Analysis of Vibration Damping Ability of Deep Cryogenic Treated AISI 4140 Steel Shaft Supported by Rolling Element Bearings

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Abstract

The main objective of the present study is to experimentally investigate and figure out the effect of deep cryogenic treatment in improving dynamic behaviors in terms of damping of rotating shaft supported by rolling element bearings. An AISI 4140 steel for rotating shaft was selected for experiment because of it is the most widely used material in most industry for a wide range of applications such as machinery components, crankshafts, motor shafts, axle shafts, and railway locomotive traction motor shafts. Untreated, conventionally heat treated, deep cryogenic treated, and deep cryogenic treated and tempered shafts were used for experiments to observe damping behavior changes of the shafts. Deep cryogenic treated and deep cryogenic treated and tempered shafts were cooled from pre-tempering temperature to $-140^\circ C$ and held for temper hold times of 12, 24, 36, and 48 hours. So, ten sets of shafts were employed for the experiment. The vibration data were captured for each of the shafts for five different shaft running speeds 600, 1200, 1800, 2400, and 3000 rpm. The results showed that damping ability of the deep cryogenic treated shaft at hold time of 36 hours was superior to the others shafts.

1. Introduction

Rotating shafts are the most widely used with great risk of failure that can effect the whole rotating machine system. The performance of any rotating machine system is very dependent on vibrations generated by rotating shaft. Rotating shaft vibration plays an important role in dynamics behavior of the system because excessive vibration amplitudes can cause inefficiency and failure. The properties of materials used for rotating shafts are important requirement for accurate stability since the materials affect the effective damping of the rotating shaft systems. Many of today's modern rotating shaft systems require the superior stability characteristics of shaft material to prevent the system instability due to vibration. There are number of treatment processes used for rotating shaft materials which cause them to vibrate differently.

Rotating machine systems play an important role in industry. They are composed of various components. One of these components is the rotating shaft. It has vital contribution to the performance of rotating machine system. The performance of any rotating machine system is very dependent on vibrations generated by the rotating shaft.

It is important to know vibrations in rotating machine system because excessive vibration amplitudes can lead to instability and extensive bearing damage. The properties of material used for the rotating shaft is important requirement for accurate stability since the material affected the effective damping of the shaft system. There are number of treatment processes used for rotating shaft material which cause it to vibrate differently. Every heat treatment of rotating shaft exhibits a characteristic vibration signature. In recent years, several studies have focus on the rotating shaft dynamics behavior along with different material treatment processes in the literature. Cryogenic process is one of used types of heat treatments. It is a processing of the material at a temperature below $-140^\circ C$ resulting in modification of its
microstructure. The cryogenic process enhances the conversion from austenitic phase to martensite phase. The deep cryogenic treatment is permanent treatment offering the entire part not just the surface.

A substantial amount of extant literatures have reported [1–6] on deep cryogenic treatment processing since it has a large range of applications in materials processing to improve the properties of steel. However, to the best of authors knowledge, very few publications can be found available in the literature that addresses the vibration damping ability of deep cryogenic treated shaft.

The influence of cryogenic treated rotating shaft made of AISI 4140 steel on the performance of rotating shaft system has been studied by [7]. It was shown that vibration amplitude values of the cryogenically treated shaft were lower when compared to that of conventional treated one. Kam et al. experimentally investigated and compared the role of cryogenic and induction surface hardening treatment considering the vibration resistance of the AISI 4140 steel shaft. It was shown that cryogenic treated shaft demonstrated higher amplitudes perturbation of vibration compare to the induction surface hardened shaft [8]. Kam and Saruhan experimentally tested and compared raw material, conventional heat treated, and deep cryogenic treated shafts in terms of stability of rotating shaft system. It was shown that deep cryogenic treated shaft had lower displacement amplitudes values and good stability characteristics compare to the others [9]. Also, cryogenic and forging treated shafts supported by rolling elements bearings were experimentally analyzed in terms of vibration. It was shown that cryogenic treated shaft was more stable than forging treated one [10]. Nowadays, it is commonly considered to use the materials which have the high damping capacity for acceptable vibration level. The motivation of this study is to figure out the effect of cryogenic treatment with respect to different temper hold times in improving dynamics behavior of rotating shaft system in terms of damping ability.

2. Experimental Setup

All experiments were utilized to examine the vibration behavior characteristics of rotating shaft made of AISI 4140 steel having distinct chemical and mechanical characteristics which make it valuable for different applications in rotating machine systems. Ten experimental sets of the shaft were employed. The sets configurations are given in Table 1.

In order to obtain different configurations of mechanical properties of the shaft material, treatment process cycles are given as follows:

**Step 1**- Standard (untreated) shaft

**Step 2**- Heating from room temperature to pre-heating temperature (420 °C) and holding for 30 minutes.

**Step 3**- Heating to austenitizing temperature (850 °C) and holding for 30 minutes.

**Step 4**- Cooling from austenitizing temperature to room temperature called as oil quenching and holding for 20 minutes.
**Step 5**- Re-heating the shaft to temperature (320 °C) to obtain pre-tempering and holding for 2 hours then cooling to room temperature.

**Step 6**- Cooling continues from pre-tempering temperature to − 140 °C and holding for temper hold times (12, 24, 36 and 48 hours) then as desired re-heating to room temperature.

**Step 7**- Re-heating the shaft continues for post-tempering to temperature (200 °C) and holding for 2 hours then cooling to room temperature.

The schematic diagram of heat treatment process cycles for the shafts used in experiments is shown in Fig. 1.

Figure 2 shows the test apparatus for vibration behavior characteristics analysis of treated rotating shafts supported by two rolling element bearings fitted in the housings. A 0.5 hp induction motor equipped with speed controller providing speeds up to 3000 rpm is employed to drive shaft via Lovejoy coupling that provides a damping effect so that any vibration coming from the motor should be minimized. The length of the shaft between the bearings is 177 mm. Loads are provided by two disk mounted unsymmetrically on the shaft at different locations between the bearings and an overhunged fan to excite the shaft to orbit.

Vibration from the inboard bearing (close to the motor) and outboard bearing were measured in both vertical (Ch1 and Ch3) and horizontal (Ch2 and Ch4) directions using four accelerometers respectively. Two non contacting eddy current probes were used to measure the vertical (Ch5) and horizontal (Ch6) motions of the shaft simultaneously. The probes are threaded in the holes of rigid support and secured to a 1.092 mm distance from the shaft. One tachometer is used to measure the shaft rotating speed. A data acquisition board (Spectra Quest software and hardware) is employed for data collection which has built in anti-aliasing filters.

### 3. Results And Discussions

The spectrum peaks of vibration signals for rotating shafts (S, CHT, DCT12, DCT24, DCT36, DCT48, DCTT12, DCTT24, DCTT36, and DCTT48) at running speed of 3000 rpm were larger than those at 600, 1200, 1800, and 2400 rpm. So, the vibrations of rotating shafts at running speed of 3000 rpm are presented.

Figure 3 gives four channels (Ch1, Ch2, Ch3, and Ch4) plots in one graph for shafts running at speed of 3000 rpm. Plots give the vibration signals captured from inboard and outboard rolling element bearings in the vertical (Ch1 and Ch3) and horizontal (Ch2 and Ch4) directions respectively.

The abscissa gives the frequency in hertz (Hz) while the ordinate is the vibration amplitude in gRMS which gives the amount of energy contained in the vibration. It can be seen from the DCT36 shaft plots that a low energy vibration is clearly observed. This indicates that temper hold time improves toughness
properties of rotating shaft to withstand vibration. Thus, damping ability of the shaft increased to absorb vibrational energy. However, temper hold time over 36 hours for DCT shaft does not bring significant improvements but for DCTT48 shaft. It can be noted that temper hold time of 36 hours are enough to obtain low vibration comparing to the other temper hold times in general.

Response vibration amplitudes in the vertical (Ch5) and horizontal (Ch6) directions within the operating range of rotating shafts are given as bode plots in Figure 5 for enhancing information. In the plots, the speed at which amplitude of vibration is maximum is noted and the minimum vibration amplitude values are observed in the cases of DCT36 and DCTT48 shafts. Also vibration displacement in the vertical (Ch5) and horizontal (Ch6) directions are combined together to obtain orbit plots are shown in Figure 6 that provide a footprint of the movement of the center of rotating shafts. It can be seen that the DCT36 shaft in relation to horizontal probe moves between + 0.1 mil (0.0254 mm) and - 0.05 mil and for the vertical probe between + 0.1 mil and – 0.1 mil. From the results, it is shown that significant reduction in vibration amplitude could be gained with modest temper hold times.

4. Conclusion

The dynamic response of rotating shaft due to vibration is primary concern in rotating shaft systems. The motivation of this study is to figure out the influence of cryogenic treatment hold time in improving structural vibration damping of the rotating shaft vibration damping can be significantly improved with use of proper treatment processing. Low structural damping of the rotating shaft degrades the stability by increasing the amplitude of vibration response. Cryogenic treatment processing gives inherent higher structural damping to rotating shaft. So, reduction in vibration amplitude could be obtained with increases in structural damping of the rotating shaft. The results obtained when adopting different treatments and temper hold times for the rotating shafts. Results showed that the variation of structural damping of the rotating shaft was varied by changing temper hold time condition. Damping ability of the rotating shaft was dependent upon temper hold time. It can be concluded that temper hold times in cryogenic treatment of the rotating shaft materials have to be chosen with care in order to maintain low vibration.

Declarations

Availability of data and materials

Not applicable

Competing interests

The authors declare that they have no competing interests

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No funding was received for conducting this study.

Authors' contributions

MK analyzed the data of experiments and prepared the design of the study, analysis, interpretation of data and in writing the manuscript. HS was a major contributor in writing the manuscript. All authors read and approved the final manuscript.

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Tables
Table 1. Sets configurations for experiment

| Set Code | Step 1 | Step 2 | Step 3 | Step 4 | Step 5 | Step 6 | Step 7 |
|----------|--------|--------|--------|--------|--------|--------|--------|
| S        | ✓      | ✓      | ✓      | ✓      | ✓      | ✓      | ✓      |
| CHT      | ✓      | ✓      | ✓      | ✓      | ✓      | ✓      | ✓      |
| DCT12    | ✓      | ✓      | ✓      | ✓      | ✓      | ✓      | ✓      |
| DCT24    | ✓      | ✓      | ✓      | ✓      | ✓      | ✓      | ✓      |
| DCT36    | ✓      | ✓      | ✓      | ✓      | ✓      | ✓      | ✓      |
| DCT48    | ✓      | ✓      | ✓      | ✓      | ✓      | ✓      | ✓      |
| DCTT12   | ✓      | ✓      | ✓      | ✓      | ✓      | ✓      | ✓      |
| DCTT24   | ✓      | ✓      | ✓      | ✓      | ✓      | ✓      | ✓      |
| DCTT36   | ✓      | ✓      | ✓      | ✓      | ✓      | ✓      | ✓      |
| DCTT48   | ✓      | ✓      | ✓      | ✓      | ✓      | ✓      | ✓      |

S-Standard shaft, CHT -Conventional Heat Treatment, DCT -Deep Cryogenic Treatment, DCTT -Deep Cryogenic Treatment and Tempering

Figures
Figure 1

Schematic diagram of heat treatment process cycle
Test apparatus; (1) Base, (2) Rubber isolators, (3) Extented deck, (4) Motor, (5) Speed controller, (6) Tachometer, (7) Rolling element bearings, (8) Bearing housing, (9) Shaft (10) Lovejoy coupling, (11) Rigid support for proxy probes, (12) Disk (5.04 kg), (13) Proxy probe, (14) Accelerometer, (15) Fan, (16) Disk (0.684 kg).

Figure 2

Schematic drawing of test apparatus.
Figure 3

Time domain plots
Figure 4

Bode plots of run up
Figure 5

Orbit plots for the vertical and horizontal positions of the shafts.