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Temperature measurement in a turbine stator assembly using an integratable high temperature ultrasonic sensor network

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ABSTRACT

Implementation of an integratable ultrasonic sensor network with associated cable connection for high temperature monitoring applications is demonstrated through application of a three-element ultrasonic sensor network for temperature measurement in a turbine stator assembly. The sensor network is composed of a piezoelectric composite film deposited on a titanium substrate with a sol-gel technique and three top electrodes deposited on the piezoelectric film. The sensor network is glued onto a selected area of the stator assembly in such a way that three subareas with different wall thicknesses are probed individually by each of the sensing elements. The ultrasonically instrumented stator assembly is first heated in a furnace to different temperatures. At each temperature and for each probed location the transit time of ultrasonic waves through assembly wall thickness is measured. Then a relationship between transit time and wall temperature is established. In a subsequent experiment, the stator assembly is heated up to 200 °C and then let cool down while the transit time in the assembly wall is being measured continuously. By using the transit time versus temperature relationship obtained earlier, the heating and cooling rates at the three probed locations are determined and then compared.

Keywords: Ultrasonic sensor network, integratable ultrasonic sensors, high temperature ultrasonic sensors, ultrasonic temperature measurement, turbine stator assembly

1. INTRODUCTION

Non-destructive ultrasonic inspection of industrial facilities at elevated temperatures is important for industries such as petroleum refinery, nuclear power generation, aerospace and manufacturing. The ability to integrate ultrasonic transducers into a facility for on-demand or continuous inspection without interrupting the service provided by the facility is highly desirable. There are a number of approaches to integrate ultrasonic transducers into a structure under inspection. The most used approaches are to clamp or bond sensing assemblies on the structure. GE's Rightrax HT system is an example of the clamping approach, whereas SMART Layer® piezoelectric transducers from Acellent Technologies Inc. and piezoelectric PZT (Lead zirconate titanate) packages from Metis Design Corporation (MDC) are good candidates for the bonding approach. Embedding is another way to integrate ultrasonic transducers into a structure. Minimal transducer footprint is usually a much desired feature for embedded applications. In this regard, piezoelectric PVDF (Polyvinylidene Fluoride) films and low-profile flexible ultrasonic transducers¹ could be good candidates. A third approach to integrate an ultrasonic transducer is to deposit the transducer directly on the structure component under inspection. Transducer deposition via PZT sol-gel spray² and aluminum nitride (AlN) room temperature sputtering³ appear to be promising. It is to note that among the above mentioned transducers, the PZT sol-gel sprayed and AlN sputtered transducers may be the only two types suitable for integrated applications at above 120 °C. Others may either be too bulky (Rightrax HT) or limited to lower temperatures due to PVDF or packing materials used.

In the present study, we explored the bonding approach to integrating PZT sol-gel sprayed high temperature low-profile flexible ultrasound transducers (FUT) to a structure. Different from SMART Layer® and MDC sensor assemblies in which electrical wires are integrated part of the sensor assembly, we used detachable wiring for electrical connection. This combination of bondable low-profile flexible transducer and detachable electrical wiring is beneficial in following aspects: (1) Transducers can be prefabricated in mass without being constrained by site limitations at the facility to be

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inspected, and as a consequence, larger quantity (which usually leads to lower costs) and higher quality could be achieved compared with on-site transducer fabrication or direct transducer deposition on the component; (2) Owing to its low-profile and flexibility, the flexible transducers can be bonded on flat and curved surfaces; (3) Wires can be serviced or replaced easily without removing the transducers already bonded on the structure; (3) Excessive mechanical stress exerted on wires may not damage transducers since wires and transducers are not physically bonded; (4) Electric cables can be connected to transducers only when inspection is to be performed. After inspection, the electrical cables can be removed conveniently, thus leaving the area clean after inspection and also eliminating the risk of damaging transducers due to unattended cables; (5) Plastic-free higher temperature electrical cables can be used.

As a demonstration of the proposed sensor integration approach, we installed a three-element ultrasonic sensor network on an aircraft turbine stator assembly for temperature measurement at up to 200 °C at three locations in the stator assembly. Different from traditional ultrasound velocity based temperature measurement which requires measurements of differences in arrival times of and in distances travelled by two echoes, we used an ad hoc method which only required that the arrival time of one echo be measured.

2. EXPERIMENTAL

2.1 Transducer fabrication

A piezoelectric PZT layer was deposited on a 75- μm -thick titanium membrane using a PZT sol-gel based fabrication process^{1,2, 4}. The process consists of six main steps: (1) preparation of high dielectric constant PZT solution, (2) ball milling of PZT powders to submicron size, (3) sensor spraying using slurries from steps (1) and (2) to form a thin film, (4) heat treating to produce a thin solid PZT composite (PZT-c) film, (5) Corona poling to obtain piezoelectricity, and (6) electrode painting for electrical connectivity. Steps (3) and (4) are repeated multiple times to produce optimal film thickness for specified ultrasonic operating frequency and performance. Silver or platinum paste was used to fabricate top electrodes. In this study, Steps (3) and (4) were repeated 10 times to form an 80- μm -thick PZT layer with operating frequencies centered at 11 MHz. Because of the thin titanium membrane used, the transducer is quite flexible and therefore termed as “flexible ultrasonic transducer” (FUT). This FUT has the following nice features: (1) It can be used at temperatures up to 200 °C; (2) It can be made small or big depending on applications; (3) It can conform to curved surfaces; (4) A transducer network can be formed easily by making multiple top electrodes (with a paint pen filled with a conductive paste) on the same PZT film. It is to note that a 500 °C FUT can be fabricated by depositing a piezoelectric bismuth titanate (BIT) composite (BIT-c) film on a substrate¹. Figure 1 illustrates an FUT fabricated.

Figure 1. An FUT fabricated.

2.2 Transducer integration

A piece of $36\text{ mm} \times 11\text{ mm} \times 75\mu\text{m}$ titanium strip coated with an $80\text{-}\mu\text{m}$ -thick, 30-mm -long and 3-mm -wide PZT-c film was bonded to the surface of an turbine stator assembly by using a high temperature adhesive and with help of a mechanical clamping setup illustrated in Figure. 2. The adhesive was cured at room temperature according to application instruction. Then top electrodes were painted at three locations on the PZT-c film to form a three-element ultrasonic sensor network (Figure 3). The locations of the top electrodes were selected in such a way that three subareas with different wall thicknesses could be probed individually by each of the sensing elements.

Figure 2. Setup for bonding a flexible ultrasound transducer onto a turbine stator assembly.

Figure 3. Photo on the left shows locations of three ultrasound transducers (UTs) as determined by the positions of three silver paste dots. Photo on the right displays an end section of the turbine stator assembly. The internal wall profile along the circumferential direction of the assembly was identical to that of the end section shown in the figure. Red lines in the figure indicate where each individual UT would be located in a cross-section passing through these UTs. Each UT probed through a distinct wall thickness.

Four metallically sheathed electrical cables were held together in a way illustrated in Figure 4(a). Of the four cables, three were stripped at the end (Fig 4(b)). The cable assembly was mounted on the turbine stator with help of a stainless steel cable as shown in Fig. 4(c). To make the mounting of the electrical cable assembly stable, a stainless steel cylinder was inserted between the cable assembly holders and the fastening stainless steel cable and a turnbuckle was used for tightening. The cable assembly was positioned in such a way that each of the three stripped wires was in touch with a top electrode whereas the fourth cable, un-stripped, was in touch with the titanium substrate (Fig. 4(b)). Owing to the electrical conductivity of the metallic holders and that of the metallic sheaths, all three signal cables shared the same ground as the transducer substrate.

(a)

(b)

(c)

Figure 4. Electrical cable assembly (a), its connection to FUT (b), and its mounting on the turbine stator assembly (c).

2.3 Experimental setup

The ultrasonically instrumented turbine stator assembly was placed in a mechanical convection oven (DKN 600) and was heated up or cooled down to different temperatures at different speeds (Fig. 5). In the mean time, air temperature in the oven as well as ultrasonic signals generated and received by the three UTs were recorded simultaneously with a one-channel ultrasonic system (SIMIS) and a two-channel ultrasonic system (GIMIS), both from PACE Simulations Inc. The ultrasonic signal sampling frequency was 100 MHz at each channel.

Figure 5. Experimental setup.

3. RESULTS AND DISCUSSION

We started the experiment by heating up the turbine stator assembly to 8 preset temperatures from 25 °C to 200 °C by increments of 25 °C. About 1 hour was allowed for the stator assembly to reach thermal equilibrium following each increase of set temperature. Then air temperatures in the oven as well as ultrasound signals generated and received at three transducer locations were recorded. Each UT was operated in pulse/echo mode whereby a diagnostic pulse wave was transmitted by the UT to the stator. The transmitted wave was reflected back and forth several times inside the stator between two opposing surfaces as shown in Figure 6, resulting in multiple echoes captured by the same UT. Figure 7 displays 1st echoes obtained at three UT locations at 31.5 °C. To facilitate comparison, a same time scale is applied in the figure although a different signal acquisition window was used for a different UT. As can be seen in the figure, the 1st echo received by UT1 arrives first whereas that received by UT2 arrives last due to different wall thicknesses probed by the UTs (see Fig. 3).

Figure 6. Illustration of multiple echoes travelling through the stator assembly wall thickness.

Figure 7. First echo signals obtained at three UT locations.

Figure 8. Ultrasound signals received at UT3 location at 25 °C (blue) and 200 °C (red).

Figure 8 shows ultrasound signals obtained at UT3 location at 25 °C and 200 °C, respectively. Compared with the signal obtained at 25 °C, that obtained at 200 °C is weaker and arrives later due to lower piezoelectric strength of the PZT-c film and lower ultrasound velocity in the stator assembly at a higher temperature.

Variation of ultrasound velocity with temperature illustrated in Figure 8 is an acoustic characteristic of a vast majority of materials and has been widely used for ultrasonic temperature measurement. In order to determine ultrasound velocity, measurements of differences in arrival times of and in distances travelled by two echoes are usually required. The applicability of this approach could be compromised by a lack of parallelism between two interfaces at which acoustic waves are reflected, a lack of similarity between two echoes caused by beam spreading, wave diffraction, and wave absorption, a lack of a 2nd echo, or inaccessibility to the probed area for thickness measurement. With a view to get around these limitations, we proposed to use only the 1st echo by following procedures described hereafter: (1) Heating up the sample to different temperatures. After the sample reaches thermal equilibrium at a preset temperature, take an ultrasound signal, measure the arrival time of the first echo, and record the temperature; (2) Establish a calibration curve between the arrival time of the 1st echo and sample temperature by using the data obtained in Step 1; (3) Utilize the established calibration curve for sample temperature measurement during a dynamic heating or cooling process. Figure 9 shows calibration data acquired at aforementioned eight preset temperatures and three UT locations at about one hour after each set temperature increase. We assume that one hour was long enough for the stator assembly to reach thermal

Figure 11 shows thus obtained results. As can be seen clearly in the figure, because of its much smaller heat capacity, the temperature of the air in the oven during the heating stage increased much faster than did the stator assembly temperatures at three UT locations. And for the same reason, the air temperature in the oven decreased much faster during the cooling stage than did the others. As can also be seen in the figure, the heating and cooling rates were different at three UT locations.

Figure 11. Evolution of temperatures during a dynamic heating and cooling process. Left: Global view; Right: A zoomed view into the cooling stage.

4. CONCLUSIONS

Integration of a three-element ultrasonic sensor network to a turbine stator assembly has been presented. The integration consists of bonding a flexible piezoelectric PZT composite membrane to a surface area of the stator assembly, depositing top electrodes at selected locations, and attaching a removable wiring assembly to the sensor network. Advantages of the proposed integration approach have been discussed. The sensor network has been applied to determining stator assembly temperatures at three locations at up to 200 °C during a dynamic heating and cooling process. An ad hoc method has been proposed for converting arrival times of ultrasound signals to stator temperatures. Different heating and cooling rates at three probed locations have been observed.

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