irregular changes of thickness in the physical structure can be included into the model updating process where the mass and stiffness are corrected for better values. However, if a joint flexibility is not included the model must be upgraded before any updating process takes place. To prove this assumption, the cases presented in here will discuss about a FE model created with and without the inclusion of the joint flexibility. Considering that both geometrical and material properties were unknown the paper will show that the model can be updated up to find the best values for predicting some of the modes measured during the experimental campaign. But, only the inclusion of the joint flexibility into the model will deliver the correct response modes. The process might look trivial but the model updating software, used in this project, requires the complete modelling of the bolts in order to perform the correct updating. And, this type of modelling is not a trivial task when approx. 150 bolts must be included, which creates redundancy and increases the computational cost. Despite the entire work is based on linear dynamic response, so nonlinarity is not even attempted, the process to upgrade and update a linear model showed not to be such a straightforward process.

## 2 EXPERIMENTAL SETUP

The test structure was suspended horizontally by using turn buckles and elastic chords as shown in Figure 1. An electromagnetic shaker was also suspended and attached on the top part of the casing on the middle section. The dynamic range selected was between 150Hz and 350Hz. The measurement points for the test were the same already selected for the validation carried out in [1]. The modal testing and analysis were carried out by LMS TestLAB (SIEMENS). The mode shapes are presented in the APEENDIX. The modal data were correlated with the ones obtained during a past research project in which the aero-engine casing was supported vertically rather than horizontally as in the presented case. Figure 2 shows the correlation map between the two sets of modal data. The map shows that the correlation does not achieve 100% for all the modes selected. The reason can be due to several factors but the most important seems to be the effect of the mass loading (due to the gravity) on the joints. In fact, the vertical configuration would equally load all the joints, which is not the case for the horizontal setup.

Figure 1 Test setup

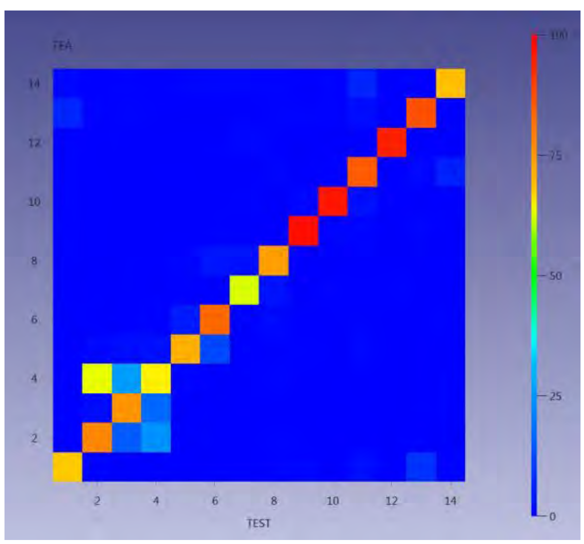


Figure 2 Correlation between the modal data obtained from vertical (Y-axis) and horizontal (X-axis) setup

## 3 FINITE ELEMENT MODELLING OF THE AERO-ENGINE CASIN ASSEMBLY

The aim of the model development was to create an FE model that was simple yet able to simulate the underlying linear behaviour of the test structure. To achieve this, the configuration and parameter errors in the model were needed to be improved. This was done by progressively increasing the complexity of the model. At each stage, mode shapes from the experimental data were matched to mode shapes from the FE model based on MAC and natural frequency difference (NFD) values. Lower NFD values are preferred as they indicate the model is able to accurately predict a mode shape at the right frequency. The model was then subjected to an updating procedure using FEMTools (DDS). Here, the software attempts to match the model results to the experimental by manipulating the parameters. The results from the updating procedures were the updated final parameters and mode shape pairs, with NFD and MAC values. Mode shape pairs in this section are defined as a mode shape pair correlated between the experiment data and the numerical model. These results were studied and a decision was made on the changes to be made to improve the model. This changed model was subjected to the same process until the ideal number of mode shape pairs with ideal NFD and MAC values were achieved: at least 10 mode shape pairs with the experimental data with MAC and NFD values above 50% and below 15% respectively. The frequency of interest was 150Hz to 350Hz. Usually, MAC values of 80% or higher are preferred. However due to the size and complexity of the structure, even the slightest mis-match between an experimental and model node behaviour resulted in a MAC below 80%. In improving the model at each stage, the parameters and/or configuration were changed. The main variables involved were the material properties (Young's Modulus, (E), and density ($\rho$)), the thickness $h$ of the model, and the physical make-up (configuration) of the model. These were dependent on one another. For example, the thickness and Young's Modulus affected the overall stiffness of the casing, and the density and thickness affected the overall mass. The configuration of the model affects the mass and stiffness as well. As such they cannot be changed independently. The initial objective was to identify the material properties. The configuration of the model was initially kept simple. It was also allowed to be flexible to fit the requirements of other parameters.

The aero-engine assembly was modelled by ABAQUS (Dassault Systems). The casings were weighted and the overall assembly was 256Kg. The major issue was to identify the material properties of the assembly. Two materials were assumed by visually inspecting the casings, these were titanium and stainless steel. Clearly, these properties could not be retrieved by the standard libraries nevertheless the nominal values were used as guess for starting the model updating. Rough measurements of the dimensions of the casings' thicknesses were also made, as shown in Figure 3. However, several features had to be neglected and assume the updating process to be able to cope with these, like the one showed in Figure 4.


Figure 3 Measurement of the casing thickness

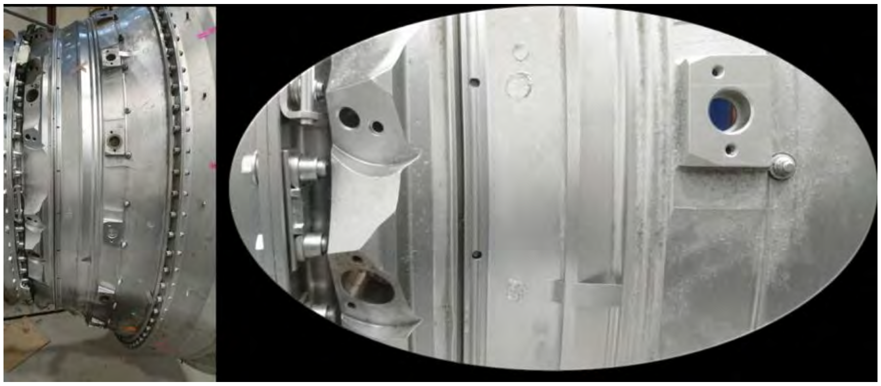
Figure 4 Geometrical features neglected in the model

It is not scientifically interesting to explain the trial and error procedure to validate the model since it is rather a procedural thing. It is, instead, useful to explain that the several attempts achieved some level of agreement between the experimental and theoretical model. The error between the two was caused by lack of information about aforesaid properties, which the model updating managed to identify at its best as presented in Table 1.

| Parameter | Section | Initial | Updated | Difference (%) |
|---|---|---|---|---|
| E | Cylinder | 1.14E+05 | 1.14E+05 | -1.02E-03 |
| E | Cone 1 | 1.14E+05 | 1.14E+05 | -8.75E-02 |
| E | Cone 2 | 2.03E+05 | 1.52E+05 | -2.53E+01 |
| $\rho$ | Cylinder | 4.40E-09 | 4.40E-09 | 2.80E-04 |
| $\rho$ | Cone 1 | 4.40E-09 | 4.40E-09 | 7.40E-03 |
| $\rho$ | Cone 2 | 8.00E-09 | 1.01E-08 | 2.68E+01 |
| Thickness | Cylinder | 1.00E+01 | 1.00E+01 | -1.97E-03 |
| Thickness | Cone 1 | 2.00E+01 | 2.00E+01 | -1.32E-01 |
| Thickness | Cone 2 | 1.00E+01 | 9.26E+00 | -7.43E+00 |

Table 1 Geometrical and material parameters

At this stage all three casings were rigidly bonded together. This was one of the reasons why the updating could not improve the correlation beyond an acceptable level. For example as presented in Figure 5. A simulation with the model updating software was carried out to verify where the most sensitive areas in the structure were. Figure 6 shows that the jointed flanges were the most sensitive locations were the model required refinements, which indicated the largest errors to be around the connections between the parts of the casing.

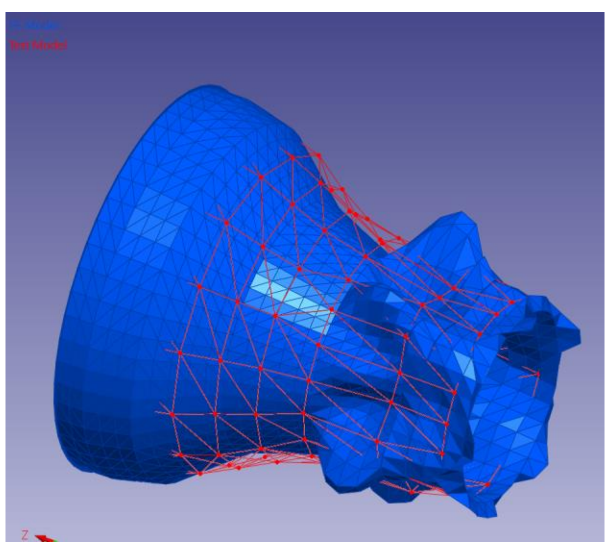
Figure 5 Correlation between measured and theoretical mode

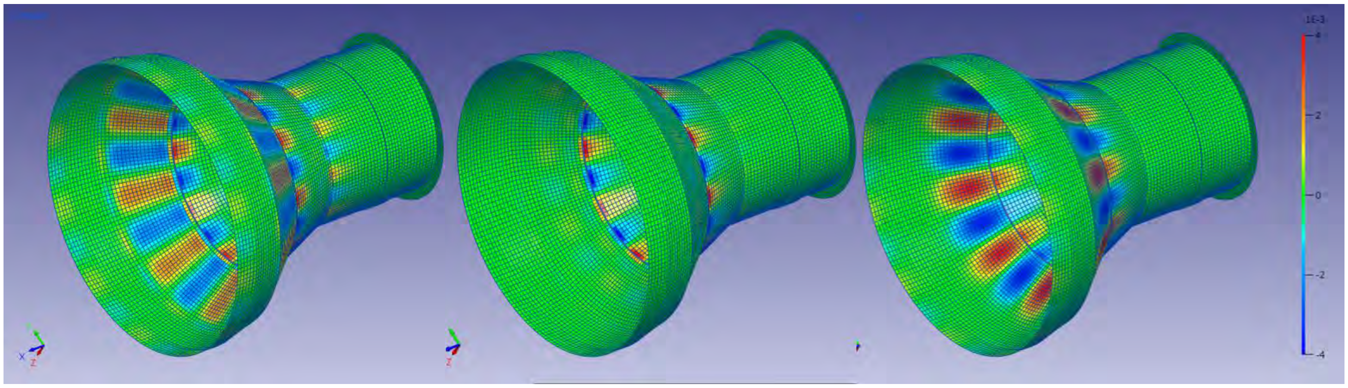

Figure 6 Sensitive areas identified by the model updating software

Another undesired effect of these types of constrains was the absence of a theoretical mode which, instead was measured during the experiments. That mode shape was located at much higher frequency because the unrealistic stiffness created at the bolted flanges. So, it was necessary to model the joints and this was carried out by using fasteners, which are linear springs. By creating a bushing 'Connector Section' in ABAQUS, a fastener could be given properties that allowed six DOFs. The fasteners can also be assigned multiple stiffness in all six DOFs with an initial value of 50 000 $Nmm^{-1}$. The benefits of fasteners over modelling the bolt itself are that fasteners are mesh-independent, easily manipulated and less computationally demanding. Partitions were made on the flanges of the model with 80 connection points. These were created on the partitions which were assigned the bushing connector section with a radius of influence of 8mm. This method was used as the number of points could be changed easily. Due to limited access to model updating, the model was manually updated. A range of frequencies of interest were selected and the parameters were changed individually and the resultant change and/or shift in mode shapes were studied. The mode shapes were monitored visually with the ABAQUS environment to ensure there was no large shift in frequency in between iterations. Figure 7 shows the theoretical mode shape which did not appear in previous calculations because beyond the dynamic range selected. The increased flange flexibility has lowered the natural frequency of the mode shape.

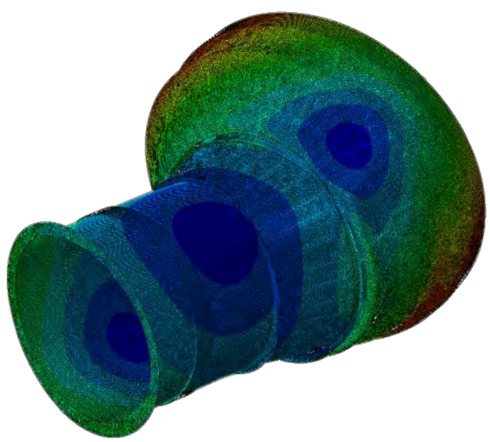

Figure 7 Theoretical mode shape with inclusion of joints

Having identified the most suitable stiffness to give to the joints a new model updating was eventually run with the upgraded model. Figure 8 shows the updated mode shapes after the upgrading FE model with the joints.

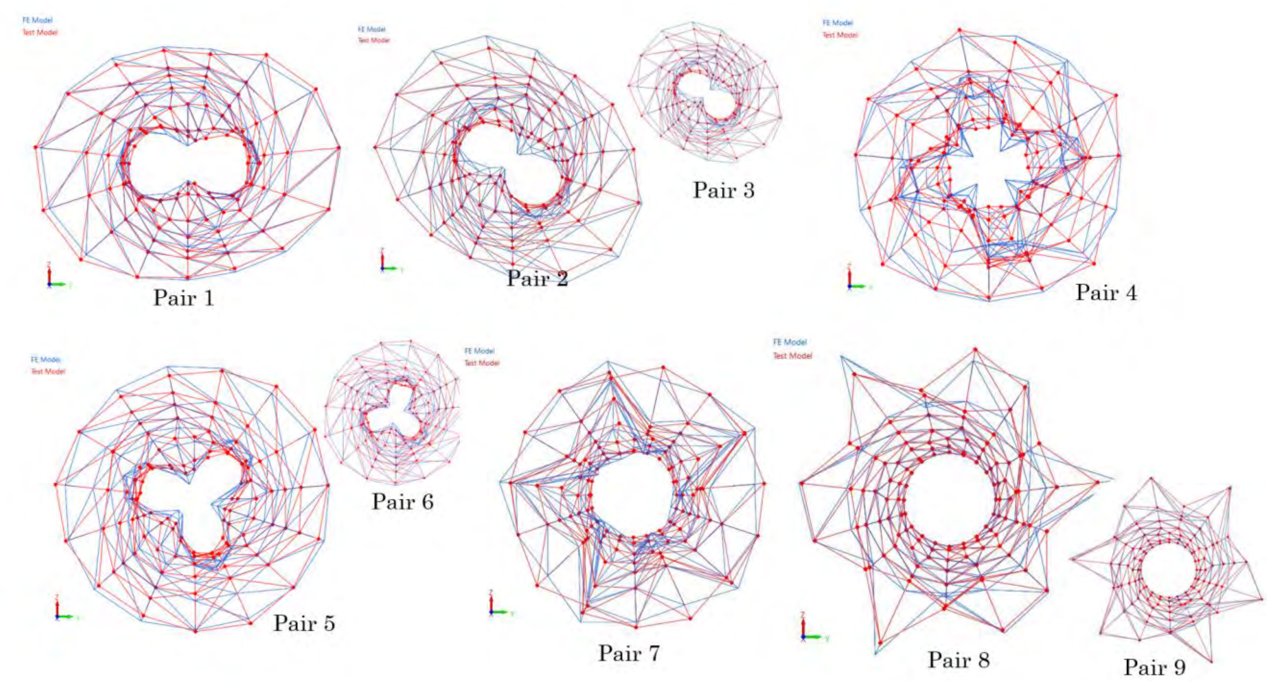


Figure 8 Final updated mode shapes

## 4 CONCLUSIONS

This piece of research work has demonstrated how important is joints modelling. The finite element modelling of the casing assembly was done and model updating of the mass and stiffness matrix was also carried out by using reference test data. The major challenge was to create a valid FE model by starting with unknown material and geometrical properties. Measurements and estimation of those help the modal updating software to converge to values which produced some acceptable MAC results. However, it was shown that if the bolts are not included into the model then it is impossible to obtain an adequate model validation. It was clear that meshing several bolts was not an option, which left the model updating software unable to perform the updating. Eventually, bolts were included by using fasteners (springs). Manual updating of the spring parameters was carried out and new model updating was gain attempted thus making the FE model of the casing validated. In ultimate instance, it worth mentioning the model updating has provided an excellent support. However, the updating process was limited until the model was upgraded with the inclusions of the stiffness of the joints.

## REFERENCES

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# APPENDIX

| FREQUENCY (HZ) | MODE SHAPES | |
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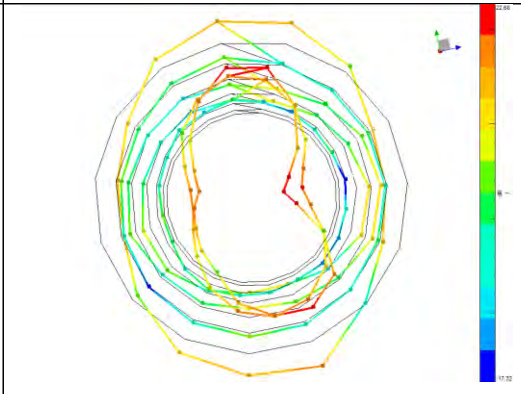
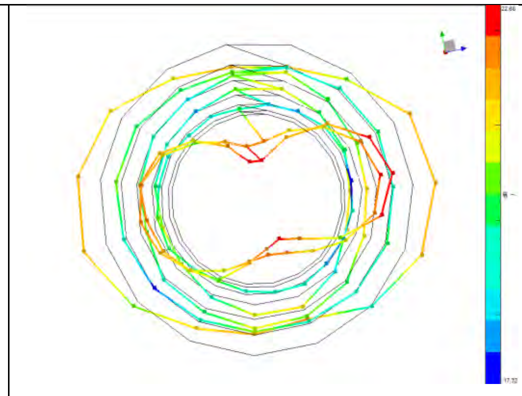
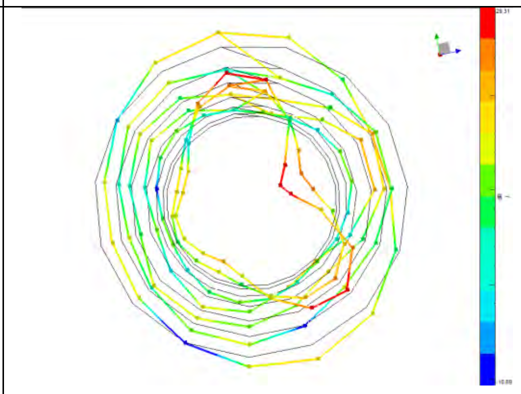
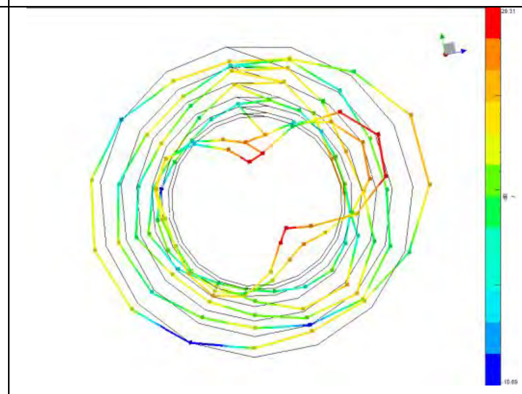
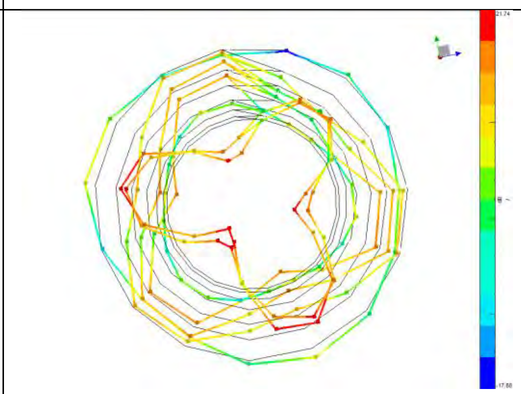
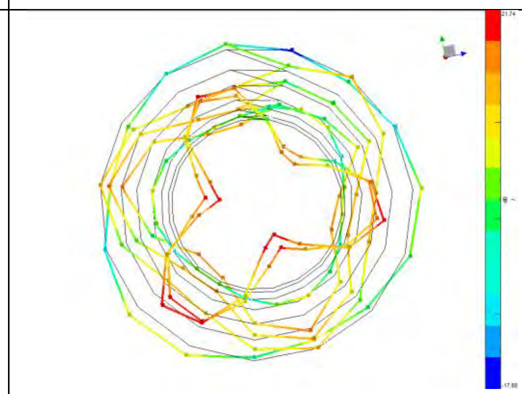
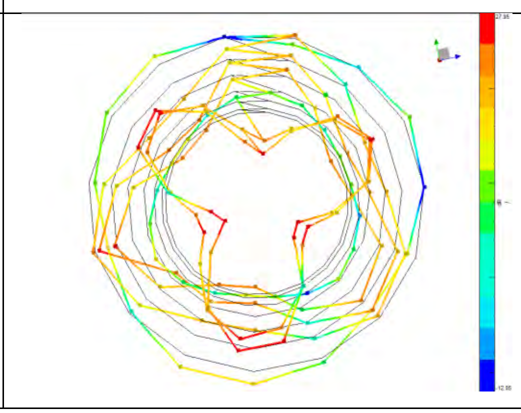
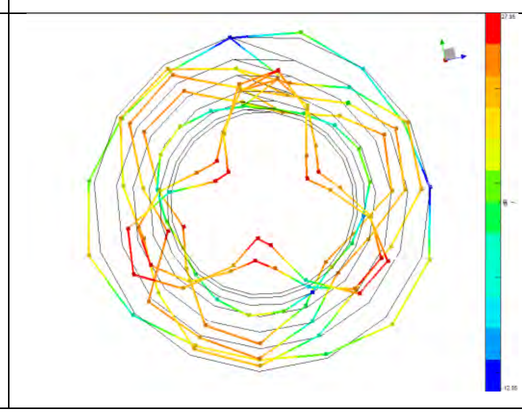
| **188.06** |  |  |
| **194.99** |  |  |
| **200.88** |  |  |
| **203.95** |  |  |

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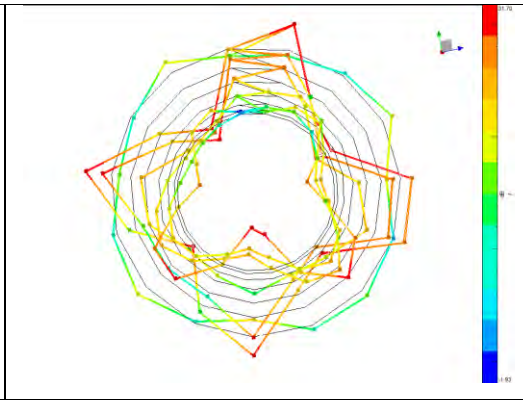
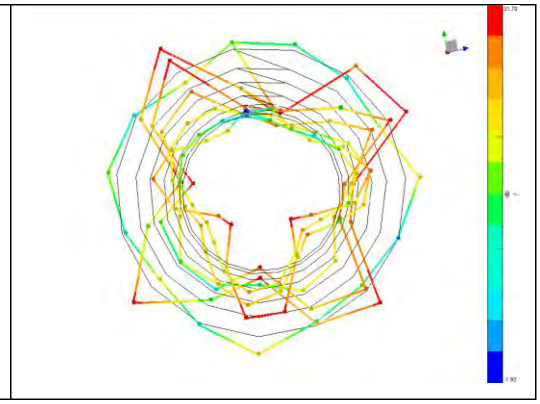
| **232.95** |  |  |

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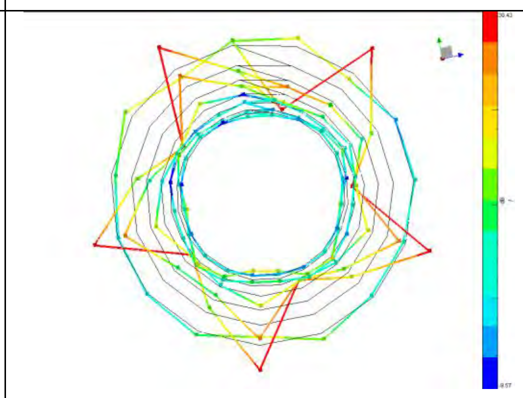
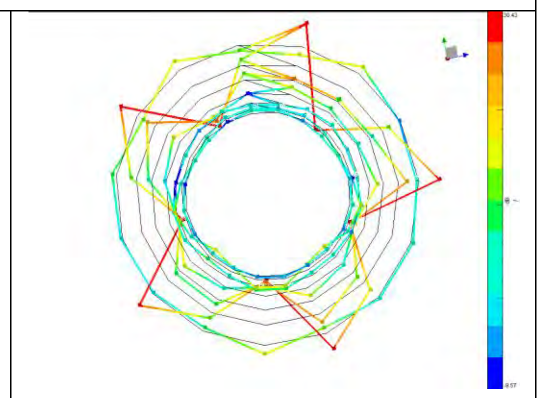
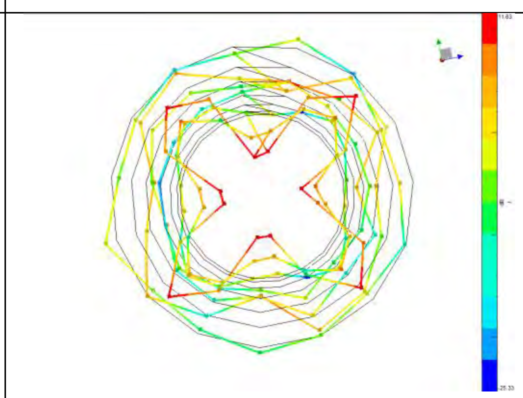
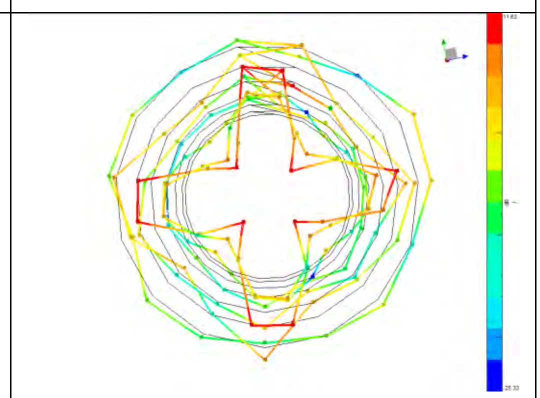
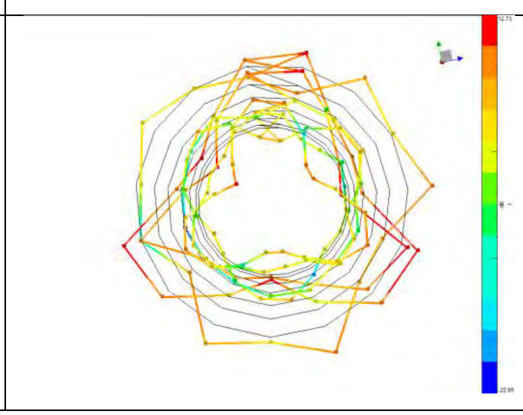
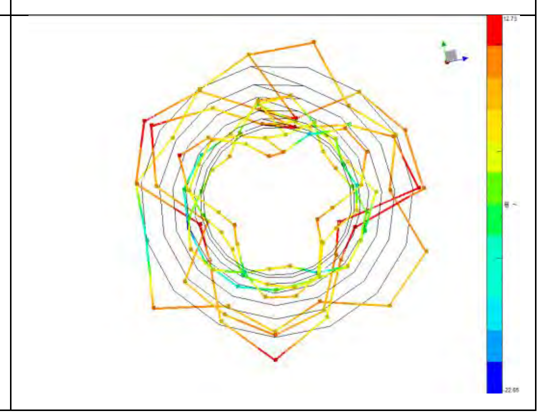
| **282.72** |  |  |
| **289.46** |  |  |
| **318.83** |  |  |

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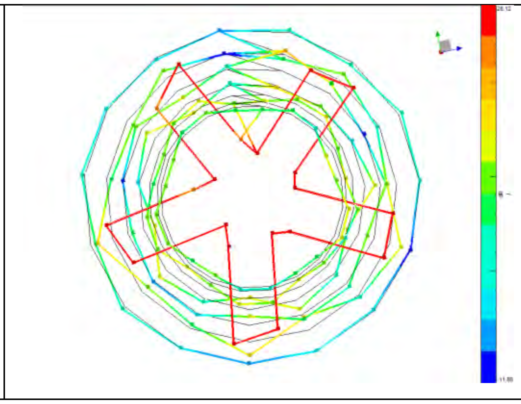
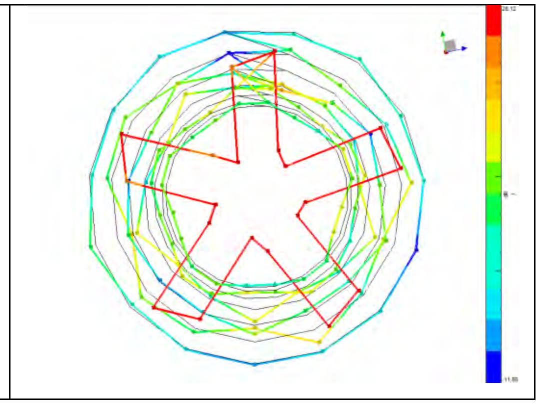
| **343.79** |  |  |