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DETERMINATION OF RESIDUAL STRESSES ON A CENTRIFUGAL COMPRESSOR IMPELLER

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ABSTRACT

This paper reports a comparison of two methods to perform residual stress measurements. The specimens tested by each method were two blades from a shrouded centrifugal compressor impeller. The first method is the conventional hole drilling strain gage method which was used to predict residual stresses across the blade surface. The residual stresses are released by drilling a hole in the blade. The second method is called the nonlinear harmonic (NLH) scanning method and is based on the principal that the magnetic domains of ferrous materials vary in a non-linear way relative to internal stress. The effects of residual stress may be either helpful or harmful, depending on the magnitude of the residual with respect to the operating stresses. If not adequately relieved by heat treatment, residual tensile stress that develops in the welding process of shrouded impellers, will add to the stress developed by rotation which moves the point to the right on the Goodman diagram and reduces allowable alternating stress. The results showed comparable residual stress measurements of the NLH method compared to the conventional hole drilling method.

INTRODUCTION

The effects of residual stress may be either helpful or harmful, depending on the magnitude of the residual with respect to the operating stresses. If not adequately relieved by heat treatment, residual tensile stress that develops in the welding process of shrouded impellers, will add to the stress developed by rotation which moves the point to the right on the Goodman diagram and reduces allowable alternating stress. Residual stress measurements were made on a failed impeller by two complimentary methods. The first method is called the nonlinear harmonic (NLH) scanning method and is based on the principal that the magnetic domains of ferrous materials vary in a non-linear way relative to internal stress [1]. The second method included the typical hole drilling strain gage method which predicts residual stresses across the blade surface. Strain gauges can only measure changes in strain once they are applied; drilling a small hole relieves stress in the surrounding material in a quantifiable way, which is used to establish residual stress [2].

A summary of the results obtained from each method as well as a comparison of the two are provided in this report.

RESIDUAL STRESS TESTING BY THE NON LINEAR HARMONIC METHOD

Residual stress analysis by all magnetostrictive methods takes advantage of the effect of stress on the magnetic permeability of ferromagnetic materials. Measurement of the nonlinear harmonics of an oscillating magnetic signal provides a measure of the magnetic permeability in the top 0.010 inches a ferromagnetic material surface [2]. This method has worked well where uniaxial stress conditions can be assumed. NLH readings are also affected by material constituents, heat treatment, surface scale or oxidation, work hardening and the heat affected zone near welds [3]. These effects tend to corrupt the signal and induce noise that must be dealt with in data analysis.

NLH measurement of residual stress is most appropriate when relative stress distributions over an area would provide useful information and a method that is nondestructive to the part and is not hazardous to health is needed. The present state of art in NLH technology has not advanced to the stage of providing results that are equivalent to strain gage readings; most importantly the direction effects are not as clearly defined. Under conditions of biaxial stress, the NLH readings are more related to the principal stress or principal shear stress rather than to stress in a given direction relative to the probe. Figure 1 shows a schematic of the NLH method setup.

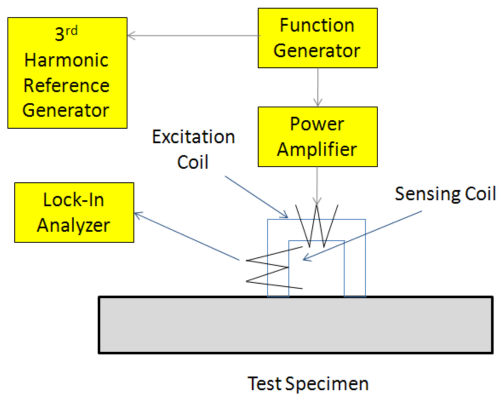

Figure 1 - Schematic of NLH Method Setup

A grid was laid out on the blade to conduct the residual stress testing by the NLH method, as shown in Figure 2. Each point was subjected to testing in three different orientation 0/45/90 degrees from the radial direction, the same as in the hole drilling strain gage method. The grid work provided a reference for aligning the probe for each direction relative to the blade.

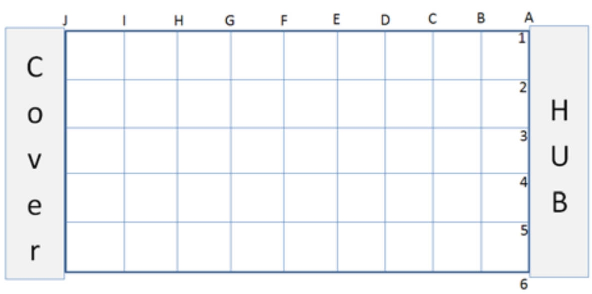

Figure 2 - Blade Grid for Residual Stress Testing

Data was recorded on the blade suction side at each point on the grid. The data was further processed using a calibration obtained from a specimen cut from the impeller to obtain stress levels on each direction. The calibration test consisted on a plate shape sample cut from the impeller to which different loads were applied. Stress was determined strain gages and the NLH method. The strain gage static strain measurements were converted to stress and then used to derive a calibration curve. Figure 3 shows a schematic of the calibration test.

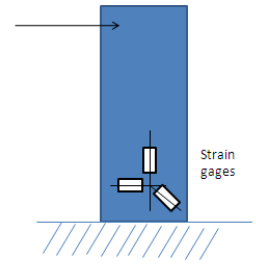

Figure 3- Schematic of Calibration Test

The magnitude and direction of the principal stresses at the impeller were determined using conventional solid mechanics equations [4]:

$$\sigma_{1,2} = \frac{\sigma_X + \sigma_Y}{2} \pm \sqrt{(\frac{\sigma_X - \sigma_Y}{2}) + \tau_{XY}^{2}} \qquad (1)$$

Where:

σ1, 2= Maximum and Minimum Principal Stress

σX= Normal stress in the X direction

σY= Normal stress in the Y direction

τXY= Shear Stress

One location was chosen on each blade for comparison with the strain gage hole drilling method A3 and F4 respectively, for blade 1 and 2. Principal stresses were normalized as shown in Figure 4 through 7. The graphs used are filled 2-D contour plots where the horizontal and vertical axes indicate the measurement location on the blade and the color represents the magnitude of the residual stress levels. In general, the stress levels were compressive across each impeller blade. Note that compressive stress levels are negative but were normalized to 1.

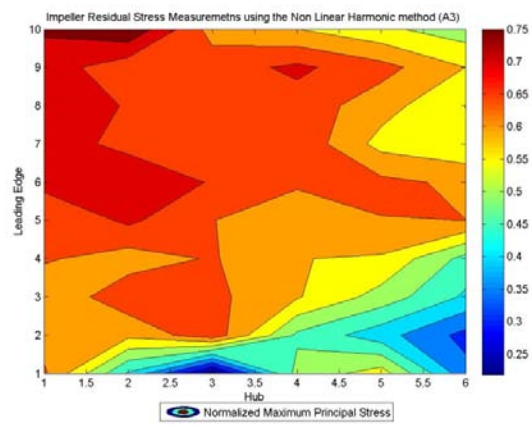

Figure 4 – Maximum Principal Stress Measurements at Blade 1 Using the NLH Method (Blade 1)

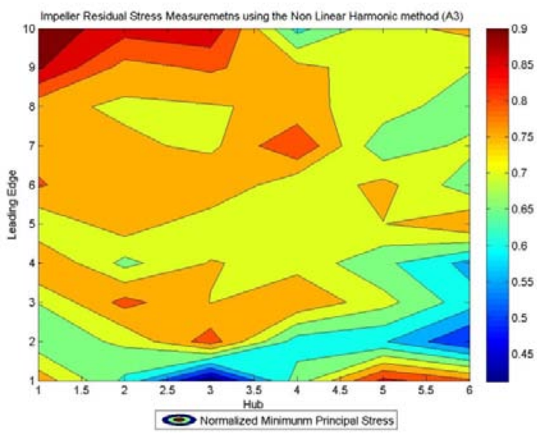

Figure 5 – Minimum Principal Stress Measurements at Blade Using the NLH Method (Blade 1)

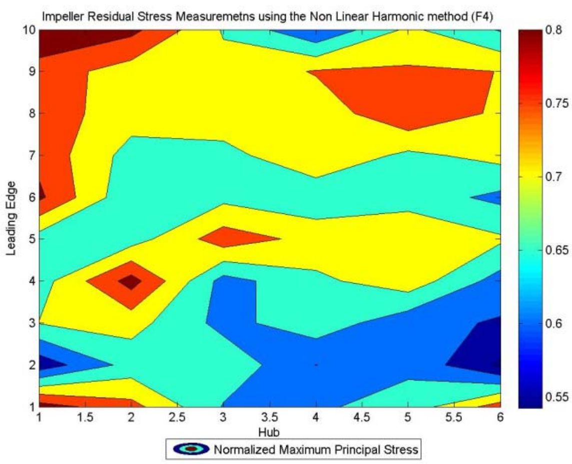

Figure 6 – Maximum Principal Stress Measurements on Blade 2 Using the NLH Method (Blade 2)

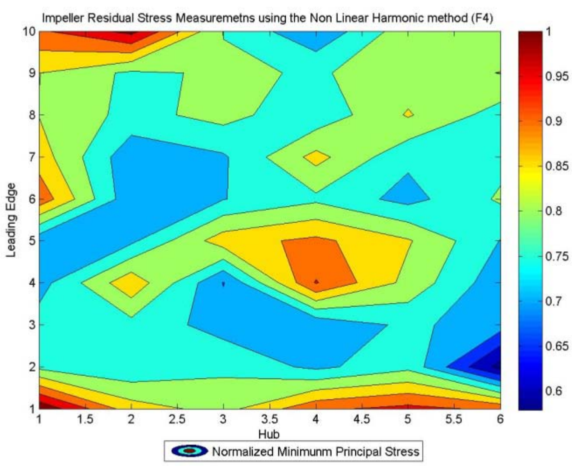

Figure 7 – Minimum Principal Stress Measurements on Blade 2 Using the NLH Method (Blade 2)

RESIDUAL STRESS TESTING BY THE HOLE DRILLING STRAIN GAGE METHOD

The hole drilling strain gage method is a conventional technique used to assess the residual stresses on a part or component. This method can be used to determine the internal stresses in the surface of the impeller blade. The residual stresses are released by drilling a hole in the blade. A three-element strain gage rosette was installed at each location where residual stress measurements were made [2]. The strain gage elements were arranged around the circumference of a circle and oriented at 0, 45, and 90 degrees on the rosette, as shown in Figure 8. The gage grids were connected to a balance and switch unit as well as a strain gage indicator to obtain the static stress measurements. Figure 8 shows a picture of strain gage hole drilling method.

$\sigma_{1,2} =$

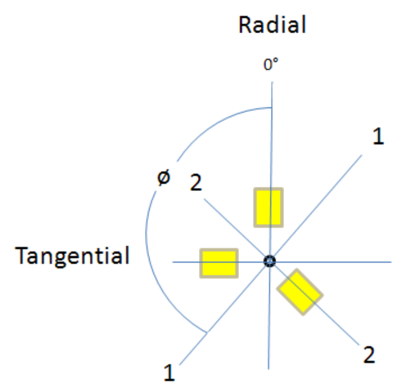

Figure 8 - Strain Gage Rosette Orientation

The surface was smoothed out with a wire brush prior to the installation of the strain gage rosette at each location. Typical surface preparation procedures were followed to install the strain gages. A precision milling guide was attached to the impeller blades at each test point location and accurately centered over the drilling target on the rosette. After zero-balancing the gage circuits, a small hole of 0.060 inches in diameter (same as rosette target hole diameter) was drilled at the geometric center of the rosette using a drill and drill bit, as shown in Figure 9.

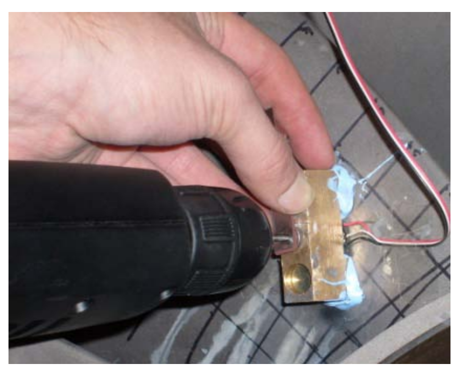

Figure 9 - Picture of Strain Gage Hole Drilling Method

Readings were made of the relaxed strains, corresponding to the initial residual stresses using special formulas derived using solid mechanics theory. Static strain measurements were made at different hole depths increments until the relaxed strain values appeared to settle. The principal residual stresses and their angular orientation were calculated from the measured strains using the following formulas [5]:

$$A^* = \frac{E}{4A} = \frac{E}{0.1894(1+\upsilon)} \qquad (2)$$

$$B^* = \frac{E}{4B} = \frac{E}{0.7576 - 0.0606(1+\upsilon)} \qquad (3)$$

$$\phi = \frac{1}{2}\arctan\left(\frac{\Delta\varepsilon_1 + \Delta\varepsilon_3 - 2\Delta\varepsilon_2}{\Delta\varepsilon_3 - \Delta\varepsilon_1}\right) \qquad (5)$$

Where:

E= Modulus of elasticity

Y= Poisson's ratio

ε= strain

A= constant

B= constant

σ1,2= Maximum and Minimum Principal Stress

ø= angle of orientation of principal directions

The same blade grid was used on the blade suction side. Only one measurement location on each blade was chosen for the residual stress measurements by the hole drilling method. The residual stresses measured on both blade surfaces were compressive. Static stress levels were measured at different depth increments on both impellers until stress levels settled as shown in Figure 10. The values taken from each graph represent the settled relaxed residual stress for each blade location.

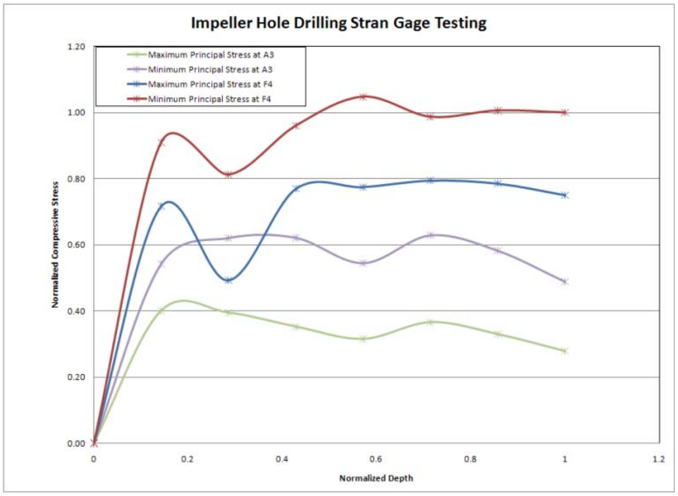

Figure 10 – Normalized Compressive Stress from Hole Drilling Strain Gage Method

COMPARISON OF RESIDUAL STRESS MEASUREMENTS

Absolute measurements show good correlation as shown in Figure 1. Moreover, the relative comparison of the hole-drilling strain gage method and the non linear harmonic method shows that the NLH method under predicted the residual stress levels up to a 22% as shown in Table 2.

Table 1 Summary of Residual Stress Measurements

Blade Location	Hole Drilling Strain Gage Method	NLH Method	Hole Drilling Strain Gage Method	NLH Method
	Normalized Maximum Principal Stress	Normalized Maximum Principal Stress	Normal Minimum Principal Stress	Normal Minimum Principal Stress
A3	0.36	0.28	0.58	0.52
F4	0.77	0.66	1.0	0.79

Table 2 Relative Comparison of Residual Stress Measurements by the NLH and Hole Drilling Method

Blade Location	Deviation of NLH Method from Hole Drilling Method Residual Stress Measurements	
	Maximum Principal Stress	Minimum Principal Stress
	%	%
A3	22.22	10.34
F4	14.29	21.00

CONCLUSIONS

This paper reports a comparison of two methods to perform residual stress measurements. The first method is the conventional hole drilling strain gage method which was used to predict residual stresses across the blade surface. The second method is called the nonlinear harmonic (NLH) scanning method and is based on the principal that the magnetic domains of ferrous materials vary in a non-linear way relative to internal stress. This study proved good correlation between residual stress measurements performed by two different methods. A disadvantage of the hole drilling method is that it is considered a semi-destructive method since a small hole needs to be drilled to relief residual stress. Therefore, the nonintrusive NLH method proves to be a method convenient to perform residual stress measurements on impellers or parts where the hole drilling method cannot be applied.

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