Smart and Reliable Assessment of Electromagnetic Environmental Effects on Ordnance made easy

How to become a successful HERO tester in 4 steps

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Abstract

Hazards from Electromagnetic Radiation to Ordnance, that is the potential for electromagnetic radiation to affect adversely munitions or electro-explosive devices is a well known problem identified since the 50's. Avoiding unwanted detonation or malfunction of Electrically Initiated Devices (EID) from a proliferation of radiated electromagnetic energy has become essential to all defense organizations. With a constant increase in power output and frequency range of transmitting equipment, the importance to reduce such threat is getting even more critical.

To make sure ordnance and armament systems remain safe and in proper service condition, test equipments were developed to measure the effect of electromagnetic energy on electro-explosive devices (EED). For a few years a new generation of instruments based on fiber optic technology is slowly replacing systems using thermocouples or infrared detectors. Very accurate and precise, the fiber optic sensor (FOS) is extremely sensitive and presents the required response time to efficiently qualify EED. Because of its dielectric nature the FOS is totally immune to Electromagnetic Interferences (EMI) that might be present in the sensing environment. With such advantageous characteristics, sensors based on fiber optic technology are now becoming the standard for HERO/RADHAZ testing. However, it is still unclear what the essential requirements are for such technology to provide reliable radiation assessment of EED devices, and how to implement this technology to fully benefit from its complete potential.

The four "must-have" requirements presented in this paper, propose a simple and easy integrated approach so as to provide reliable assessment of EMI/HIRF effects on ordnance using fiber optic technology: i) Accurate & flexible sensor; ii) Reliable EED assembly; iii) Precise EED induced current response; iv) All-in-one instrumentation.

1. Accurate and flexible sensors

1.1. The technology

The HERO/RADHAZ testing method presented in this paper is based on a very sensitive and accurate fiber optic sensing technology called the SCBG (Semiconductor BandGap) technology. The SCBG-based fiber optic sensor is designed to measure EM-induced temperature rise in EED bridge wire or similar devices. The SCBG is a mature technology based on a simple, yet robust spectrophotometric technique. The technology principle relies on the temperature dependence of the optical transmission properties of GaAs monocrystal. Simply stating, GaAs crystal is an opaque material for all wavelengths of light below a specific wavelength transition region called the bandgap and oppositely is a transparent material for all wavelengths of light above that bandgap. The wavelength transition region, i.e. the bandgap spectral position, is a function of the temperature. Measuring the bandgap spectral position changes for monitoring the temperature is the principle behind the SCBG technology.

The schematic of the SCBG technology is shown in Figure 1. The fiber optic temperature sensor is composed of a miniature GaAs crystal bonded to the tip of an optical fiber. Light injected from the signal conditioner into the optical fiber is guided up to the GaAs crystal. The later absorb wavelengths of light below the bandgap spectral position and reflect back to the signal conditioner those wavelengths above the bandgap. Light reflected back to the signal conditioner goes into a miniature optical spectrum analyzer (OSA) that spatially decomposes the light into its wavelength constituents. A linear CCD array of optical detectors measures the intensity of light at these wavelengths. Each pixel of the CCD array corresponds to a specific calibrated wavelength and therefore the whole detector array provides the spectral intensity distribution of the light reflected back by the GaAs crystal. A typical spectral intensity distribution curve is shown in Figure 1.

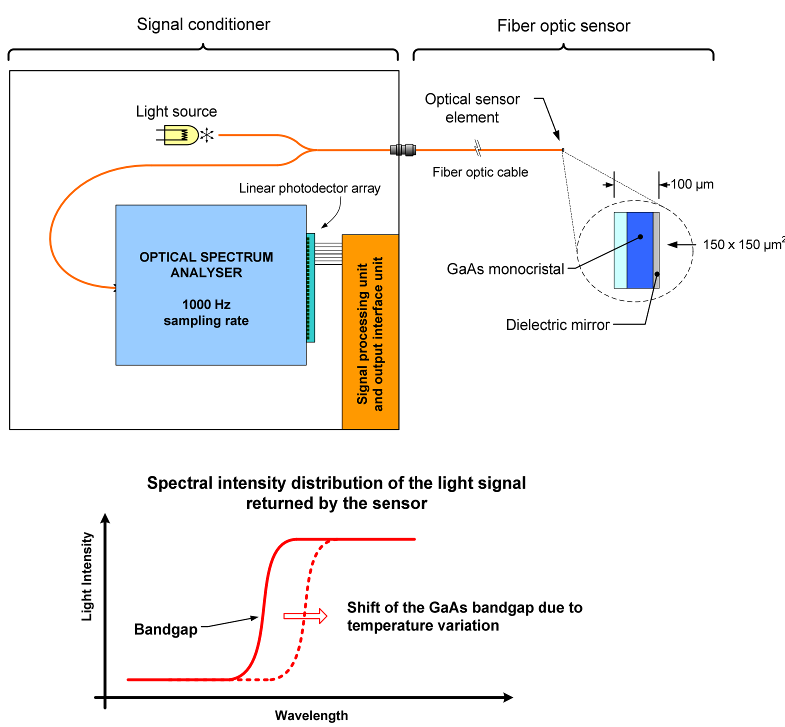

Figure 1: Schematic of the SCBG technology

The bandgap spectral position is calculated from the light spectral intensity distribution and converted into an absolute temperature reading. As opposed to interferometric techniques used in similar applications, the SCBG spectrophotometric technique is not sensitive to mechanical vibration and fiber-optic movement, which is critical for HERO and RADHAZ applications.

Absolute and relative measurements without the need of calibration factors

The SCBG technology offers both absolute and relative temperature measurements and this, without having to provide the measurement system with calibration factors prior to use the sensor. Sensors can be mixed and matched with all the measurement channels of the system without calibrating the sensor to the specific channel. The benefits of these features are numerous:

- Eliminate manual entries to system, thus reducing risk of human related errors
- Avoid inaccurate result caused by calibration factor mismatch with sensor used during testing process
- Sensor to sensor consistency
- Greatly improve setup time and productivity with a simple *connect & measure* feature

The user should be able to easily switch from absolute to relative temperature measurements, which is the difference between the actual temperature and a reference temperature point.

1.2. The requirements

Complete immunity to EMI

Because of the nature of HERO/RADHAZ requirements and for applications such as electromagnetic compatibility testing and assessment of EED, the sensor must be totally immune to EMI. The SCBG technology provides this complete EMI immunity

Resistance to cable movement, vibration and manipulation

To provide reliable and precise results, the sensor must demonstrate no measurable susceptibility or sensitivity to optical fiber movements. Sensors should not be sensitive to mechanical vibrations as well. This is also true for optical fiber bending and optical fiber connections/disconnections. This can affect the capacity to support more than one connection without any degradation of the sensor sensitivity and accuracy.

These external disturbances can generate significant output reading errors and unusable measurement results such as with fiber optic interferometric technology for instance. Thanks to the spectrophotometric principle of the SCBG technology which provides complete immunity to these effects. For example, multiple connections can be set without impacting measurement accuracy. In addition, sensors can be used in high vibration environment such as those found in fighter aircrafts.

Adaptability

The sensor should be easy to assemble for all types of bridge wire based EEDs. The SCBG technology provides a miniature sensor (150 x 150 x 100 um^3 or less) to fit in very small spaces or for EEDs with compact design. With minimum encumbrance, the sensor bare section and cable sheath material should be easily adaptable to the test environment.

2. Reliable EED assembly method

The success of HERO/RADHAZ testing depends mainly on the quality of the assembly. Fiber optic sensors are useless if not mounted properly on the bridged-wire EED.

2.1. The setup

Installing a sensor not bigger than a human hair on a fragile bridge wire, sometimes hidden at the bottom of a very small EED requires appropriate tools and proper assembly methods. The use of an installation bench with simple micromanipulators and magnifier lenses and holders is a must to make robust assembly.

A proper assembly bench avoids time wasting manipulations and greatly reduces the chances of mounting the sensor incorrectly on the EED. But most importantly, the usage of a proper designed EED holder assembly (called the EED adaptor) where the EED and the sensor are held together is required.

The installation bench allows putting the sensitive part of the sensor, i.e. the GaAs crystal, in thermal contact with the bridge wire of the EED. The sensor is fixed in order to maintain a slight positive pressure on the bridge wire (see the assembly details shown next).

2.2. The assembly

For maximum sensitivity, the tip of the sensor (i.e. the crystal) must be in thermal contact (conduction) with the bridge wire. Note that gallium arsenide crystal can be placed in direct contact with the bridge wire without altering its inherent electrical and Electromagnetic characteristics.

However, it is important to apply a moderate tension on the bridge wire. Over tensioning the bridge wire can damage the crystal (e.g. crystal can detach from the fiber tip) and it can create heat sink effects if the bridge wire comes in contact with the EED housing.

The next figures illustrate a typical EED assembly bench with the minimum required equipment:

The installation bench, as seen on the right side figure, provides the required control to efficiently mount the sensor on the EED bridge-wire. Binocular, holders, and micromanipulators are all what's needed.

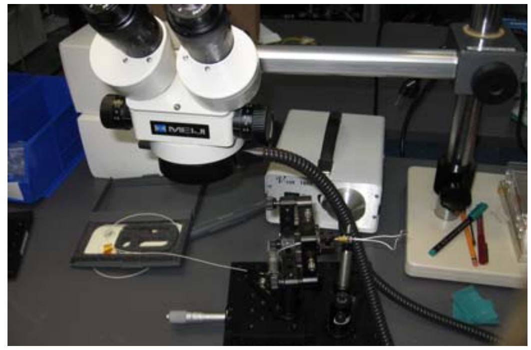

Figure 2: Overview of the EED installation bench

Fixing the EED with exposed bridge-wire on the installation bench. By using adapted holding parts, the EED is installed so as to avoid any movement during the installation process.

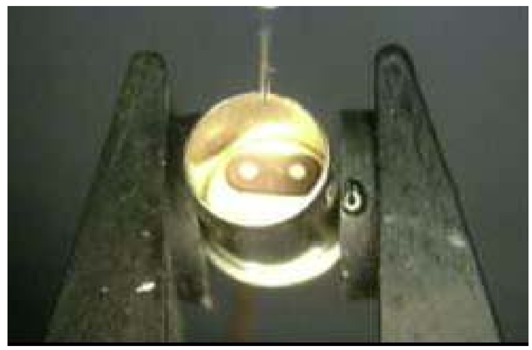

Figure 3: EED with exposed bridge wire

The temperature sensor is installed near the EED. The sensor is firmly held to avoid unwanted lateral movement.

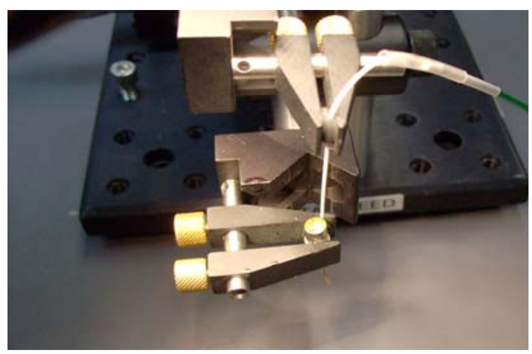

Figure 4: Installation of sensor

The sensor is positioned in contact with the bridge wire using micromanipulators.

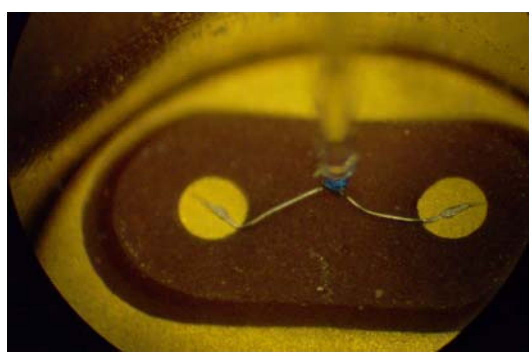

Figure 5: Contact with bridge-wire

The installation is completed by fixing the optical fiber to the EED adaptor.

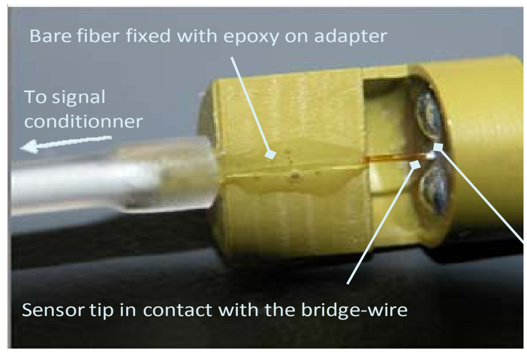

Figure 6: Special adaptor designed to hold the sensor to the EED

2.3. Adaptability

Electro-Explosive Devices come in a variety of shapes and models. From the standard MK1 to sophisticated and custom made EED, the sensor must adapt to the EED device without altering its electrical characteristic and its electromagnetic susceptibility.

The temperature sensor should be easy to mount on standard and common EEDs like the MK1 and the PR-2. The figure on the right shows a properly designed adaptor used to maintain the optical fiber with the EED device and provide the required assembly robustness.

Figure 7: PR-2 EED assembly

It is necessary that the sensor geometry adapts to different EED bridge wire designs and this with minimum encumbrance. For example, Figure 8a on the right shows a bridge-wire coiled around a cylinder and where the user encumbrance requirements are such that the optical fiber must be placed parallel to the cylinder. A specially designed sensor with its crystal mounted on the side of the optical fiber (Figure 8b) is used for this application.

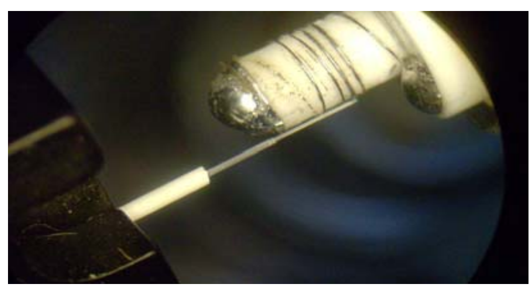

Figure 8a: coiled bridge-wire

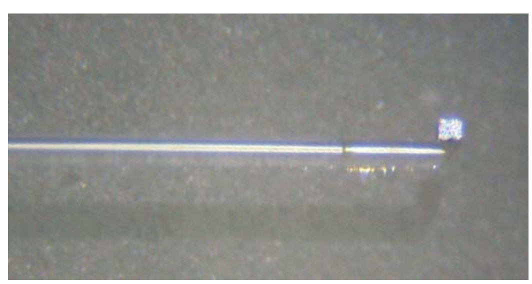

Figure 8b: crystal mounted on the side of the optical fiber

3. Precise EED induced current response measurements

3.1. Accurate calibration made easy

An instrumented EED (i.e. EED/sensor assembly) has to be calibrated prior to provide measurements of the induced current response when subjected to electromagnetic radiation. The calibration curve establishes the relationship between the injected current in the EED bridge wire and the bridge wire temperature increase as measured by the temperature sensor

The table of Figure 9 shows the numeric calibration data while the graph shows the calibration curve of an instrumented MK1 EED. This figure clearly demonstrates that the calibration curve follows with very good accuracy the theoretical square law response of EED devices, where the increase of the bridge wire temperature is proportional to the square of the current flowing through it. The proportionality constant, called the I-square sensitivity S_c, is easily calculated from this curve and is equal to 0.004758 °C/mA^2 in this particular case.

I (mA)	ΔT (°C)
0	0
3	0.042
4	0.088
5	0.157
10	0.466
20	1.930
30	4.284
40	7.598

Table 1

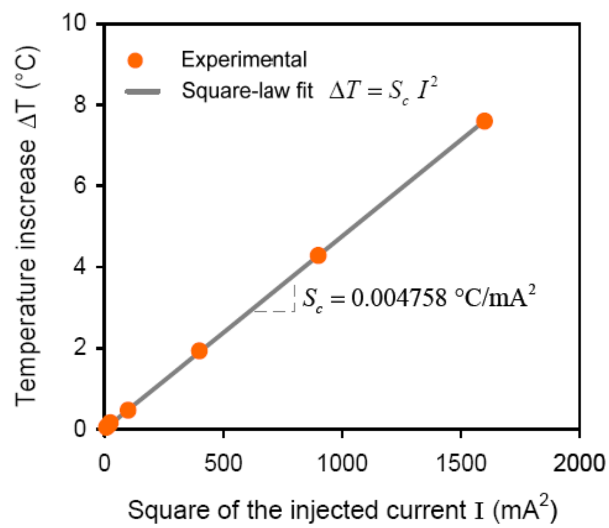

Figure 9: Calibration results

Once S_c is determined for a particular EED, it is easy to setup the control and readout instrument (RadSens signal conditioner) to output in various units such as in milliampere, in decibels below NFT (No Fire Threshold) and in microwatt in addition to the standard temperature units (absolute or relative temperature) as shown next.

3.2. EED induced current response in various units (mA, dB, µW)

The following EED current response examples were taken with an OTG-R fiber-optic temperature sensor (designed for EED testing) assembled to a Mark-1 (MK1) Electro-Explosive Device (EED). The MK-1 EED has a no-fire threshold (NFT) of 300 mA and an ohmic resistance of 1.2 ohm. The MK1/OTG-R assembly was connected to a PSR-100 measuring module of the RadSens signal conditioner. The calibration curve provided the I-square sensitivity S_c, which is equal to 0.004758 °C/mA^2 in this case. The data were collected in real time at sampling rate of 1 kHz through the Ethernet/LAN port of the RadSens instrument.

Current response in milliampere

The current response in milliampere was measured by setting the RadSens instrument to output in mA. The figure on the right shows the current response in mA of the instrumented MK1. As anticipated, the response is very linear.

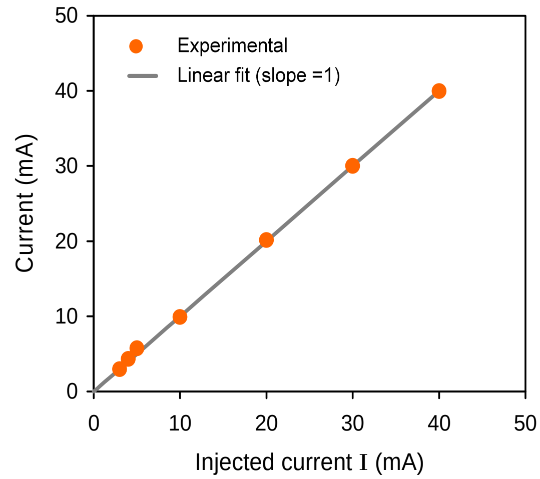

Figure 10: Current response in mA

Current response in decibel below NFT

The current response in decibel below the No Fire Threshold was measured by setting the RadSens instrument to output in dB. The figure on the right shows the response curve. As expected, the response follows a logarithmic curve.

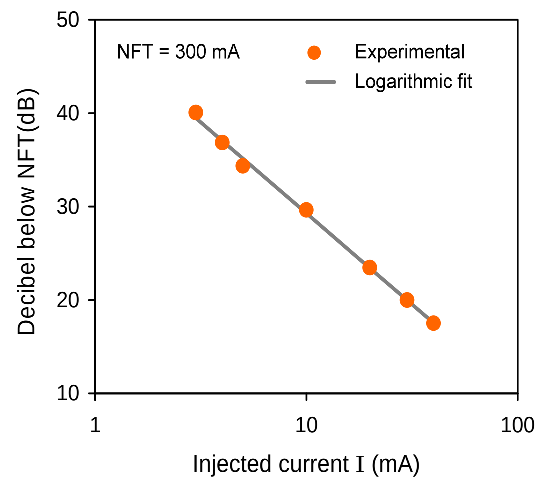

Figure 11: Current response in dB

Current response in microwatt

The current response curve in microwatt was measured by setting the RadSens instrument to output in µW. The figure on the right shows the response curve and as expected, the response follows a power law curve (shown on log-log scale).

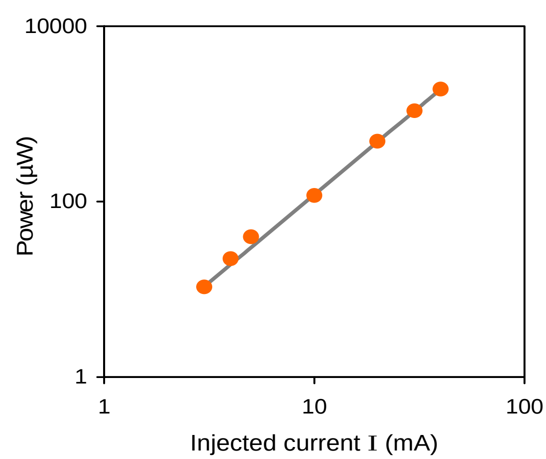

Figure 12: Current response in µW

3.3. Ultimate current sensitivity and response time

Figure 13 shows the smallest current detected on an instrumented MK1. The output of the RadSens instrument was set in dB below NFT. A minimum of 1.6 mA current was clearly detected. This current corresponds to 45 dB below the NFT point of the MK1 EED. (Note: for practical reasons, all readings above 99 dB are coerced to that limit value).

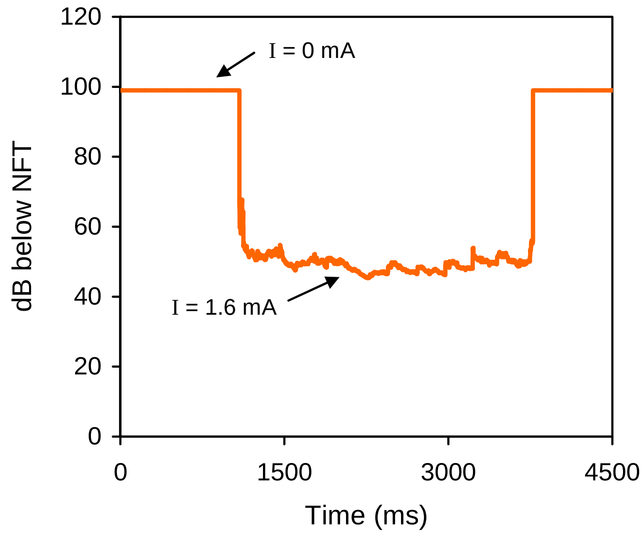

Figure 13: Ultimate current sensitivity

The OTG-R sensor used for the instrumented EEDs has a response time of 10 ms or smaller. The EED/OTG-R assembly has a typical response time of 375 ms or smaller.

3.4. Adaptive noise removal filter

There is always some noise associated to the signal obtained from the measurement of observable physical quantities such as temperature for example. The strength of this noise can be significantly reduced by performing electronic analog or digital filtering. Nowadays, digital filters can attain characteristics not practically achievable with analog filters and for that are the preferred ones in signal processing applications. Signal conditioner with 100% digital electronics and digital signal processing capabilities can perform digital filtering of almost any type.

The running average filter is the most common digital filter to remove the noise components of the measured signal. The output of this digital filter is the average of the N most recent measurement values. The noise removal performance of this filter depends of the value of N; a higher value means a better noise cancellation. The running average filter is a very good filter for noise removal; however this filter comes with two major drawbacks. The first one is that this filter is not causal and therefore it always introduces a delay (equal to N / 2 sampling period) into the signal. So higher noise removal performances come with longer delay. The second drawback is that the filter attenuates the high frequency components of the signal; in other words the filter is unable to track rapid signal variations. As explained next, adaptive filtering alternative can eliminates these drawbacks.

High performance digital noise removal adaptive filter can greatly improve the resolution of signal conditioner without compromising response time. The term adaptive means the filter is able to adapt itself in real time to the various signal conditions and select the optimal filtering parameters. The adaptive filter presented here is a real causal filter that does not introduce additional delay in the signal. While this filter is able to reduce the noise by orders of magnitude, it remains able to respond to fast signal variations with minimum attenuation of the signal high frequency components. For those familiar with digital filtering, an adaptive filter can be thought of as a discrete first-order low-pass filter with self-adjusting filter time constant.

Figure 14 clearly demonstrates the outstanding performances of an adaptive filter compare to the running average filter. The light blue curve represents the raw measurement data, i.e. unfiltered, while the red and the dark blue curves represent the running average and adaptive filtered data respectively. From the measurements of the left (< 2000 ms) where the temperature does not vary much, one can see that both types of filters produce very good and similar noise removal. However the performances of these filters get quite different when the signal changes rapidly. One can see from the first signal spike on the left that the running filter is unable to track the rapid variations of the signal.

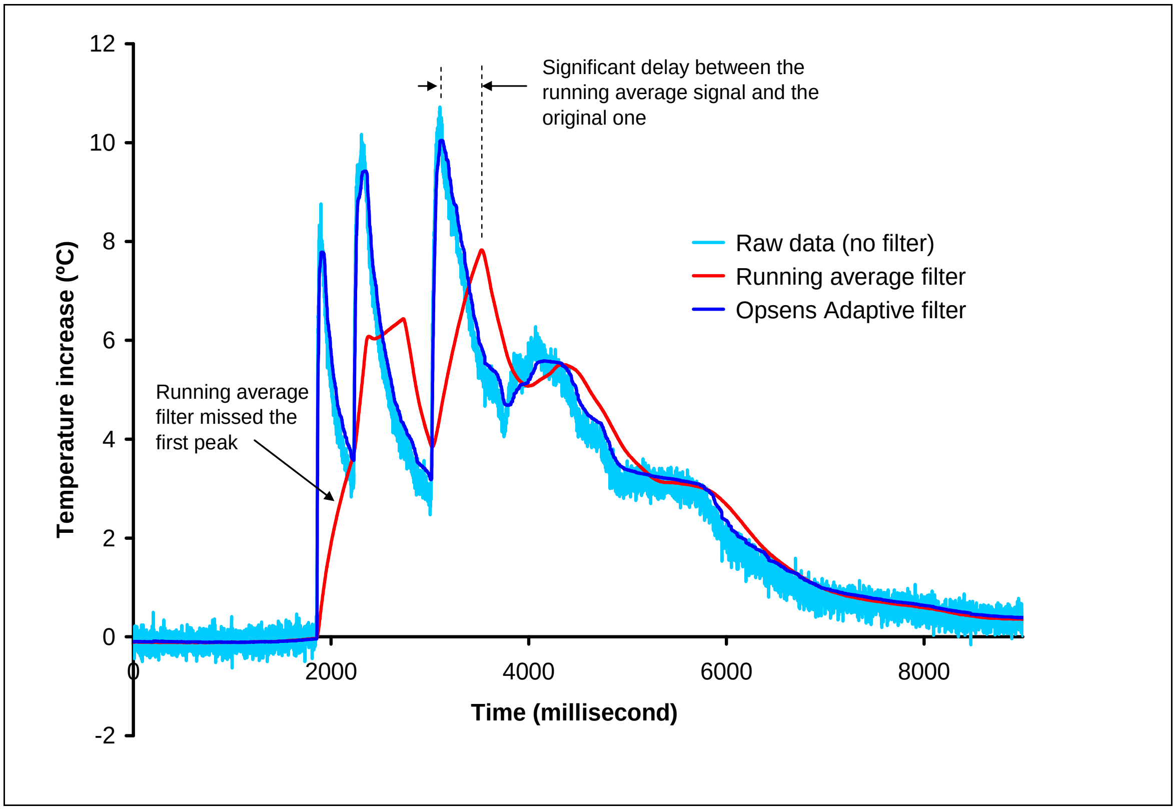

Figure 14: Noise removal filters performances

The average filter severally attenuates the high frequency components of the input signal hence its poor capability to output the original signal correctly. Also worth noting is the delay in the output signal of this filter which can be seen on the third signal spike (from the left) where the output signal peak of the running average filter occurs hundreds of milliseconds later than the raw signal peak. On the other hand the adaptive filter has no problem to follow the rapid variations of the signal. These measurements show that there are no significant delay and attenuation between the input raw signal and the output adaptive filtered signal.

3.5. Embedded current source and automatic calibration software

Calibrating the instrumented EEDs is mandatory before making any measurements. This can be a long and demanding task when dealing with large quantity of EED devices. The combination of an embedded current source with automation calibration software provides the test technician with a very efficient EED calibration tool. This way each instrumented EED can be calibrated in a consistent manner with a minimum of efforts and risk of errors.

Once the user has determined the number of required current calibration points, specifically designed software can perform the calibration and automatically calculate the I-square sensitivity S_c as described in Section 3.1. The calibration results should be displayed in numeric and graphical forms and be saved in MS Excel™ compatible or similar format.

4. All-in-one instrumentation

Nowadays, there is a real trend toward all-in-one instrumentation when it comes to sophisticated monitoring and measurement applications. A minimum number of instruments required for HERO/RADHAZ testing is something desired by everyone involved in this field. Using different instruments for every steps of the measurement chain (signal conditioning, data acquisition, data treatment, analysis, and management, etc.) increase the risk of errors and of inconsistent results. An all-in-one instrument should offer the following features:

- Digital signal processing and conditioning at sampling rate up to 1000 Hz
- On-board computer for real time data acquisition and transfer
- User-friendly interface with meaningful results displayed in numeric and graphical forms
- Integrated calibration tool and software
- Embedded data filtering and analysis
- Integrated data storage for local data management
- Ethernet interface for PC real time data download and remote control

User-friendly graphical interface which can display real time measurements in various numerical and graphical forms along with measurements statistics allow the test technician to promptly validate the performance of on-going tests and to react in case of problems or unexpected results (See next figures).

Waveform graph display

Measurements can be displayed in line graph format like an electrocardiogram waveform (EKG display) where each EED monitored is shown with a different color line plot for efficient data comparison.

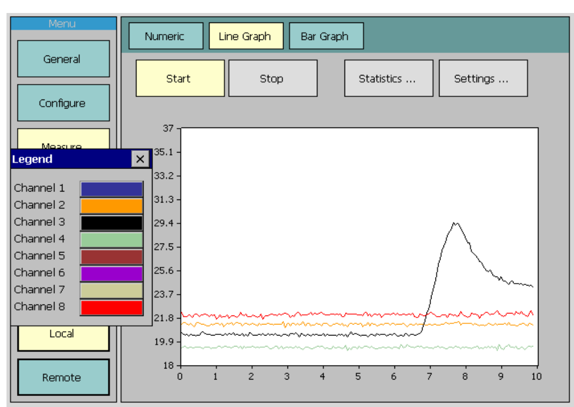

Figure 15: Waveform graph display

Bar graph display

Measurement results can be displayed in bar graph format to present peak level and identify problematic assemblies with user-adjustable alarm level indicator.

Figure 16: Bar graph display

Measurement statistics

Statistics of the measurements (Min, Max, Average, Standard Deviation) are calculated and displayed in real-time. No-signal condition is also tracked.

Statistics

#	Minimum	Position (s)	Maximum	Position (s)	Average	Deviation	NoSig?
1	18.1501	12	18.252	0.6	18.188	0.0286	No
2	19.9449	1.5	19.9615	9.6	19.953	0.0129	No
3	29.2735	9.6	29.3924	5.4	29.341	0.0301	No
4	-0.0047	5.7	0.0544	6.6	0.01	0.0137	No
5	25.1628	6.3	25.38	0	25.237	0.036	No
6	-0.02	0.3	-0.02	0	-0.02	0	No
7	-0.02	0.3	-0.02	0	-0.02	0	No
8	-	-	-	-	-	-	No

Figure 17: Measurement statistics

Conclusion

Becoming a successful HERO tester does require following certain rules. Even the latest fiber optic sensing technology solution won't help you much if it doesn't meet the basic requirements for SMART and RELIABLE results. Such solution does require accurate and flexible sensors, easy to install on any kind of EED. Adapted with military grade material, the sensing solution should offer precise calibration features and provide measurement results in various engineering units. It must offer smart data processing, with real time readings, and provide efficient noise filtering feature for optimal results. With built-in data management functionalities, a "ready to use" solution should offer user friendly interfaces without requiring additional analog to digital converter, software programming or computer system.

Mastering all these steps is essential for smart and reliable results for HERO/RADHAZ tests. Because such compliance validation requires more than just a measuring tool, it needs to confirm without a doubt, that unwanted detonation or malfunction of Electro-Explosive Devices won't occur.

References

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