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. Therefore, jet engine combustion components must deal with high temperatures. Free-air-flow cooling holes are critical for cooling the components. But the process of drilling cooling holes has numerous problems, and back wall strike is the major problem that must be solved. This thesis presents innovative approaches to designing controllers to process the output of the sensor that receives laser-induced, thermal diffusion shock waves during the laser percussion drilling process. The controllers process the sensor output digitally to determine the exact moment of breakthrough to eliminate back wall strike, which damages the adjacent surface of jet-engine turbine components. There were two methods to process the sensor output digitally; the software method and the hardware method. 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 test results proved that both approaches were promising and had unique advantages and disadvantages.

Key Words: Laser-Induced, Thermal Diffusion Shock Waves, Back Wall Strike, Breakthrough

INTRODUCTION

A. Statement of the Problem

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 is 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."

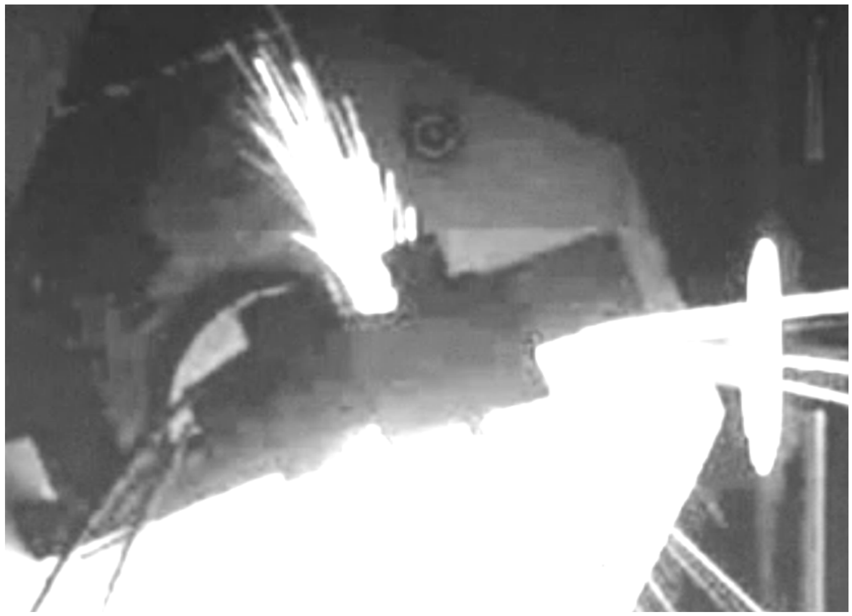


Figure 1. Laser Percussion Drilling Process at Connecticut Center for Advanced Technology

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 after the exact moment of full breakthrough. 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 the FFT. Also, it can be detected by spectrum changes of the percussion-drilling arc. It can also be detected by a video camera that is mounted to view the area being drilled through a path coaxial with the drilling laser beam [1]. In this project, the PCB-106B pressure sensor was used to measure laser-induced thermal diffusion shock waves to detect the moment of full breakthrough. The output of the PCB-106B pressure sensor was processed to show clear evidence of the moment of full breakthrough when the laser beam completely penetrated the sample.

B. Hypothesis

Temperature Changes and Laser-Induced Thermal Diffusion Shock Waves

Temperature changes are directly related to the progress of the laser percussion drilling process. The temperature of the sample dramatically increases when the laser impinges upon the sample surface, and it dramatically decreases right after full breakthrough. In order to prove the relationship between the output of the pressure sensor and the temperature conditions of the sample, the following experiments were conducted in a laboratory. A cigar lighter was ignited, and the flame was passed in front of the PCB106B52 pressure sensor as shown in Figure 2. Then it was moved away from the sensor and extinguished. The results are shown in Figure 3, and summarized as follows:

1. When the flame was passed in front of the PCB106B52 pressure sensor, the output of the second derivative was positive.
2. When the flame was moved away from the PCB106B52 pressure sensor, the output of the second derivative was negative.

Therefore, it was considered that it might be possible to determine the moment of full breakthrough by measuring the output of the pressure sensor that receives the thermal diffusion shock waves from the heat source. The major difference between this lab experiment and the laser percussion drilling experiment at CCAT was the magnitude of the thermal diffusion shock waves. The magnitude was approximately 3.5kPa in the lab experiment and approximately 81kPa in the percussion laser drilling process at CCAT. The PCB-106B52 pressure sensor was used in this lab experiment instead of the PCB106B pressure sensor because the PCB-106B52 pressure sensor provides the highest sensitivity and the lowest resolution in the PCB-106 series pressure sensors [2].

Figure 2. PCB106B52 Sensor Setup

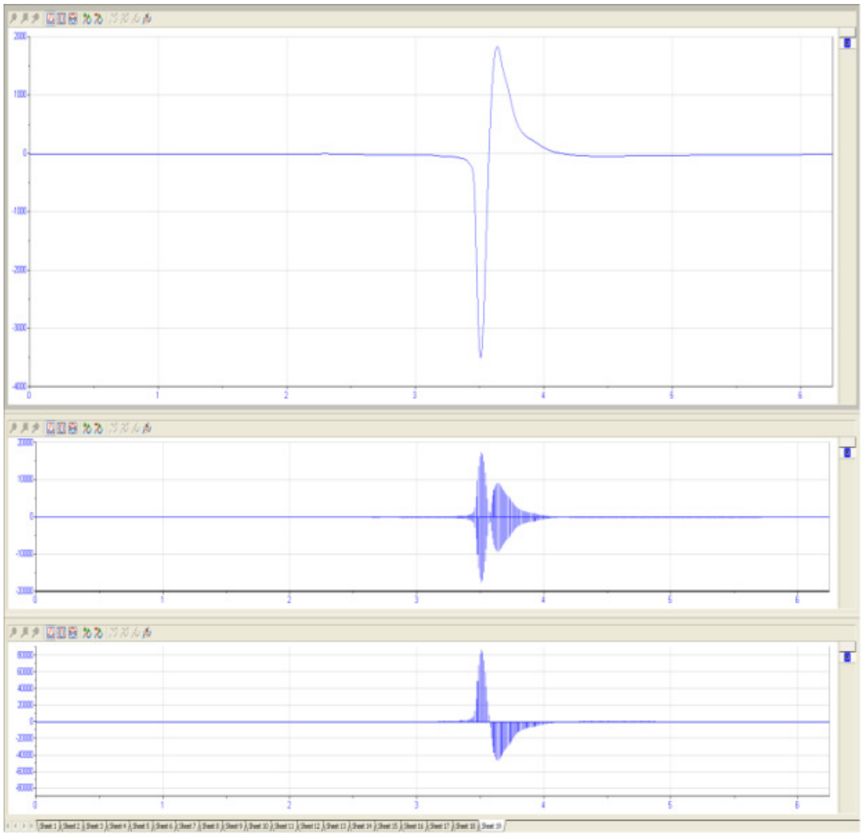


Figure 3. PCB106B 52 Pressure Sensor Output (top)
First Derivative (middle) and Second Derivative (bottom)
XAxis: Time in Second Y Axis: Sensor Output

C. Partial Breakthrough and Full Breakthrough

In the percussion drilling process, the laser beam penetrates the sample after drilling repeatedly and makes a small diameter hole. This condition is called partial breakthrough. At the following laser shot, the laser beam completely penetrates the sample and makes a big diameter hole. This condition is called full breakthrough. These conditions are shown in Figure 4. The diameters of these holes can be estimated using the diameter of calibration dots.

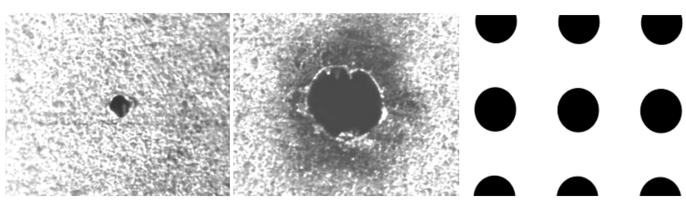
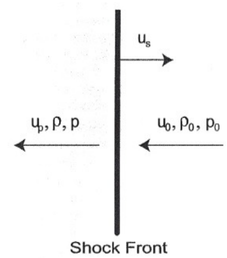


Figure 4. Partial Breakthrough, Full Breakthrough and Calibration Dots (0.25mmØ)

D. Laser-Induced Thermal Diffusion Shock Waves

The effects of laser induced thermal diffusion shock waves have been investigated and the fundamental equations were established by Sorasak Danworaphong, Gerald J. Diebold and Walter Craig 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 ρ, and pressure P−are dramatically different before the shock front and after the shock front. The figure of the shock front was extracted from the book and is shown in Figure 5 [3].



Source: Danworaphong, Sorasak, Gerald J. Diebold, and Walter Craig. *Laser Induced Thermal Diffusion Shock Waves.* Saarbrűcken, Germany: VDM Verlag Dr. Műller.
Figure 5. “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 mass diffusion in thermal diffusion shock waves. But the speed of thermal diffusion shock waves will be eventually equal to zero even in the absence of mass diffusion. The dissipating force is viscous damping in fluid shock waves.

The thermal diffusion shock waves is governed by the following equation [4]:

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

The significance of this equation is stated as follows:

1. The first term corresponds to thermal diffusion shock waves, and the second term corresponds to mass diffusion shock waves [4].
2. The sinusoidal function governs the first term, which represents thermal diffusion shock waves.

3. α is the thermal diffusion factor that is expressed as follows:

$$\alpha = \frac{D' \, T_0}{D} \tag{2}$$

D’ is the thermal diffusion constant, D is the mass diffusion constant and To is the temperature. This α is the magnitude that governs the dominance of thermal diffusion shock waves over mass diffusion shock waves [4].

METODOLOGY

A. Setup

The laser percussion drilling process setup at CCAT is shown in Figure 6. 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. After full breakthrough, subsequent laser shots continuously drilled the adjacent sample surface, and this condition is the major problem in the laser percussion drilling process.

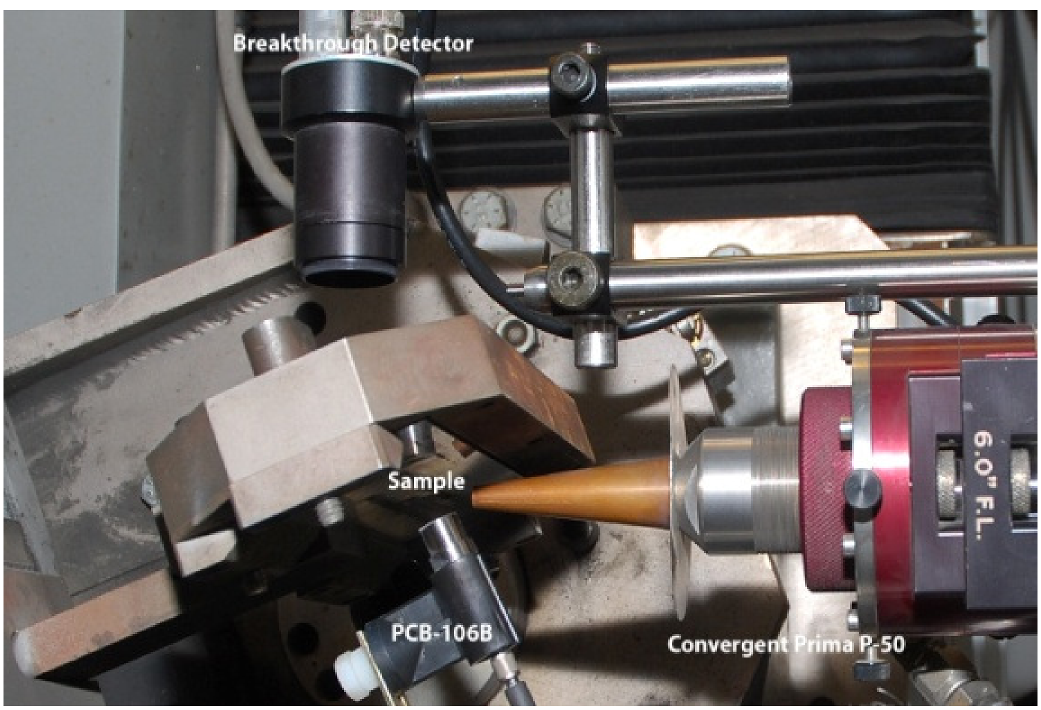


Figure 6. Laser Percussion Drilling Process Setup at Connecticut Center for Advanced Technology (CCAT), Breakthrough Detector (top) and Pressure Sensor (bottom)

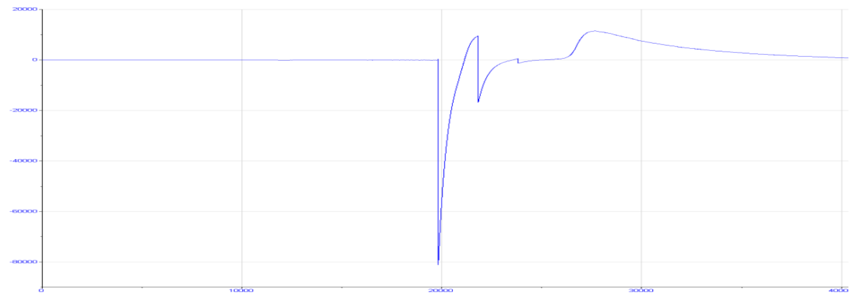
In order to eliminate the effect of back wall strike, the exact moment of full breakthrough must be detected by processing the output of the PCB-106B pressure sensor, and the controller must turn off the laser immediately after the exact moment of full breakthrough. There are two approaches to process the output of the PCB-106B pressure sensor, the analog approach and the digital approach, and the analog approach is focused in this paper.

APPARATUS

The National Instruments PXI-4462 Dynamic Signal Acquisition Device and the LabVIEW breakthrough detection program were used for the analog approach; the National Instruments PXI-4462 Dynamic Signal Acquisition Device is shown in Figure 7. This analog approach uses LabVIEW to differentiate the PCB106B pressure sensor output twice to get the second-derivative output that indicates temperature changes of the sample during the percussion laser drilling process. When the laser beam impinges upon the sample surface, the sample is in the heating stage, and the second-derivative value becomes positive. When the laser beam completely penetrates the sample after full breakthrough, the sample is in the cooling stage, and the second-derivative value becomes negative. When the absolute value of the negative second-derivative value exceeds a certain threshold value, it is considered full breakthrough, and the resulting signal shows a clear indication of full breakthrough to turn off the laser to prevent back wall strike.

Figure 7. National Instruments PXI-4462 Dynamic Signal Acquisition Device (the first module from the right)

PCB106B Pressure Sensor Output, X Axis: Samples Y Axis: Pascals



1. Sensor Output after High Pass Filter

Extraction

2. Shock Pulse after Comparator

Digitization

3. Laser Pulse after Comparator

Digitization

4. Breakthrough = Laser Pulse – Shock Pulse

Breakthrough Detection

Figure 8. Breakthrough Detection Process

1. Software Method

The LabVIEW breakthrough detection program for the digital approach is shown in Figure 9. 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 is subtracted from the laser pulse using the subtraction block, which is in the upper middle of the program. Finally, the program records the following three signals in the TDMS format and saves the data on the hard drive:

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

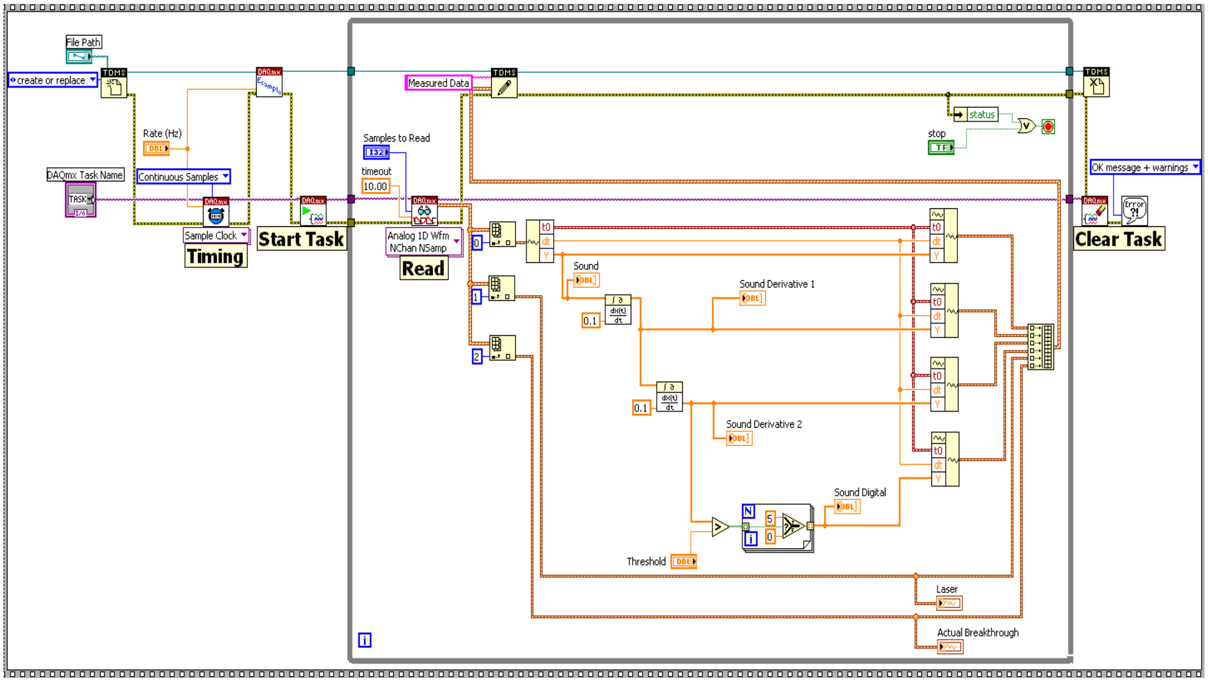


Figure 9. LabVIEW Breakthrough Detection Program for the Analog Approach

2. Hardware Method

A. Breakthrough Detection Circuit

The Cadence Allegro Design Entry CIS breakthrough detection schematic is shown in Figure 10. 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 is subtracted from the laser pulse using the subtraction circuit that is the far right operational amplifier. 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.

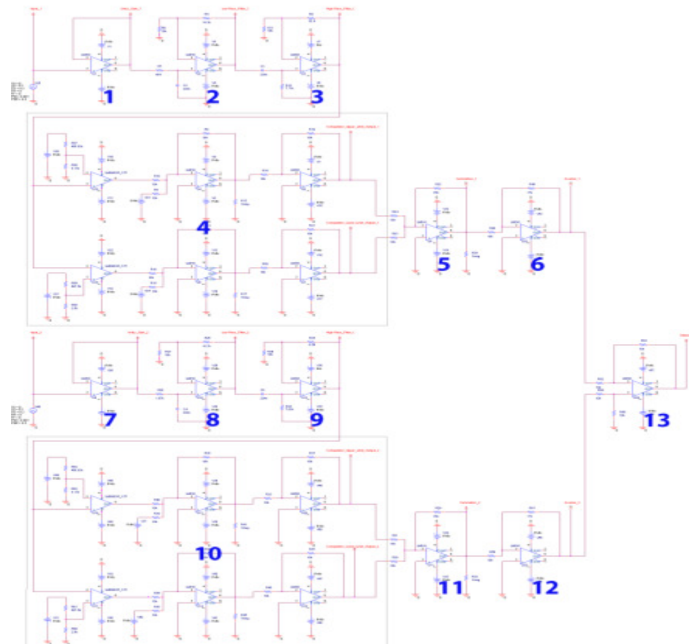


Figure 10. Cadence Allegro Design Entry CIS, Breakthrough Detection Schematic

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. Subtraction

The actual circuit is shown in Figure 11. There are thirteen integral circuits. Eleven of them are operational amplifiers (NTE941M), and two of them are comparators (Texas Instruments LM2903P). Their functions are as follows:

First Raw ICs: Pressure Sensor Circuit

1. Unity-Gain Buffer 2. Low-Pass Filter 3. High-Pass Filter 4. Comparator 5. Summation 6. Inverter

Second Raw ICs: Laser Power Circuit

7. Unity-Gain Buffer 8. Low-Pass Filter 9. High-Pass Filter 10. Comparator 11. Summation 12. Inverter

Far Right IC: Subtraction Circuit

13. Subtraction

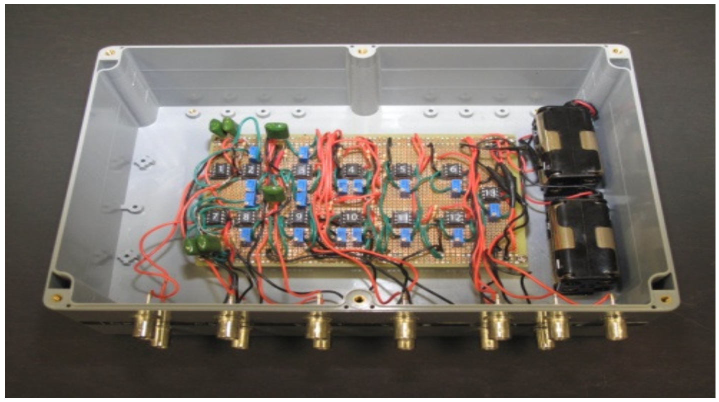


Figure 11. Breakthrough Detection Circuit

B. Testing Hardware

The data was recorded to the TDMS file using the National Instruments PXI-4462 Dynamic signal acquisition board and the LabVIEW breakthrough detection program. The 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, which is 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.

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.

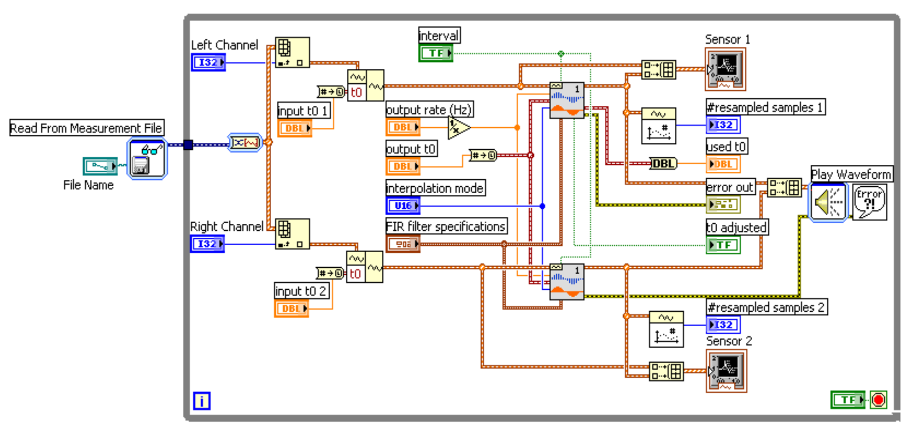


Figure 12. LabVIEW TDMS File Playback Program

Results

A. Digital Approach software Method

Laser Pulse and Shock Pulse

Figure 13 shows the laser pulse and the shock pulse from the result. The top red line indicates the laser pulse, and the bottom blue line indicates the shock pulse. The third laser shot produced partial breakthrough, and the fourth laser shot produced full breakthrough. But the third shot did not indicate partial breakthrough using this method and indicated that the laser did not penetrate the sample. Please refer to Figure 15 and Figure 16 of the hardware method. These results have much higher resolution and clearly show the moment of partial breakthrough as the time delay between the laser pulse and shock pulse at the third shot.

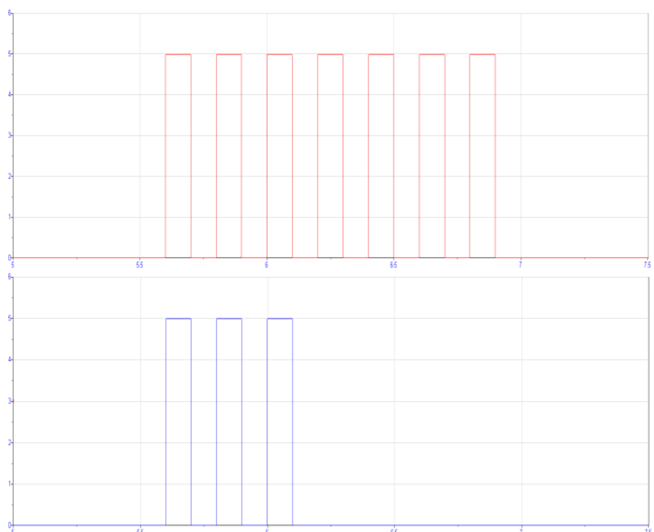


Figure 13. Laser Pulse (top) and Shock Pulse (bottom) of the Software Method
X Axis: Time in Second Y Axis: Sensor Outputs in Voltage

Breakthrough Detection

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

1. The first shot did not appear. The shock pulse was subtracted from laser pulse, so that result was zero.
2. The second shot also did not appear. The shock pulse was subtracted from laser pulse again, so that result was also zero.

3. The third shot also did not appear. The shock pulse was subtracted from the laser pulse again, so that result was also zero. Therefore, the third shot did not indicate partial breakthrough. Please refer to Figure 15 and Figure 16 to compare the results of the software method and 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 also positive. The laser beam further cleaned up the existing hole.
7. The seventh shot was also positive. The laser beam further cleaned up the existing hole.

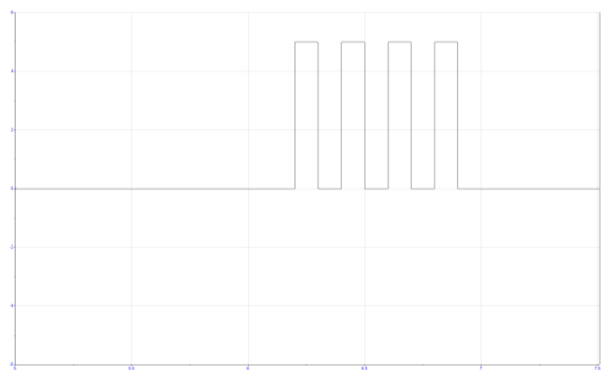


Figure 14. Breakthrough Detection of the Software Method (only fourth, fifth and sixth shots appeared) X Axis: Time in Second Y Axis: Output in Volts

B. Digital Approach Hardware Method

Laser Pulse and Shock Pulse

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

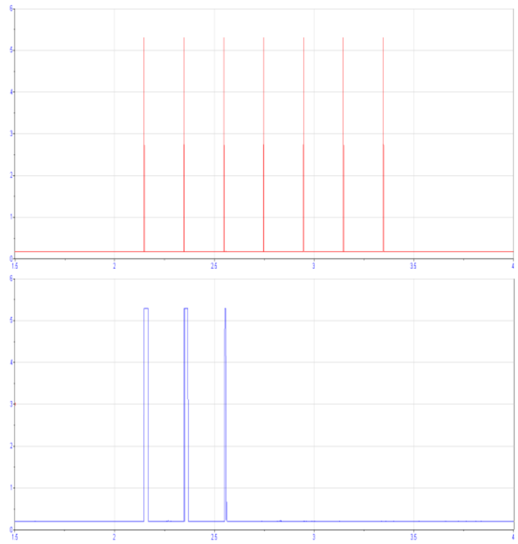


Figure 15. Laser Pulse (top) and Shock Pulse (bottom) of the Hardware Method
X Axis: Time in Second Y Axis: Sensor Outputs in Voltage

Breakthrough Detection

In order to determine the moment of breakthrough, the shock pulse is subtracted from the laser pulse. Figure 16 shows the results of this subtraction that is 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 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 also positive. The laser beam further cleaned up the existing hole.
7. The seventh shot was also positive. The laser beam further cleaned up the existing hole.

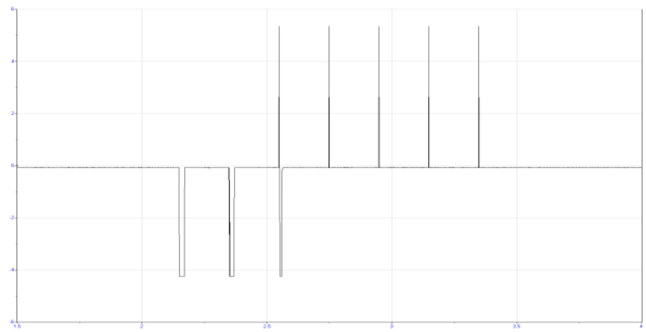


Figure 16. Breakthrough Detection of the Hardware Method
X Axis: Time in Second Y Axis: Output in Voltage

Discussion

A. Pressure Sensor versus Microphone

The PCBD20 ICP array microphone had been used from 2006. But it was damaged by high pressure caused by the percussion drilling process in the summer of 2007. The PCB106B series pressure sensors were recommended by PCB engineers, and they have been used from the summer of 2007 to the present. In addition, PCB engineers decisively said that pressure caused by the percussion drilling process was beyond the microphone's measurement range and completely agreed that the pressure sensor was more appropriate than the microphone for breakthrough detection at CCAT. The 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 80 percent of the theoretical limit pressure of 101.325kPa at 1 atmosphere environmental pressure [5]. 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 [2]. The PCB377A12 microphone is one of the lowest sensitivity microphones made by PCB and is used in a high-pressure environment. Even if the PCB377A12 microphone is used for breakthrough detection, it does not provide high sensitivity for the laser-induced thermal diffusion shock waves as the PCB106B pressure sensor does. So the major advantages of the PCB106B pressure sensor over the microphone are the high pressure resistance and high sensitivity for the laser-induced thermal diffusion shock waves. Therefore, the pressure sensor must be used in the laser percussion drilling process at CCAT to establish a consistently reliable control system that works under any conditions.

B. Cleanup Shots

After full breakthrough, the resolidified material might be left in the hole. A photograph of resolidified material is shown in Figure 13. The size of it can be estimated using the diameter of the calibration dots. In order to take out the resolidified material from the hole, cleanup shots are required after full breakthrough. But cleanup shots continuously drill the adjacent sample surface after full breakthrough, and we are in a dilemma as to whether to continue the laser shots or stop them. Therefore, the minimum amount of laser power that is required to take out the resolidified material from the hole is consumed for cleanup shots after full breakthrough. After cleanup shots, the laser must be immediately stopped to prevent damage to the adjacent sample surface.

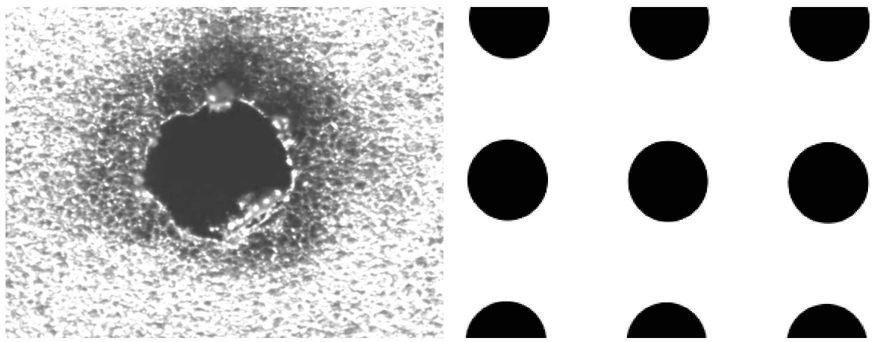


Figure 17. Resolidified Material and Calibration Dots (0.25mm Ø)

Conclusion

In the digital approach, the PCB106B pressure sensor output showed distinctive patterns that 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 will be tested under many different conditions to establish a consistently reliable control system that works under any conditions.

Future Plan

The first fundamental experiments have been accomplished in a limited time period to prove that this method is feasible. The future objectives of this project are as follows:

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 that works under any angle conditions.

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 long distance to penetrate under this angle condition. But the tested Waspalloy samples have a thickness of only 0.05 inches; thicker samples have not been tested in this graduate project. 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 graduate project. Therefore, coated samples will also be tested in the future.

As mentioned above, this project requires a long time period to collect data to prove that this method works under any conditions, and I hope that this article will be the very first step for great success in the future.

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