DIGITAL BREAKTHROUGH DETECTION USING LASER-INDUCED, THERMAL DIFFUSION SHOCK WAVES

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Abstract

The efficiency of a jet engine is improved by increasing the temperature in the engine combustion components. Combustion chamber temperatures have increased up to 1600°C over the past decade [1]. Therefore, jet engine combustion components must deal with these increased temperatures. Free-air-flow cooling holes are critical for cooling the components, but the process of drilling cooling holes presents numerous problems. The main problem to be addressed is "back wall strike". This study looked at innovative approaches to designing controllers for the laser percussion drilling process to determine the exact moment of breakthrough that could eliminate back wall strike, which damages the adjacent surface of jet-engine turbine components. The PCB 106B pressure sensor was used to measure thermal diffusion shock waves, and National Instruments LabVIEW computer program was used to establish control algorithms. The controllers process the sensor output digitally to determine the exact moment of breakthrough, thereby eliminating back wall strike. There were two methods for processing the sensor output digitally: software and hardware. In the software method, LabVIEW was used to extract pulse signal components from the sensor output and the laser power output. In the hardware method, operational amplifiers were used to extract pulse signal components from the sensor output and the laser power output. The processed sensor output showed distinctive patterns, which indicated the relationship between the laser pulse and the shock pulse at the moments of breakthrough. Therefore, the system successfully detected the breakthrough using the digital approach.

Introduction

The laser percussion drilling process at the Connecticut Center for Advanced Technology (CCAT) is shown in Figure 1. The laser beam was generated by the neodymium-doped yttrium aluminum garnet (Nd: YAG) laser of the Convergent Prima P-50 laser drilling machine at CCAT. The laser beam passed through the center of the copper nozzle and impinged upon the surface of a Waspalloy steel plate sample. The angle between the laser and sample was 20 degrees, which is the standard for cooling-hole drilling for jet engine turbine blades. After a few percussion drilling operations, the laser beam started penetrating the sample and making a small diameter hole on the sample surface; this process is known as partial breakthrough. At the next laser shot, the laser beam completely penetrated the sample; this process is known as full breakthrough. But subsequent laser shots continuously drilled the adjacent sample surface after full breakthrough in the laser percussion drilling process of actual jet engine turbine blades. This unavoidable process is known as back wall strike. In order to diminish the effect of back wall strike, Loctite Hysol 7901 polyamide hot melt might be injected in cavities of jet engine turbine blades. But the adjacent sample surface might receive serious surface damage despite the existence of the hot melt. In order to solve this problem, the exact moment of full breakthrough must be detected by the sensor, and the controller must turn off the laser immediately at the exact moment of full breakthrough.

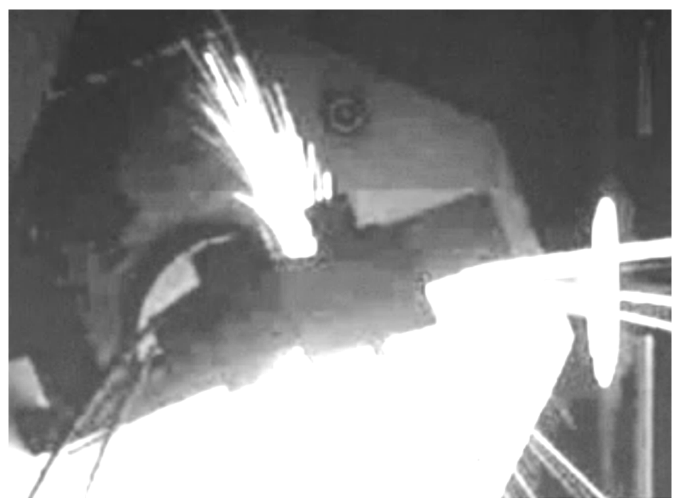

Figure 1. Laser Percussion Drilling Process at Connecticut Center for Advanced Technology (CCAT)

Many approaches have been developed to minimize the effect of back wall strike. Full breakthrough can be detected by frequency changes of the drilling sound signatures using Fast Fourier Transform (FFT). It can also be detected by spectrum changes of the percussion drilling arc. Another possibility is detection by a video camera, which would be mounted to view the area being drilled through a path coaxial with the drilling laser beam [2]. In this project, the PCB-106B pressure sensor was used to measure Laser-Induced Thermal Diffusion Shock Waves to examine the thermal contact between the laser beam and the turbine blade to detect the exact moment of full breakthrough. The output of the PCB-106B pressure sensor and the output of the laser power sensor were digitized using the software method or the hardware method to produce the shock pulse and the laser pulse. Finally, the shock pulse was subtracted from the laser pulse to detect the exact moment of full breakthrough when the laser beam completely penetrated the sample.

Related Research

The effects of Laser Induced Thermal Diffusion Shock Waves have been investigated and the fundamental equations were established by Danworaphong et al. [3] in the book "Laser Induced Thermal Diffusion Shock Waves." When a neodymium-doped yttrium aluminum garnet (Nd: YAG) laser induces a thermal diffusion shock wave, the thermodynamic properties−speed U, density r, and pressure P−are dramatically different before the shock front and after the shock front. The figure of the shock front is shown in Figure 2.

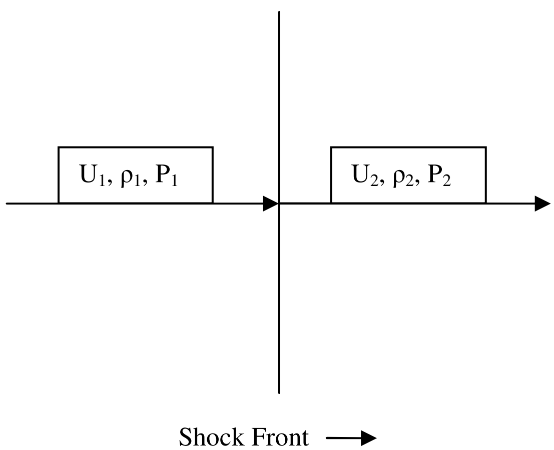

Figure 2. "Shock Front"

Thermal diffusion shock waves have several properties identical to fluid shock waves generated by supersonic flight [4]. The difference between thermal diffusion shock waves and fluid shock waves is as follows [4]:

1. Thermal diffusion shock waves depend on the existence of externally imposed temperature gradients, while fluid shock waves have no such requirement.
2. Thermal diffusion shock waves always appear as a pair of identical shock fronts that propagate in opposite directions.
3. The dissipating force is viscous damping and mass diffusion in thermal diffusion shock waves. Therefore, the speed of thermal diffusion shock waves will eventually be equal to zero even in the absence of mass diffusion.

The thermal diffusion shock waves and the mass diffusion shock waves are governed by the following equation [4]:

$$\frac{\partial c_{(z,t)}}{\partial_\tau} = \alpha \frac{\partial}{\partial_z}\{c(z,t)[1 - c(z,t)]\cos z\} + \frac{\partial^2 c(z,t)}{\partial z^2} \quad (1)$$

The significance of this equation is stated as follows [4]:

1. The first term corresponds to thermal diffusion shock waves, while the second term corresponds to mass diffusion shock waves.
2. The sinusoidal function governs the first term that represents thermal diffusion shock waves.
3. α is the thermal diffusion factor that governs the dominance of thermal diffusion shock waves over mass diffusion shock waves and is expressed as

$$\alpha = \frac{D' T_0}{D} \quad (2)$$

where

D = Mass Diffusion Constant
D' = Thermal Diffusion Constant
To = Temperature.

Partial Breakthrough and Full Breakthrough

In the percussion drilling process, the laser beam was generated by the neodymium-doped yttrium aluminum garnet (Nd: YAG) laser. It passed through the center of the copper nozzle and impinged upon the surface of a Waspalloy steel plate sample. It penetrated the sample after repeated drilling and made a small diameter hole. This condition is called partial breakthrough. At the following laser shot, the laser beam completely penetrated the sample and made a large-diameter hole. This condition is called full breakthrough. These conditions are shown in Figure 3. The diameters of these holes can be estimated using the diameter of calibration dots.

Methodology

The laser percussion drilling process setup at CCAT is shown in Figure 4. The laser beam was generated by the neodymium-doped yttrium aluminum garnet (Nd: YAG) laser of the Convergent Prima P-50 laser drilling machine at CCAT. The laser beam passed through the center of the copper nozzle and impinged upon the surface of a Waspalloy steel plate sample. The thermal diffusion shock waves were measured by the PCB-106B pressure sensor that was placed under the sample. Also, the penetrating laser power was measured by the breakthrough detector that was placed above the sample in order to confirm the moment of breakthrough that was detected by the PCB-106B pressure sensor.

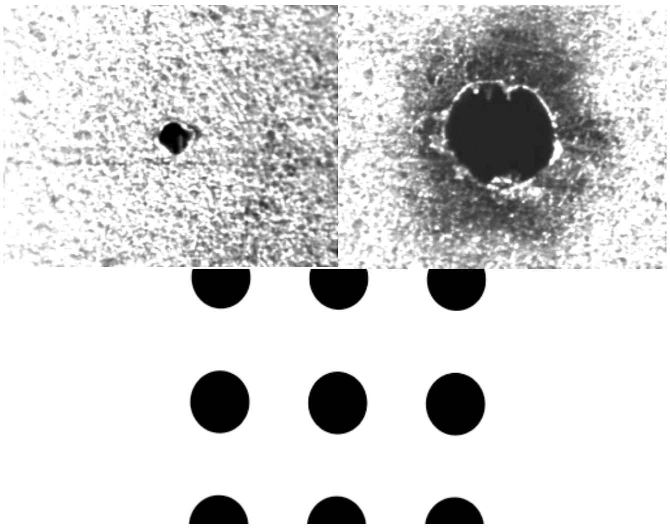

Figure 3. Partial Breakthrough, Full Breakthrough and Calibration Dots (0.25mmØ)

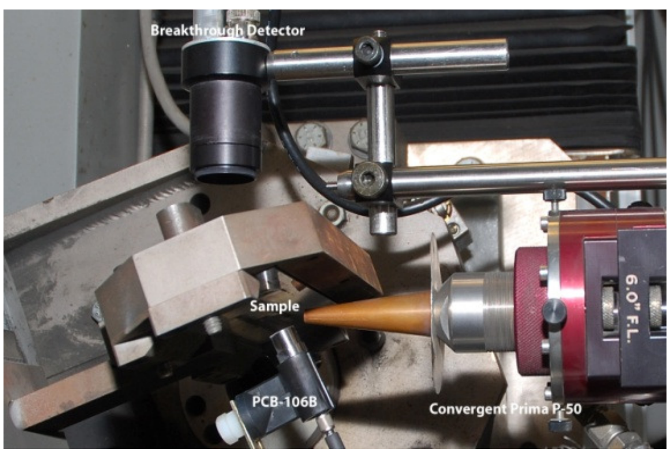

Figure 4. Laser Percussion Drilling Process Setup at Connecticut Center for Advanced Technology (CCAT) Breakthrough Detector (top) PCB 106B Pressure Sensor (bottom)

After full breakthrough, subsequent laser shots continuously drilled the adjacent sample surface in the actual laser percussion drilling process, which became the major problem to be solved. In order to eliminate the effect of back wall strike, the exact moment of full breakthrough had to be detected by processing the output of the PCB-106B pressure sensor, and the controller had to turn off the laser immediately after the exact moment of full breakthrough in order to prevent the excessive laser drilling process that damages the adjacent sample surface.

Apparatus

The National Instruments PXI-4462 Dynamic Signal Acquisition Device and the LabVIEW breakthrough detection program were used for the digital approach; the National Instruments PXI-4462 Dynamic Signal Acquisition Device is shown in Figure 5. The vertical line of the PCB106B pressure sensor output was extracted and digitized. This digital signal is called shock pulse. The laser power was also digitized. This digital signal is called laser pulse. The shock pulse was subtracted from the laser pulse in order to detect the moment of breakthrough. This process is shown in Figure 6. There are two methods to process the output of the PCB-106B pressure sensor in the digital approach: software and hardware.

Figure 5. National Instruments PXI-4462 Dynamic Signal Acquisition Device (the first module from the right) and PXIe-1062Q PXI Express Chassis

Software Method

The LabVIEW breakthrough detection program for the digital approach is shown in Figure 7. The top row of three Express VIs represents the pressure sensor block diagram that produces the shock pulse. The bottom row of three Express VIs represents the laser power block diagram that produces the laser pulse. In order to detect breakthrough, the shock pulse was subtracted from the laser pulse using the subtraction block, which is in the upper middle of the program. Also, the program recorded the following three signals in the TDMS format and saved the data on the hard drive:

1. Shock Pulse
2. Laser Pulse
3. Breakthrough Detection Signal

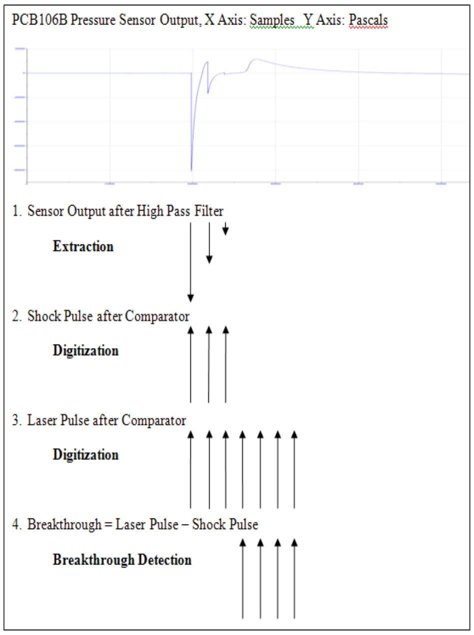

Figure 6. Breakthrough Detection Process using the Digital Approach

Hardware Method

Breakthrough Detection Circuit

The Cadence Allegro Design Entry CIS breakthrough detection schematic is shown in Figure 8. The top three rows of the operational amplifiers are the pressure sensor circuits that produce the shock pulse. The lower three rows of the operational amplifiers are the laser power circuits that produce the laser pulse. In order to detect breakthrough, the shock pulse was subtracted from the laser pulse using the subtraction circuit that is the far right operational amplifier circuit. The dual differential comparator for the pressure sensor circuits consists of six operational amplifiers, which are the left three operational amplifiers in the second and third rows. The dual differential comparator for the laser power circuits also consists of six operational amplifiers, which are the left three operational amplifiers in the fifth and sixth rows.

The schematic circuit of Figure 8 includes the following:

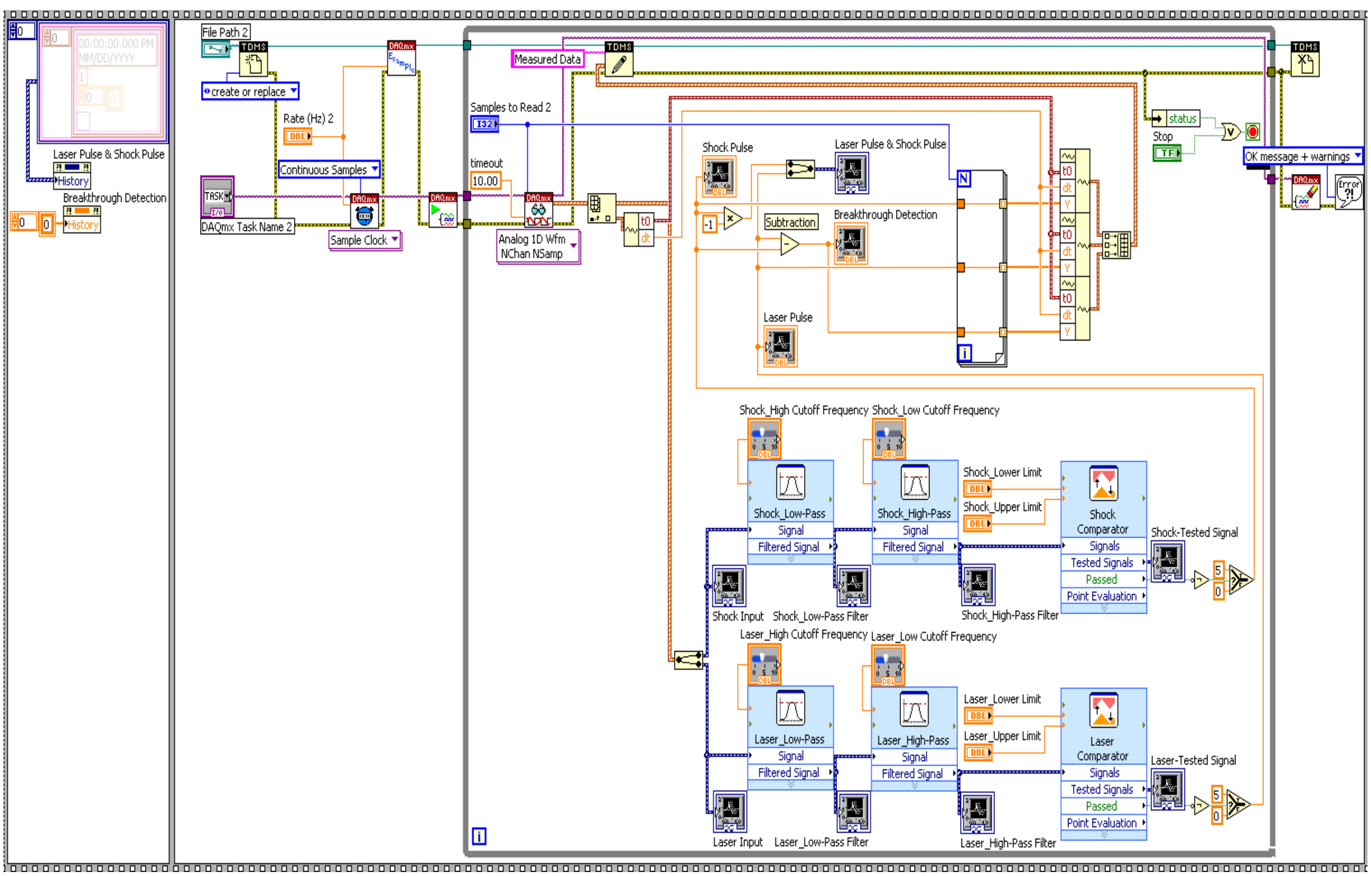

Figure 7. LabVIEW Breakthrough Detection Program for the Digital Approach

- Pressure sensor circuit (1)
- Unity-gain buffer (2)
- Low-pass filter (3)
- High-Pass Filter)4)
- Comparator (5)
- Summation (6)
- Inverter Laser Power Circuit (7)
- Unity-Gain Buffer (8)
- Low-Pass Filter (9)
- High-Pass Filter (10)
- Comparator (11)
- Summation (12)
- Inverter Subtraction Circuit (13)

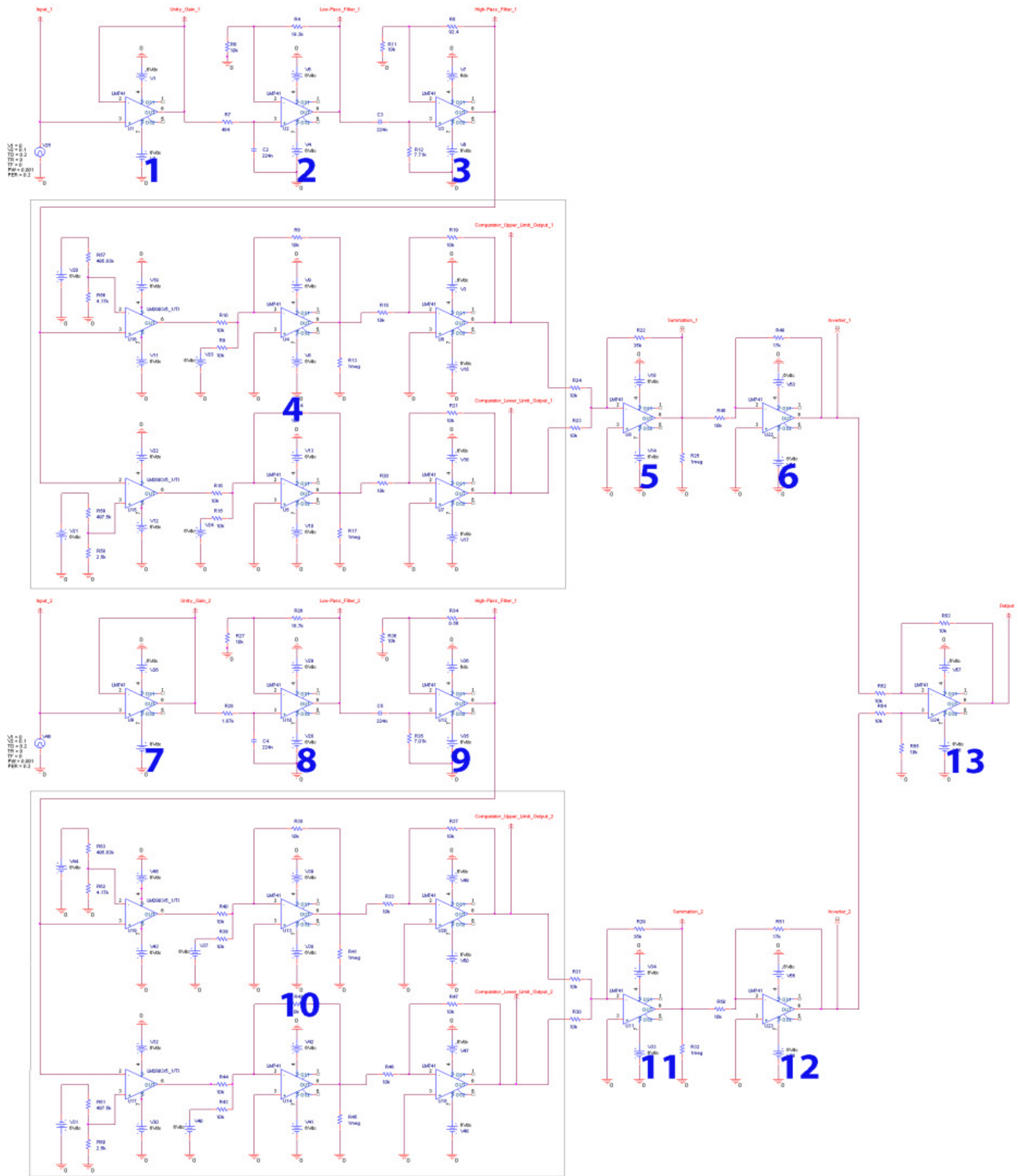

Figure 8. Cadence Allegro Design Entry CIS Breakthrough Detection Schematic

The actual circuit is shown in Figure 9. There are thirteen integral circuits. Eleven of them are operational amplifiers (NTE941M) and two of them are comparators (Texas Instruments LM2903P).

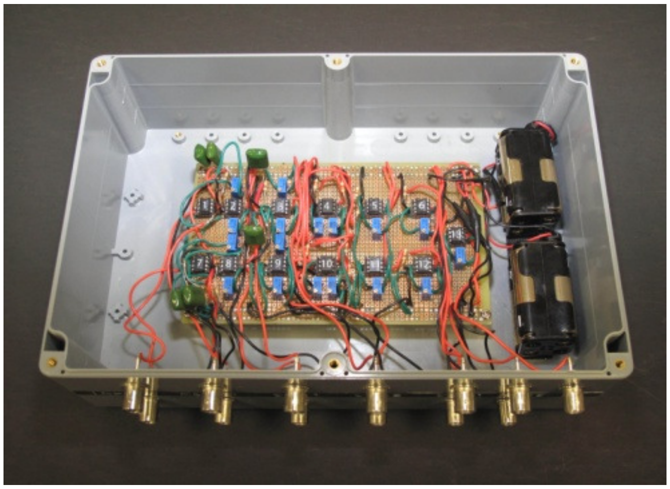

Figure 9. Breakthrough Detection Circuit

Testing Schematic

In order to test the design for the digital approach hardware method, the CIS program was exported to National Instruments Multisim, where it was simulated using the recorded TDMS file. The exported Multisim program is shown in Figure 10, and the simulation results are shown in Figure 11.

Testing Hardware

The breakthrough detection circuit was tested using the recorded data, and the data were recorded to the TDMS file using the National Instruments PXI-4462 Dynamic signal acquisition device and the LabVIEW breakthrough detection program. A sampling rate of 10kHz was used to record the data. The PCB106B pressure sensor signal and the laser pulse signal were extracted from the original TDMS file to produce the new TDMS file. This new TDMS file was played back by the LabVIEW TDMS file playback program, shown in Figure 12, to test the breakthrough detection circuit. This program has the following features:

1. It can play back the TDMS files that are recorded using any sampling rates.
2. It can play back two channels in the TDMS file simultaneously for comparison.
3. It can output the signal to any sound cards to produce the analog output waveform.

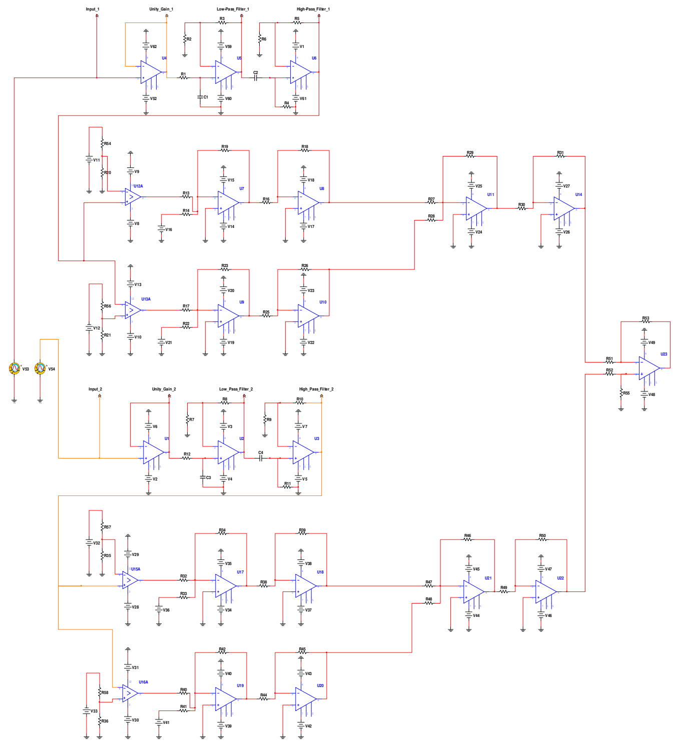

Figure 10. National Instruments Multisim Breakthrough Detection Schematic

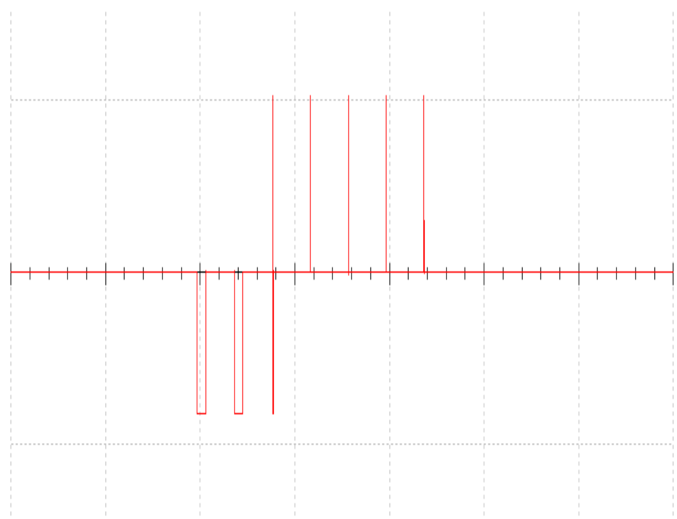

Figure 11. National Instruments Multisim Simulation Results. X Axis: Time in 500 ms/division Y Axis: Sensor Output in 5 volts/division

The Creative Sound Blaster X-Fi Titanium sound card was used to produce the analog input for the breakthrough detection circuit. The sound card can produce a fairly accurate analog signal compared to the original digital signal because of the 16-bit digital-to-analog conversion and the PCI Express bus connection.

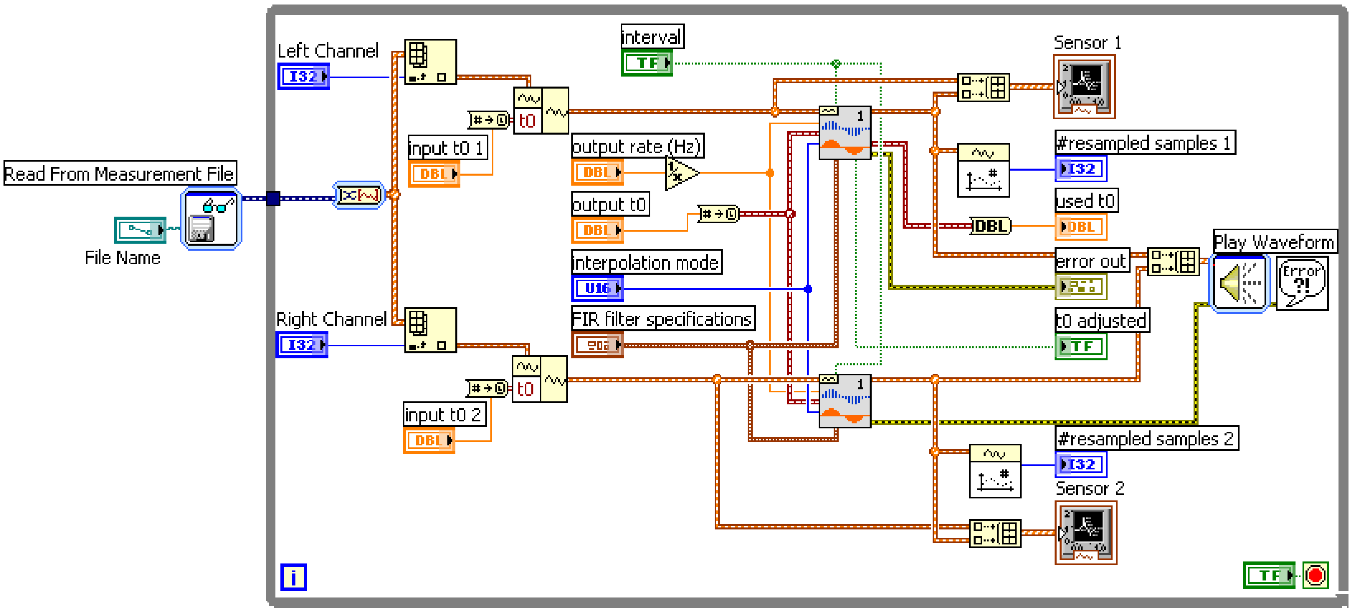

Figure 12. LabVIEW TDMS File Playback Program

Results

Software Method: Laser Pulse and Shock Pulse

Figure 13 shows the laser pulse and the shock pulse from the results. The top red line indicates the laser pulse and the bottom blue line indicates the shock pulse. The third laser shot produced partial breakthrough, while the fourth laser shot produced full breakthrough. But the third shot did not indicate partial breakthrough using this method, but rather that the laser did not penetrate the sample (refer to Figure 15 of the hardware method). The hardware result has much higher resolution and clearly shows the moment of partial breakthrough as the time delay between the laser pulse and shock pulse at the third shot.

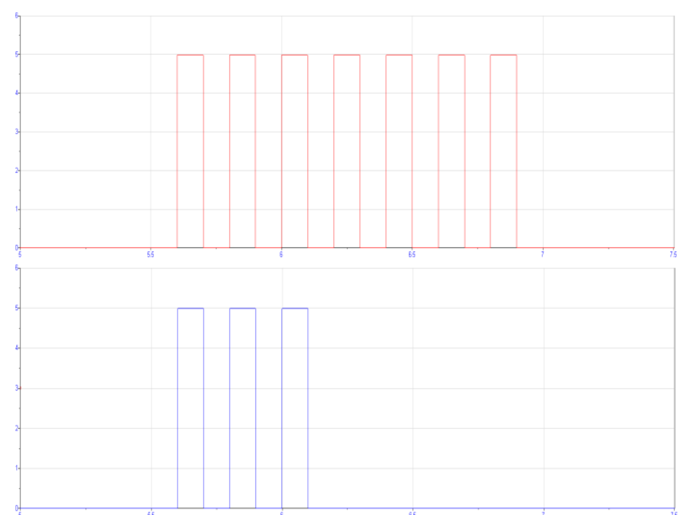

Figure 13. Laser Pulse (top) and Shock Pulse (bottom) of the Software Method. X Axis: Time in Second Y Axis: Sensor Outputs in Voltage

Software Method: Breakthrough Detection

In order to determine the moment of breakthrough, the shock pulse was subtracted from the laser pulse. Figure 14 shows the results of this subtraction or breakthrough detection. The descriptions of seven laser shots are as follows:

1. The first shot did not appear. The shock pulse was subtracted from the laser pulse, thus that result was zero.

2. The second shot also did not appear. The shock pulse was subtracted from the laser pulse, again resulting in zero.

3. The third shot also did not appear. The shock pulse was subtracted from the laser pulse yielding, again, a result of zero. Therefore, the third shot did not indicate partial breakthrough (refer to Figure 16 to compare the results of the software method to the hardware method).

4. The fourth shot was positive and indicated full breakthrough. The negative component, which was the shock pulse, completely disappeared and the positive component, which was the laser pulse, kept appearing.

5. The fifth shot was also positive. The laser beam cleaned up the existing hole.

6. The sixth shot was positive. The laser beam further cleaned up the existing hole.

7. The seventh shot was positive. The laser beam further cleaned up the existing hole.

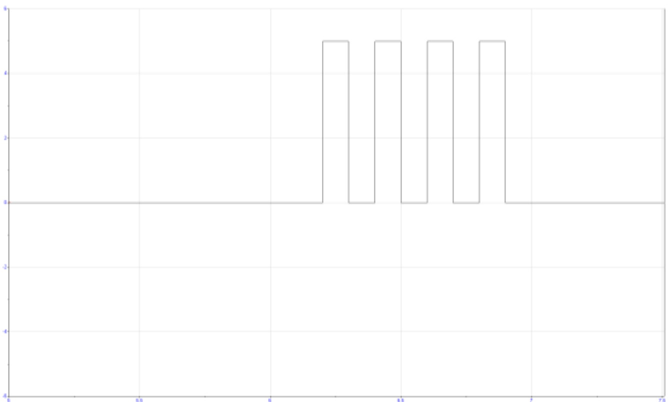

Figure 14. Breakthrough Detection of the Software Method (only fourth, fifth and sixth shots appeared)
X Axis: Time in Second Y Axis: Output in Volts

Hardware Method: Laser Pulse and Shock Pulse

Figure 15 shows the laser pulse and the shock pulse from the results. The top red line indicates the laser pulse and the bottom blue line indicates the shock pulse. The third laser shot produced partial breakthrough, where the fourth laser shot produced full breakthrough.

Hardware Method: Breakthrough Detection

In order to determine the moment of breakthrough, the shock pulse was subtracted from the laser pulse. Figure 16 shows the results of this subtraction or breakthrough detection. The descriptions of seven laser shots are as follows:

1. The first shot was negative. The negative component, which was the shock pulse, fully appeared. It indicated that drilling was in progress.

2. The second shot was also negative. The negative component, which was the shock pulse, appeared again. It indicated that drilling was still in progress.

3. The third shot was both positive and negative and produced partial breakthrough. The negative component, which was the shock pulse, partially appeared and the positive component, which was the result of the subtraction, started appearing.

4. The fourth shot was positive and produced full breakthrough. The negative component, which was the shock pulse, disappeared and the positive component kept appearing.

5. The fifth shot was also positive. The laser beam cleaned up the existing hole.

6. The sixth shot was positive. The laser beam further cleaned up the existing hole.

7. The seventh shot was positive. The laser beam further cleaned up the existing hole.

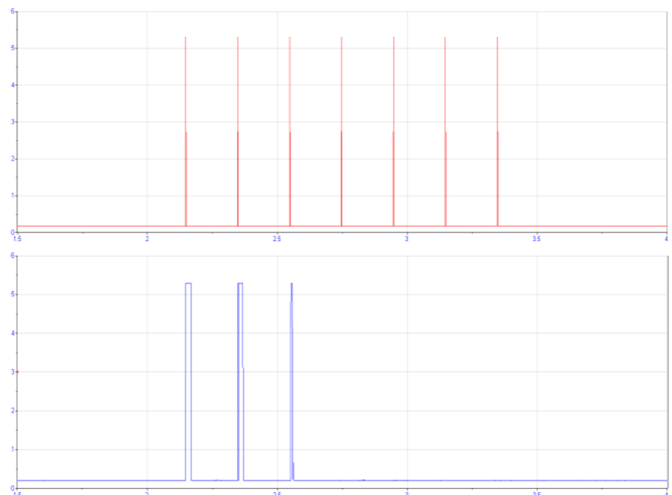

Figure 15. Laser Pulse (top) and Shock Pulse (bottom) of the Hardware Method. X Axis: Time in Second Y Axis: Sensor Outputs in Voltage

Discussion

Pressure Sensor versus Microphone

The PCBD20 ICP array microphone had been used from 2006, but was damaged by high pressure caused by the percussion drilling process in the summer of 2007. Therefore, the PCB106B series pressure sensors were recommended by PCB engineers. They decisively said that pressure caused by the percussion drilling process was beyond the microphone's measurement range. A system based on a microphone is inappropriate for the percussion drilling process because the maximum pressure reaches 81.099kPa at 1 inch from the sample. This pressure is approximately 80 percent of the theoretical pressure limit of 101.325kPa at 1 atmosphere environmental pressure [6]. Even if the distance is increased twice to decrease the pressure to 20.275kPa, it is still over the allowable maximum pressure, 15.9kPa, of the PCB377A12 microphone that has a sensitivity of 0.25mV/Pa [5]. In addition, the PCB377A12 does not provide high sensitivity for the laser-induced thermal diffusion shock waves as does the PCB106B pressure sensor. The PCB377A12 microphone is one of the lowest sensitivity microphones made by PCB and is used in a high-pressure environment. Therefore, the pressure sensor must be used in the laser percussion drilling process at CCAT to provide both the high-pressure resistance and the high sensitivity for the laser-induced thermal diffusion shock waves to establish a consistently reliable control system that works under any conditions.

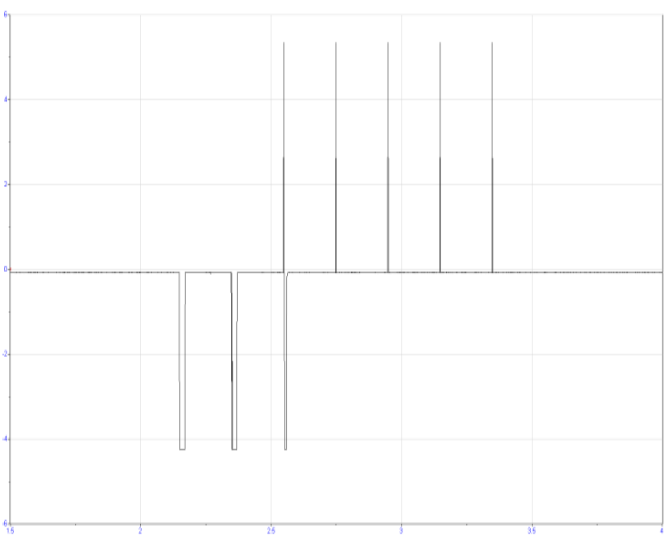

Figure 16. Breakthrough Detection of the Hardware Method X Axis: Time in Second Y Axis: Output in Voltage

Cleanup Shots

After full breakthrough, the re-solidified material might be left in the hole. A photograph of re-solidified material is shown in Figure 17. The size of it can be estimated using the diameter, 0.25mm, of the calibration dots. In order to take out the re-solidified material from the hole, cleanup shots are required after full breakthrough. But cleanup shots also continuously drill the adjacent sample surface after full breakthrough. The dilemma, then, is whether or not to continue the laser shots. Therefore, the minimum amount of laser power should be used for cleanup shots after full breakthrough.

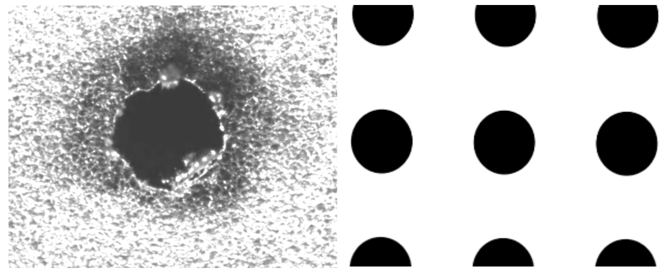

Figure 17. Re-solidified Material and Calibration Dots (0.25mm Ø)

Next Research Phases

The first fundamental experiments were accomplished in a limited time period to prove that this method is feasible. In the actual percussion laser drilling process, the turbine blade would always be rotating and all parameters continuously changing. But the exact moment of breakthrough has to be determined regardless of these unsteady conditions. Therefore, tests will be conducted under the following conditions.

1. The angle between the laser and the sample:
   Because the 20-degree laser shot is the standard for cooling hole drilling for jet engine turbine blades, this laser angle shot was used in this project. Varieties of angles will be tested to establish a consistently reliable control system.

2. The thickness of the sample:
   The thickness of the sample is significant because the 20-degree shot is the standard, and the laser beam has a relatively long distance to penetrate at this angle. But the Waspalloy samples tested here only had a thickness of 0.05 inches. Therefore, thicker samples will be tested in the future.

3. The coating of the sample:
   It is known that the thermal coating on the sample surface dramatically increases the sound signature. But coated samples have not been tested in this project. Therefore, thermal coated samples will be tested in the future.

Summary

In the digital approach, the PCB106B pressure sensor output showed distinctive patterns, which indicated the relationship between the laser pulse and the shock pulse, as shown in Figure 16. Therefore, the system successfully detected the moments of breakthrough using the digital approach. Also, these results showed that the digital approach had unique advantages and disadvantages. For example, it resulted in distinctive patterns that indicated the relationship between the laser pulse and the shock pulse. But the circuit required precise calibrations for inductance, capacitance and resistance values. Because all drilling conditions are constantly changing during actual fabrication of jet engine turbine blades, it must be tested under many different conditions to establish a consistently reliable control system that works under any conditions.

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