Chapter

Automated Classification of Microwave Transmitter Failures Using Virtual Sensors

Ayax D. Ramirez, Stephen D. Russell, David W. Brock and Narayan R. Joshi

Abstract

Each year, nearly $100 M is spent replacing high-power microwave tubes in the fleet. In many cases (estimated at over 25%), tubes that are operating perfectly are inadvertently replaced because there are insufficient in-situ monitoring equipment available to diagnose specific problems within the system. High-power microwave vacuum tubes used in radar or communications systems have minimal condition-based maintenance capability and no means to identify specific component failures. This chapter presents the results from a system that uses cathode current and acoustic emission sensors combined as a virtual sensor to locate and classify microwave transmitter failures. Data will be shown which differentiate the failure mode from subsystems on a radar klystron and from a communications system magnetron. The use of the integrated condition assessment system (ICAS) to acquire and track virtual sensor data will also be described. These results offer promise of a low-cost, nonintrusive system to monitor microwave transmitters, which correctly identifies component failures avoiding incorrect replacement of high-value klystrons, magnetrons, or traveling wave tubes. This advanced technique also offers the possibility of developing built-in prognostic capabilities within the radar system to provide advanced warning of a system malfunction.

Keywords: microwave tubes, acoustic emission, virtual sensor, magnetron, klystron, integrated condition assessment system

1. Introduction

Microwave vacuum tubes used in high-power radar and communications systems have a lifetime of a few thousand active hours before refurbishment is required. When one of these microwave vacuum tubes fails, it is generally impossible to determine the sequence of events leading to its failure. Each year, nearly $100 M is spent replacing high-power microwave tubes in the fleet. In many cases (estimated at over 25%), tubes that are operating perfectly are inadvertently replaced because there is insufficient in-situ monitoring equipment available to diagnose specific problems within the system. This results in high maintenance and refurbishing costs.

At present, microprocessor-based systems with sensors are designed to monitor tube performance, provide tube protection, and record a comprehensive tube failure history. A major limitation of these systems results from the small amount of time available during the inter-pulse period of the tube for data buffering and fault analysis. The present monitoring systems work well if the microwave tube is operated with 200 or less pulses per second (pps). Normally, the radar tubes are operated at up to 1000 pps with pulse duration of a microsecond. Increasing the A/D conversion speed will, in some cases, make the situation worse, since it increases the amount of data that must be transferred and analyzed during the small time interval available. These high vacuum devices (10^{-7}–10^{-8} Torr) have electrode voltages that can run up to more than 10 kV, while their heat dissipation ranges from 100 W to 10 kW. The complexity of these systems makes them very expensive to produce, maintain, and replace. This provides a motivation for the development of alternative, more effective monitoring and diagnostic techniques.

In recent years, research has established acoustic emission (AE) sensing as a very effective technique for machine condition monitoring and analysis. This technique has been tested and evaluated in a variety of systems as an alternative to conventional techniques. A novel application of this technique is the in-situ performance monitoring of high-power microwave (HPM) tubes. This report addresses two questions: (1) Would the microwave radar tubes operating under normal or abnormal conditions be able to generate AE signals? (2) If so, can the observed signals provide signatures to discriminate among different types of failures?

Acoustic emission (AE) may be defined as stress or pressure waves generated during dynamic processes in materials. AE is elastic energy that is spontaneously released by materials when they undergo deformation and is typically generated in the form of ultrasound waves created by local mechanical instabilities within the material. AE is generally detected by means of ultrasonic transducers coupled to the material with a suitable coupler to decrease impedance mismatch. Among many mechanisms that produce AE activity, the principal mechanisms are crack initiation and growth, magneto-mechanical realignment or growth of magnetic domains (Barkhausen effect), dislocation movements, twining, phase changes, fracture of brittle inclusions, fiber breakage in composite materials, chemical activity, and cavitation. Some stimuli are necessary to trigger acoustic emissions. Stress, a major type of stimuli, may be mechanically applied, thermally generated, or caused by a changing magnetic field. Acoustic emission could thus act as a passive nondestructive technique (NDT) and be used to monitor and analyze normal and abnormal performance of microwave vacuum tubes.

The research presented in this paper demonstrates the detection of anomalous RF pulses and system failures using acoustic emission and magneto resistive or inductively coupled current sensors. It also demonstrates the ability to discriminate among the different types of failures. This innovative system has been tested on a klystron as part of an AN/SPS-49(V)5 radar system and on a radar system magnetron (Model 2J55). An added feature of this innovative system is the fact that the outputs from the sensors have been successfully interfaced with the ICAS (Integrated Condition Assessment System) software currently used by the U.S. Navy.

Once the output of the sensors was integrated with the ICAS software, a method was developed for integrating a plurality of sensor data in such a way to produce greater information than any individual sensor or combination of sensors. This method is particularly useful for detecting and predicting failures and for life cycle monitoring in microwave vacuum devices. This method has been defined as a virtual sensor.

2. AE as an advanced nondestructive technique

The fundamental principle of this method is based on the phenomenon of the generation of an acoustic pulse when a shock wave is generated inside a solid [1–4].

Generally, AE stress waves disperse throughout the medium until interaction with an interface or boundary produces a reverberating field. Although this energy will be mostly absorbed by the medium, some of the energy can be detected by the use of a high-frequency piezoelectric ceramic transducer. Assuming that all mechanisms of energy loss in the structure and measurement system are constant, the measured electrical signal energy from the transducer is proportional to the AE event energy [5],

$$AE_{energy} \propto \int_{0}^{T} V(t)^2 dt \tag{1}$$

where T is the time length of transient signal produced and V(t) is the transient voltage. Thus, the measured electrical signal energy is often referred to as the AE energy descriptor and is written as

$$E_{AE} \propto \left(\frac{1}{R}\right) \int_{0}^{T} V(t)^2 dt \tag{2}$$

where E_{AE} refers to the AE energy measured in the transducer and R is the impedance of the complete measuring circuit. The power of the acoustic emission signal of the detected event is proportional to the power of the source event. The advantage of energy measurement over ring down counting is that energy measurements can be directly related to important physical parameters without having to model the acoustic emission signal. Energy measurements also improve the acoustic emission measurement when emission signal amplitudes are low. Squaring the measured energy signal produces a simple pulse from a burst signal and leads to a simplification of event counting.

3. Causes of microwave tube failures

There are several well-known causes of microwave tube failure. These include:

3.1 Cathode emission decrease

A decrease in emission normally results in lowering of both the upper and lower mode boundaries. When this shift downward in current becomes significant, the operating point current has to be adjusted downward to avoid instability and oscillation. The operating point is adjusted periodically during the life of the tube. The tube remains operable until either its output power is low or the shift in mode boundaries due to cathode emission precludes stable operation over the frequency band. Cathode emission degradation is a long-term event that requires regular and careful monitoring.

3.2 Loss of vacuum

Loss of vacuum is a catastrophic failure, which may not be determined with electrical monitors. From experience, it is known that the heater bushing is the predominant failure. Other key vacuum seals include the RF input and output ceramic-to-metal seals.

3.3 Heater failure

Heater failure is a catastrophic event and results in inability to start cathode emission. Shorted heaters are more typical than open heaters. The cause of this fault cannot be determined with electrical monitors.

3.4 Other

Seal failures and inverse pulses are termed as transient events causing tube failures.

4. Application of the AE technique to klystron tubes

The results presented in this section were obtained at the Naval Surface Warfare Center, Port Hueneme Division, Dam Neck Detachment (NSWC PHD DN), and the Fleet Training Center (FLETRACEN) San Diego [6]. A simplified description of the field test unit utilized in these experiments is shown in **Figure 1**.

The radar system utilized during this test was the AN/SPS49 (V)5 radar with a 5-cavity klystron amplifier. The pulse repetition frequency (PRF) was set at 213 pps. This unit typically generates two pulses with durations of 2 and 125 μs, respectively. This klystron unit had 48 channels between 851 and 942 MHz. Channels 1–16 cover the low band; channels 17–32 cover the middle band; and channels 33–48 cover the high band. Channel 8, with a center frequency of 894.33 MHz, was frequently utilized

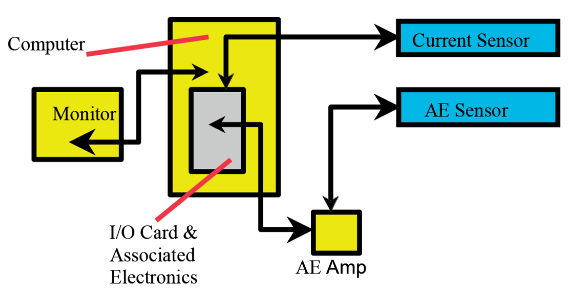

Figure 1.
Simplified field test unit.

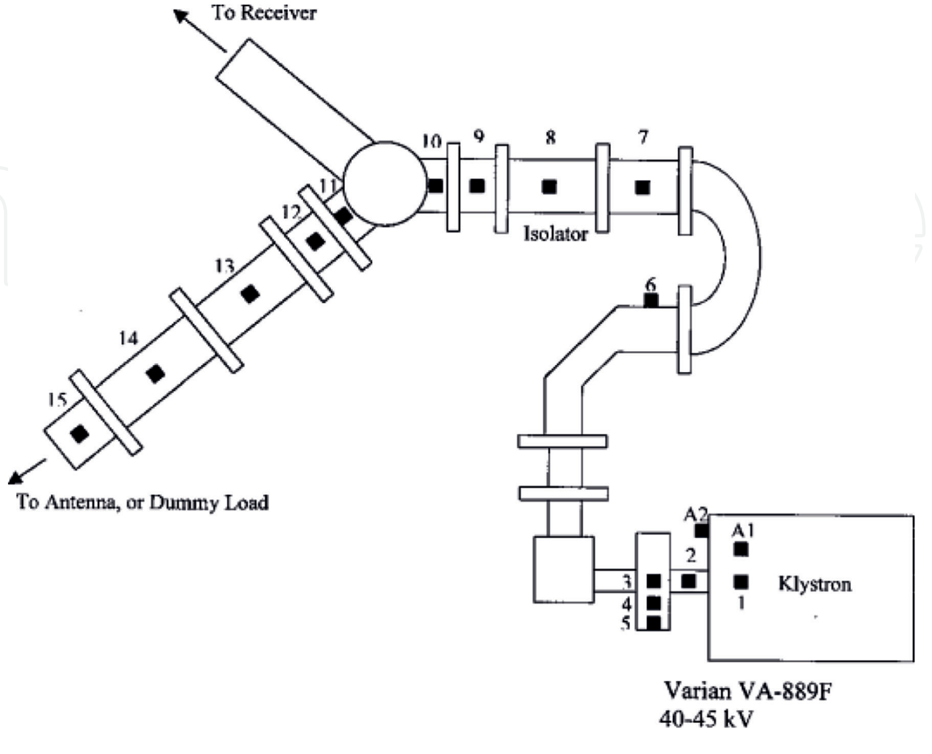

Figure 2.
Sensor location on klystron system.

in this experiment. The klystron unit was connected to a dummy load at the end of the waveguide. The dummy load was cooled by circulating water. During normal operation, the cathode was held at −42 kV with respect to the grounded collector.

The cathode current sensor was connected directly to the control panel of the radar transmitter. The acoustic emission system included a general-purpose R50 transducer, a preamplifier, and a post amplifier, all supplied by Physical Acoustics Corporation. **Figure 2** shows the different locations on the radar, denoted by black squares, where the AE transducer was attached in order to collect the acoustic emissions generated during normal and abnormal stressed operation. Locations include the coax, low pass filter, RF isolator, and several portions of the waveguide. A LeCroy 9354AM 500 MHz digital oscilloscope was used to detect and store signals from the generated acoustic emission, the input (RF drive) of the klystron amplifier, and the beam current sensor.

Figures 3 and **4** show typical signature signals from the sensors for the AE detection of the RF pulse and the cathode current (CC) for different locations on the klystron system under normal operation. These plots show the strong correlation between acoustic emission and RF emission.

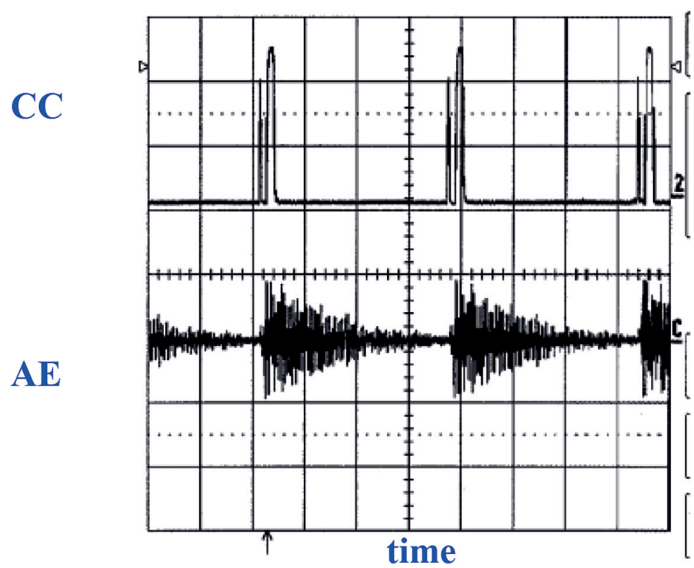

Figure 3.
Signature signals from acoustic and cathode current sensors at 45° waveguide bend, location 6.

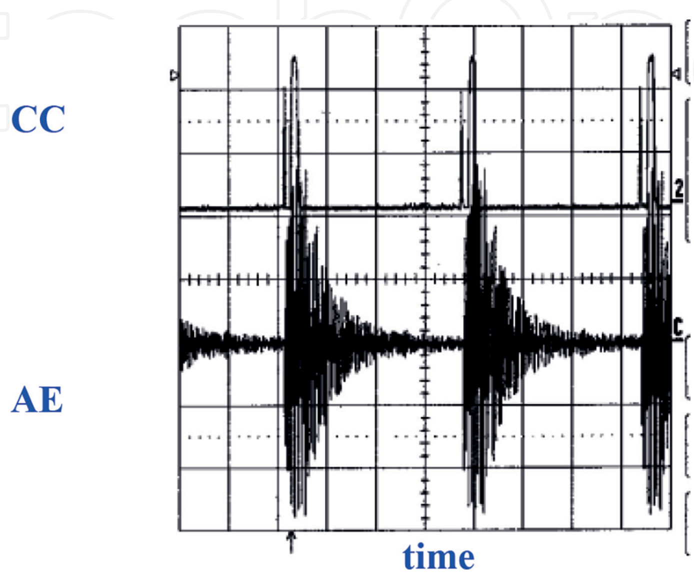

Figure 4.
Signature signals from acoustic and cathode current sensors at RF isolator, location 8.

A threshold amplifier was used to discriminate between normal and anomalous current pulses. Further details of the experiments can be found in Ref. [6].

Anomalous pulses were generated by several methods, including increasing the klystron voltages above normal operating specifications, up to 45 kV. This increase in voltage generated anomalous cathode current and acoustic pulses. **Figure 5** shows a typical anomalous current pulse under stress conditions.

Figure 6 shows a detection of a fault in the system induced by stress conditions. An anomalous cathode current pulse was detected. The corresponding acoustic emission pulse shows a slight increase in the detected acoustic signal. **Figure 7** shows the detection of a very different type of fault. In this case, an anomalous cathode current pulse was detected during a crowbar fault but no acoustic emission was detected. In this case, a catastrophic failure of a modulator tube was responsible for the fault. The absence of acoustic energy along with the detection of an

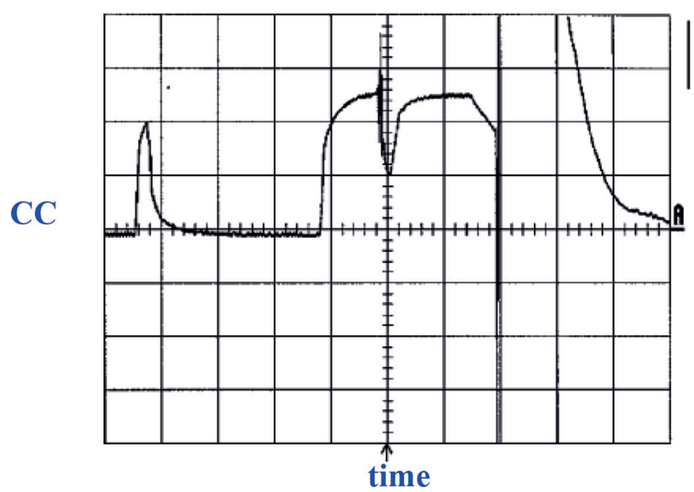

Figure 5.
Anomalous current pulse under stress conditions.

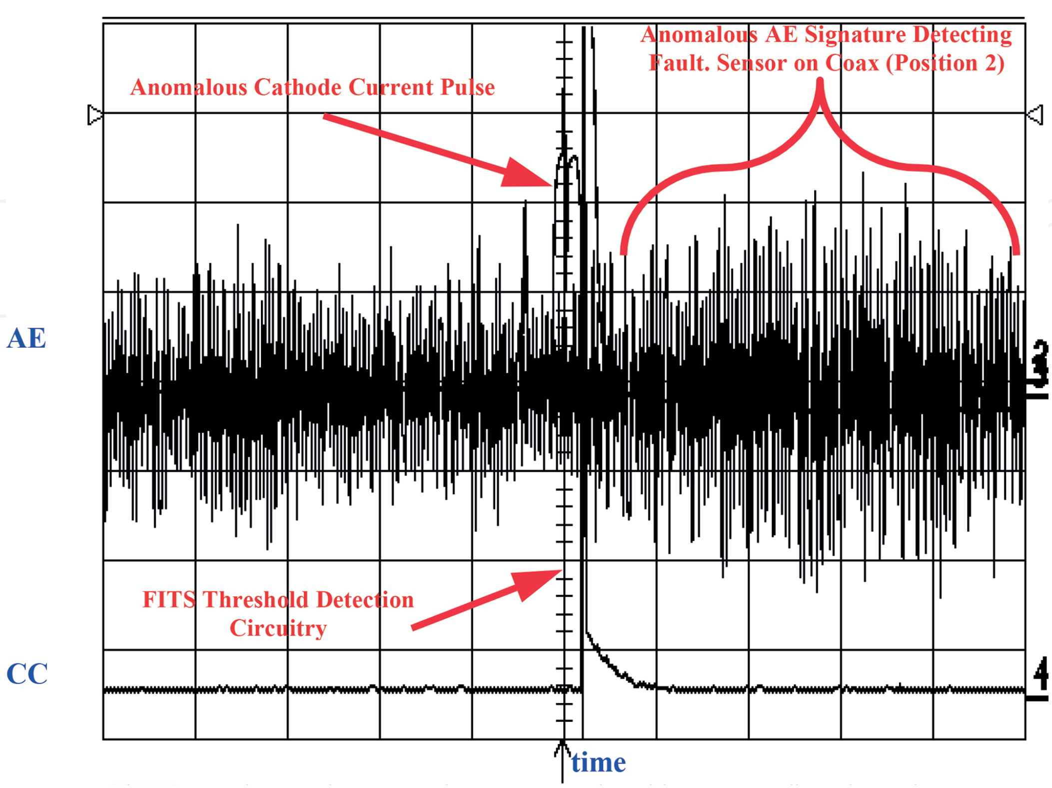

Figure 6.
Fault detection: anomalous current pulse with corresponding change in AE.

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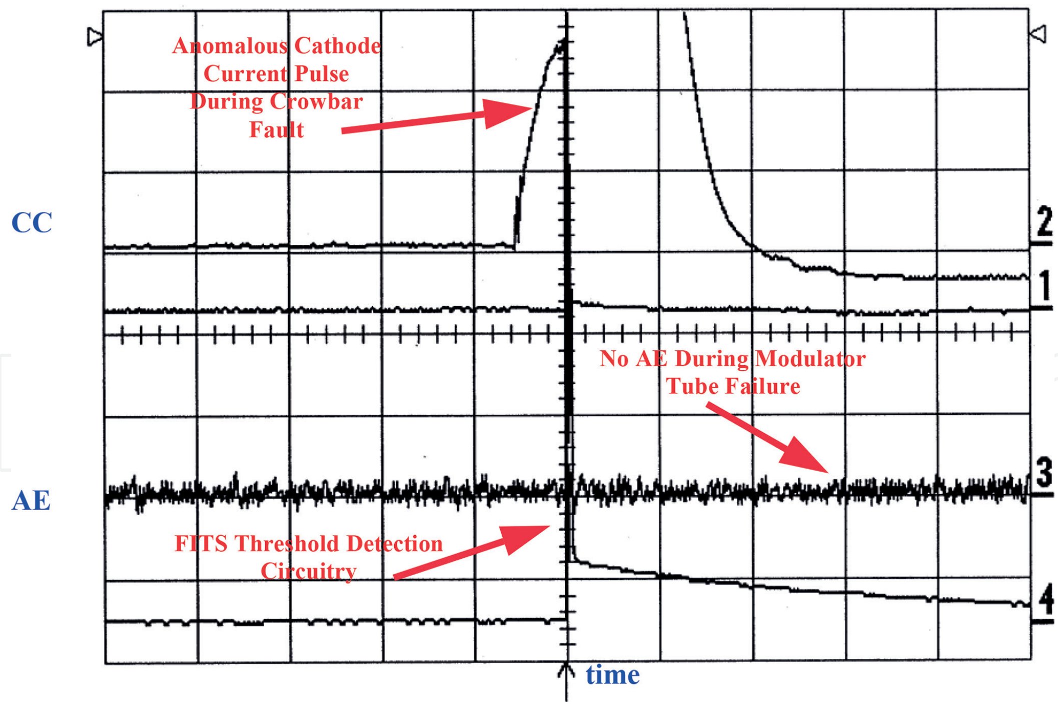

Figure 7.
Fault detection: anomalous current pulse with no AE.

anomalous cathode current pulse provides a possible signature for modulator tube failure. The system demonstrated the ability to discriminate between normal and anomalous pulses in klystron devices using current and acoustic sensors, and it showed a correlation between the two types of detection. The system also demonstrated the ability to characterize different types of failures.

5. Application of the AE technique to magnetron tubes

This section presents the effects on AE during normal and abnormal functioning of a magnetron. The experiment was conducted at the SPAWAR Systems Center, San Diego microwave radar tube laboratory [7]. The proper operation of a magnetron device depends upon the amplitude of the pulsed voltage applied, the temperature, the filament voltage, and the proper loading of the magnetron by the RF system. The normal operating parameters of the magnetron tube (2J55) utilized for this experiment were intentionally changed in order to stress the magnetron tube and induce abnormal functioning. **Table 1** shows the magnetron parameters for the experiments described below.

It was observed that when the tube was stressed, it typically produced an anomalous current pulse with a resulting anomalous RF pulse. The pulses were captured utilizing the masking feature of a 500-MHz digital LeCroy 9354AM oscilloscope, where a mask is defined based on a normal pulse shape, and pulses which lie outside the mask are captured. A fast Fourier transform was performed on the captured AE signal.

Figures 8 and **9** were obtained by using a type S9208 AE transducer, and they show the normal and abnormal pulses, respectively. In both cases, the pulse rate was adjusted to 100 pps, and the oscillator filament primary voltage was set at the normal value of 115 V. Channel 3 on the oscilloscope was connected to the output of the acoustic emission post amplifier and is shown in the upper trace. Channel B was connected to the current sensor of the magnetron, and it shows a zoom trace of the current pulse (see lower curve in figures). The mask was set on channel D

Parameter	Typical values	Stressed condition
Filament voltage	6.3 V AC	3.2 V AC
Pulse rate	1000 pps	1000–10,000 pps
Case temperature	95°F	Cooling fan shut off, temperature increased to over 150°F.
Reflected power	0%	100%
Pulse voltage	15 kV	15–21 kV

Table 1.
Magnetron parameters.

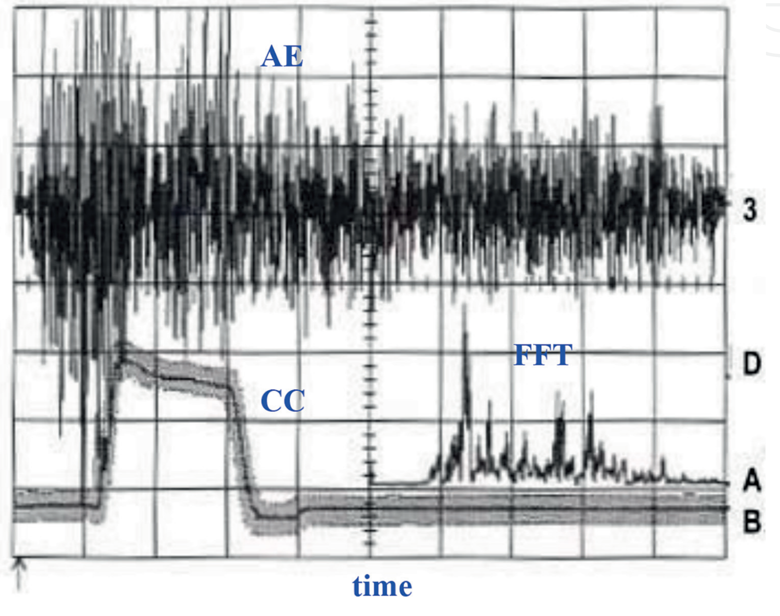

Figure 8.
Magnetron under normal operation with pulse voltage of 15 kV.

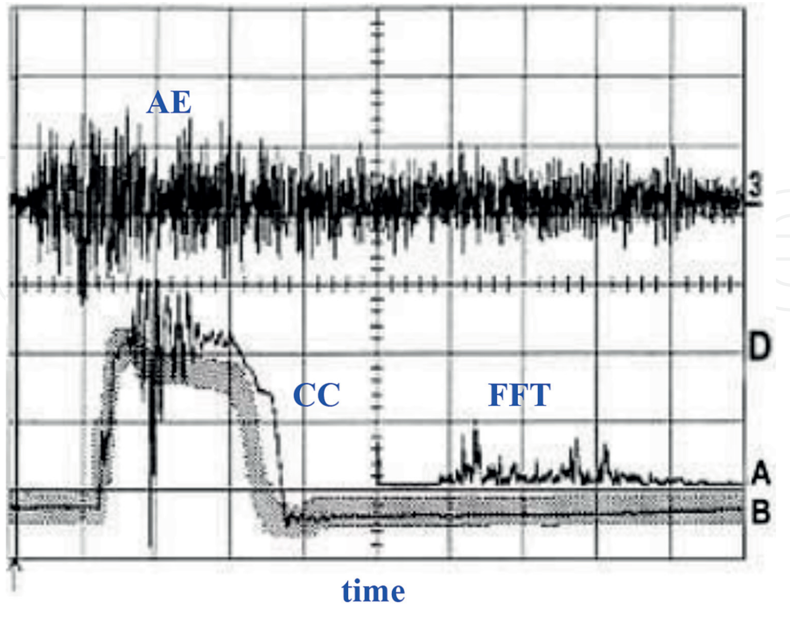

Figure 9.
Magnetron under abnormal operation with pulse voltage of 19.5 kV.

(zoom trace) and is shown superimposed on the current pulse. Channel A shows the magnitude FFT of the acoustic emission signal from channel 3. The amplitude of the AE signal decreased considerably during the detection of an anomalous pulse when compared with the AE under normal operation.

The experiment was repeated again using a type S9208A AE transducer. All parameters were initially set to normal values (filament primary at 115 V, pulse voltage at 15 kV, pulse rate at 1000 pps, and all RF power delivered to the matched load). Abnormal conditions were then obtained by gradually reducing the oscillator filament primary voltage from 115 V to zero. **Figures 10** and **11** show the results of this experiment under normal and abnormal conditions, respectively.

Once again, the amplitude of the acoustic emission signal decreased considerably during the detection of an anomalous pulse. Similar behavior was observed when the magnetron was stressed under different conditions. The system demonstrated the ability to detect anomalous pulses under different stress conditions. Further details of the experiments can be found in Ref. [7].

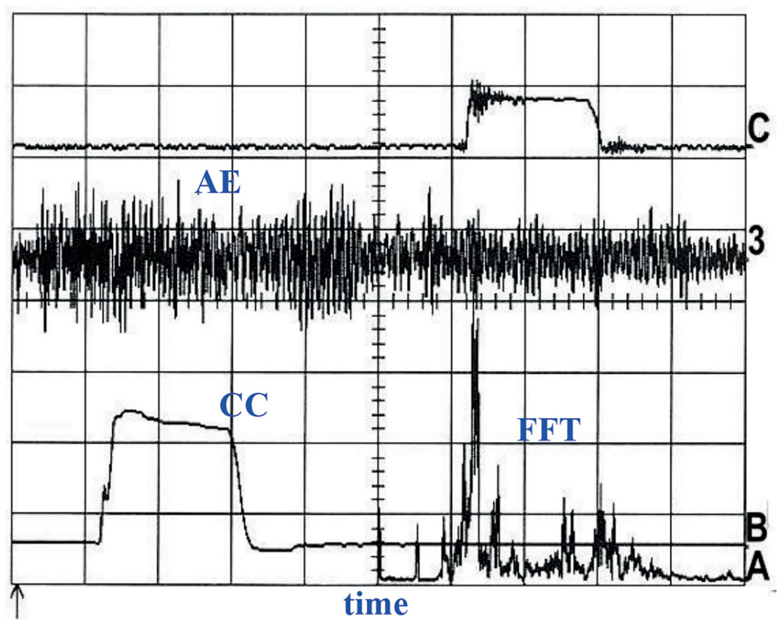

Figure 10.
Magnetron under normal operation with filament voltage of 115 V.

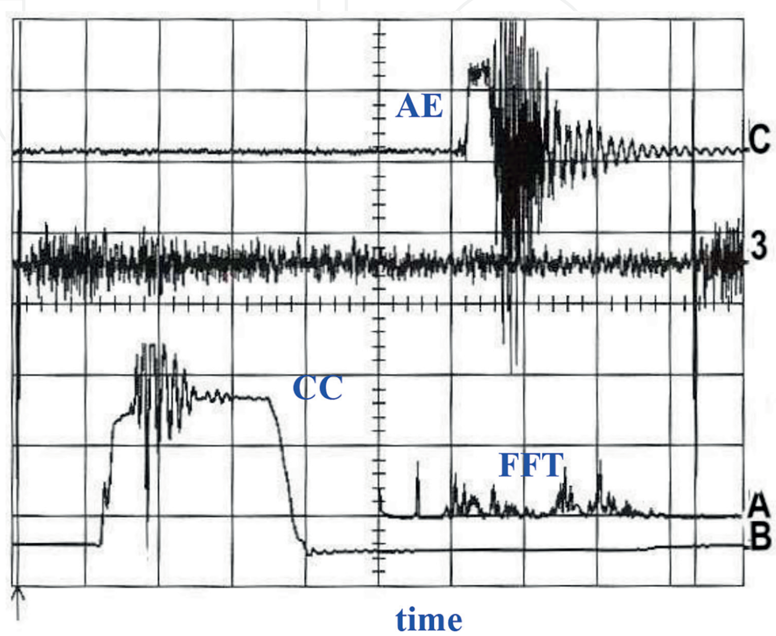

Figure 11.
Magnetron under abnormal operation with filament voltage of 0 V.

6. Integration with ICAS

The next step was to integrate the laboratory nondestructive AE test system into field applications for performance monitoring of a high-power microwave radar tube [8]. Currently, the Navy is using ICAS version 4.11 (IDAX Inc. Norfolk, VA) for the performance monitoring of mechanical systems on ships. The Integrated Condition Assessment System (ICAS) is a 32-bit Microsoft Windows NT based plant data analysis and integration tool. It is a predictive maintenance program that combines state-of-the-art performance monitoring techniques with computerized maintenance management. ICAS provides data acquisition and display, equipment analysis, diagnostic recommendations, and decision support information to plant operators and maintenance personnel. The system also provides user-defined performance alarms that alert the operator to machine problems. It provides the hybrid diagnostic system (HDS) diagnostic advisories that assist in diagnosing approaching failures and initiating the restoring process. The hybrid intelligent system is a fault-modeling environment that comprises both crisp logic and fuzzy logic rules.

The integration with ICAS required substantial electronics development in order to process, into a form compatible with ICAS, the acoustic emission and current signals collected during the normal and abnormal functioning of high-power radar tubes. An OPTO22 SNAP B3000 BRAIN unit was utilized to collect the data from the current and acoustic sensors. Two interface circuits were developed, one for each type of sensor, to interface with the ICAS software. **Figures 12** and **13** show the block diagrams for the developed electronics. The details of the electronics are beyond the scope of this paper. Further details on the ICAS interface and the electronics designed for this effort can be found in Ref. [8].

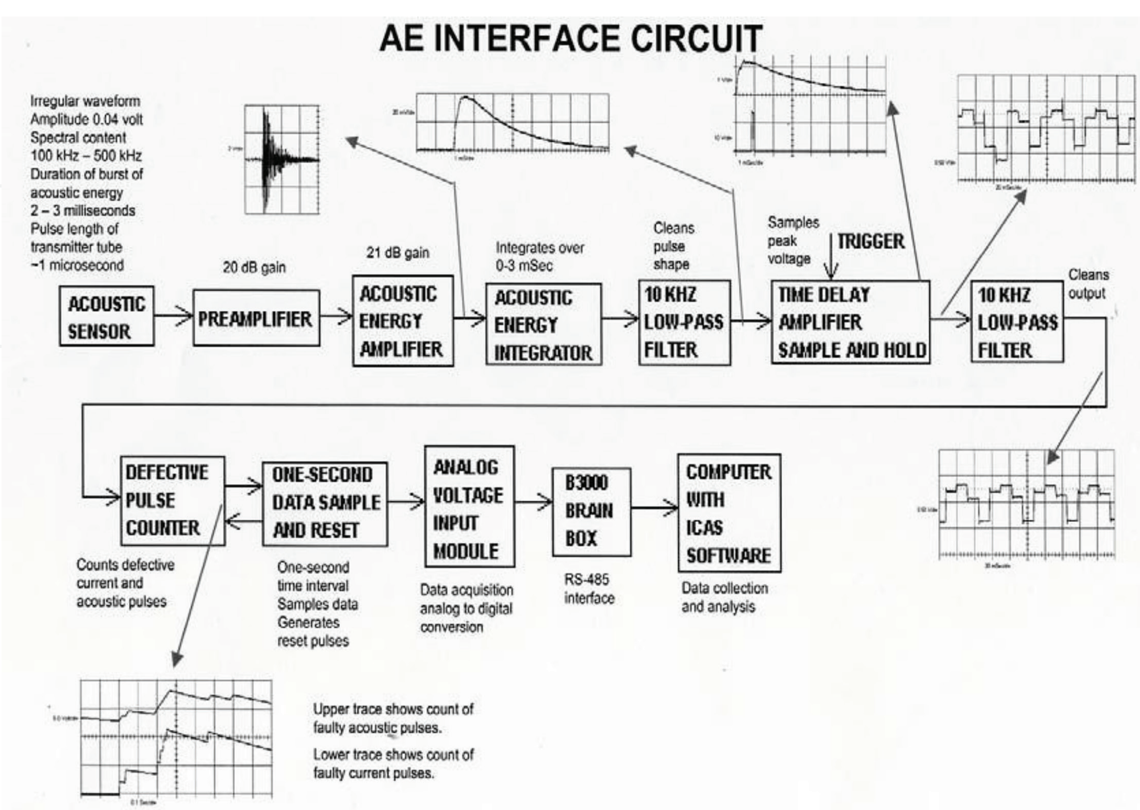

Figure 12.
Interface circuit for acoustic emission sensor.

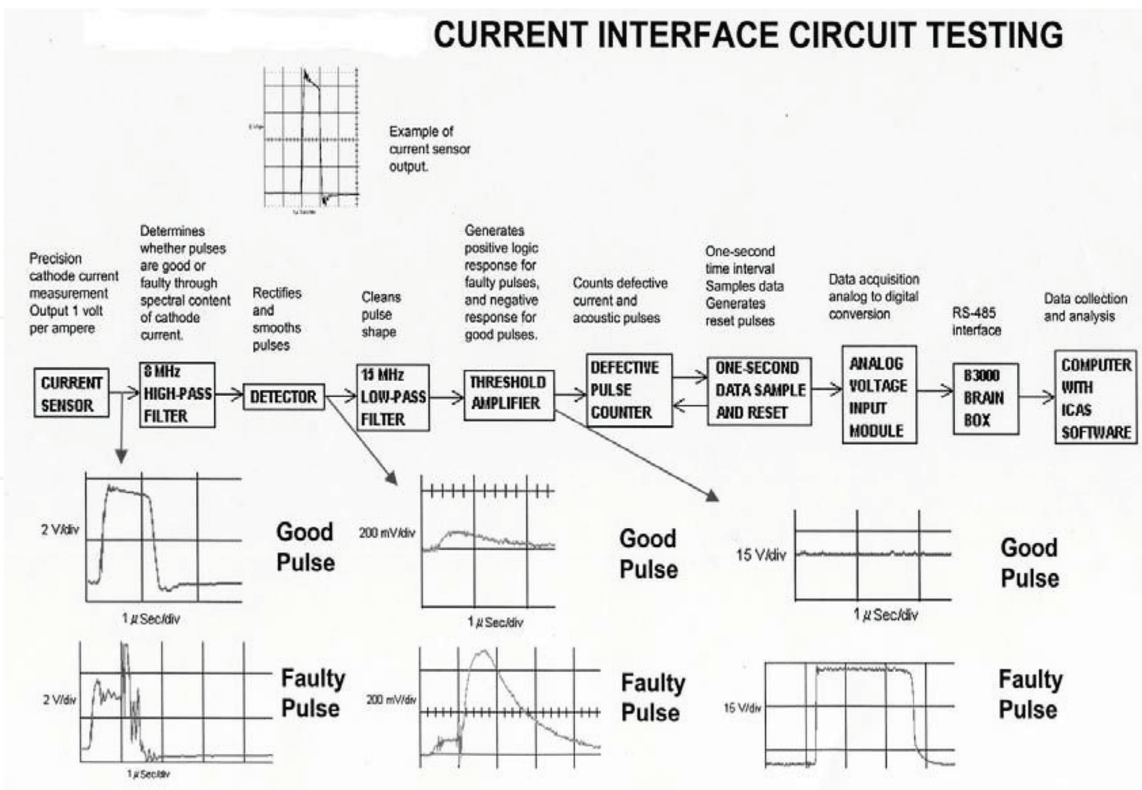

Figure 13.
Interface circuit for cathode current sensor.

7. Virtual sensor

One of the main advantages of the ICAS software is that it allows mathematical manipulation and combination of inputs from real sensors. This is essential in the development of what has been defined in this report as a virtual sensor. The generalized concept behind the virtual sensor is that a characteristic signature of a failure, denoted by F, is a function of more than one parameter (x_1, x_2, x_3,…,x_i). Thus, the characteristic signature of the failure, F, can be written mathematically as

$$F = F(x_1, x_2, x_3, \ldots, x_i) = \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=0}^{\infty}\sum_{l=0}^{\infty} C_{ijkl} X_i^k X_j^l \tag{3}$$

where C_{ijkl} are calculation coefficients and X^k and X^l correspond to each of n number of sensor parameters. The function F can generally be represented by a polynomial expansion.

As an example, if the failure is a function of just two parameters, then

$$F = F(x_1, x_2) = a + bx_1 + cx_2 + dx_1x_2 + ex_1^2x_2 + fx_1x_2 + \ldots \tag{4}$$

where the coefficients C_{ijkl} are represented by a, b, c, d, …, and the functional parameters X^k are represented by x_1 and x_2. Note that this expansion does not specifically require that the parameters have the same units or appear correlated at first appearance. Monitoring the value of F will therefore provide a measure of the system status and/or identify or differentiate failures. Using the virtual sensor formalism allows one to concatenate sensor information to provide more information than normally derived from either sensor alone or used in normal combination. An alternative approach to simply combining sensor data in the manner just described would be to define specific ranges of values for each sensor parameter and assign weighted values to each specified range.

Single sensor data can be used to detect faulty behavior but cannot readily differentiate or identify failures in the trigger sources, microwave tube, or other modulator electronics. This virtual sensor method can be applied to the monitoring of anomalous acoustic and cathode current pulses which are characteristic of a failed RF pulse. More specifically, this method can be used to count the number of anomalous pulses from each one of the sensor interfaces described in Section 4 and **Figures 12** and **13**.

To illustrate the advantages of a virtual sensor, consider the combined failure function, F, for a particular placement of an acoustic emission sensor whose parameter is represented by E_{AE} and a current sensor whose parameter is represented by I_c, where

$$F = |I_C| + \int_0^t E_{AE}(t)dt. \tag{5}$$

A virtual sensor for this function which represents the magnitude of the current pulse and the integrated AE energy can be used to add the number of faulty counts from the two real sensors producing a virtual sensor output. Long-term trends and analysis can be used to characterize the behavior and identify trend signatures for different types of microwave tubes. This synergistic effect of virtual sensing adds diagnostic and, more importantly, prognostic capabilities to the ICAS or any other monitoring system. The failure function, F, can be adapted to the needs and complexity of any system and can be defined to extract specific information required from that system.

This technique was demonstrated on a magnetron tube (2J55). The experiment was conducted at the Microwave Tubes Built-In Test Project laboratory at SPAWAR Systems Center, San Diego. The upper section of **Figure 14** shows an ICAS screen capture of the cathode current (green) and acoustic emission (yellow) faulty pulse counts. The lower section shows the virtual sensor outputs where two failure functions, F1 and F2, have been defined and measured. Function F1 = x−y (yellow), where the difference between the outputs of the two real sensors represents virtual sensor 1, with x = cathode current and y = acoustic emission; and function F2 = x*y (green), where the product of the outputs of the

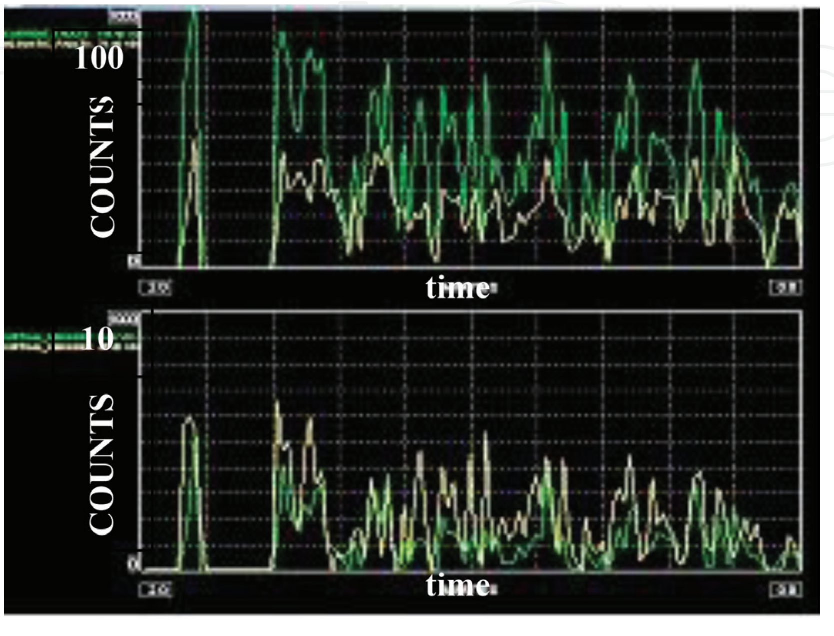

Figure 14.
Cathode current and acoustic emission faulty pulses and failure functions.

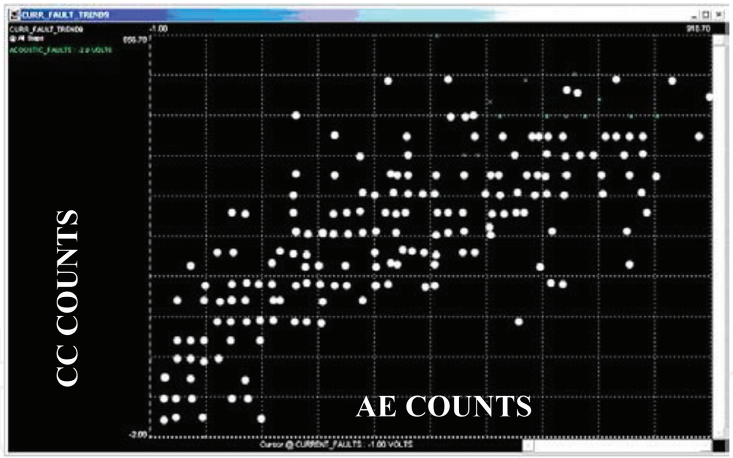

Figure 15.
Graph of faulty cathode current counts versus faulty acoustic emission counts.

two real sensors represents virtual sensor 2. These figures represent a 2-minute span of data collected during a period where the microwave tube was being stressed to produce faulty RF pulses.

The ICAS trending features were also demonstrated in this experiment. **Figure 15** shows a trend of the current faults count (vertical axis) versus the acoustic faults count (horizontal axis). This trend forms a band with few scattered points, indicating a strong correlation between both types of faulty counts and confirming the results obtained in previous experiments.

8. Conclusion

The experimental results presented in this paper demonstrate the use of advanced acoustic emission techniques as a nondestructive testing method for in-situ performance monitoring of high-power radar tubes such as pulsed magnetrons, TWTs, and klystrons. It was shown experimentally that changes in the amplitude and frequency content of the cathode current pulses are strongly correlated to changes in acoustic emission pulse energy both under normal and stressed operational conditions. The necessary electronics were developed to successfully interface the outputs of the current and acoustic emission sensors with the integrated condition assessment system (ICAS) used by the U.S. Navy. ICAS was used to demonstrate the use of virtual sensors where data from real sensors are combined into a failure functions F and captured in trend and single sensor format. In summary, this technique has demonstrated the unique ability to monitor, detect, and identify microwave tube performance. It has also demonstrated the ability to be utilized as a diagnostic tool by looking at long-term performance trends. More experimental research is needed to identify particular trends and signatures for the behavior of different types of microwave tubes under different circumstances to provide a fully prognostic capability for microwave tube systems.

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