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Real-Time Monitoring and Diagnosis Platform for a Machining Process

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Abstract: This paper presents the design and development of a real-time monitoring and diagnosis system for diagnosing degraded cutting regimes in Wire Electrical Discharge Machining (WEDM). The detection in advance of the degradation of the cutting process is crucial since this can lead to the breakage of the cutting tool (the wire), reducing the process productivity and the required accuracy. This work presents the design and development of a real-time monitoring system that alerts of degraded operation. Unlike other works found in the literature review, which are focused on proprietary hardware, the present paper proposes a flexible real-time platform based on a commercial data acquisition board that can be easily configured for different purposes. It has been applied to develop a real-time monitoring and diagnosis system that uses virtual sensors to diagnose the process degradation. The results of this work show a satisfactory performance of the presented approach.

1. INTRODUCTION

In Wire Electro-discharge Machining (WEDM) the anticipation of the breakage of the tool (the wire) is crucial in order to improve the process productivity (Ho, et al., 2004). The main advantage of WEDM is its capability for the production of intricate shapes and profiles with a high degree of accuracy, independently of the mechanical properties of the material, such as hardness, brittleness and resistance. Therefore, this non-conventional process is appropriated to cut difficult-to-machine materials. However, it is still difficult to understand all the aspects concerning EDM due to its strong stochastic nature and the multiple parameters of the process. WEDM is based on material removing through a series of electrical discharges applied between the electrodes (the tool -wire- and the workpiece). During the cutting process, dielectric fluid is injected into the *gap*, which is the space between the electrodes. In order to provoke a discharge, the machine power supply applies a voltage between the electrodes so as the discharge is produced after the dielectric ionization. The period of time necessary for the ionization is the *ignition delay time*.

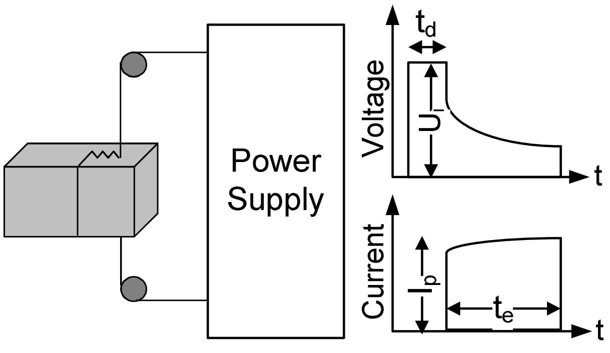

Fig. 1 Schema of WEDM process.

Between two consecutive discharges, the dielectric cools the gap and removes the erosion debris during an adjustable period of time known as *off-time*. The discharge rate is about few microseconds. Fig. 1 shows a schema of the WEDM process.

Some references can be found in the literature review related to monitoring and diagnosing in advance wire breakage. One of the most interesting lines is based on the detection of the discharge position on the wire (Guo, et al., 2003), (Kunieda, et al., 2001), (Lauwers, et al., 1999), (Obara, et al., 1990), (Shoda, et al., 1995). Some of these works are based on mathematical models. However, WEDM has a strong stochastic nature whose features depend definitely on the machining parameters. Therefore, accurate modelling is difficult if not impossible (Yan, et al., 1996).

Another interesting research line considers discharge classification in order to identify different types of degraded phenomena (Liao, et al., 1997a, b) (Yan, et al., 1995), (Watanabe, et al., 1990), (Wu, et al., 2001).

One of the remarkable aspects is that most of works are based on the development of proprietary hardware for monitoring some of the relevant process magnitudes. The time invested in the design and development of these proprietary HW systems is significant. Besides this, most of the systems have been designed for specific conditions, such as workpiece material, machine power supply and machining parameters. Therefore, the system should be re-designed in order to analyze other operational conditions and/or other magnitudes.

In general, the final goal of the works found in the literature is to detect degraded situations that allow to predict wire breakage. However, the symptoms related to wire breakage are still not completely identified and understood and, consequently, it is a very active research line.

Thus, based on the results of previous works of the authors, Cabanes (2008) and Portillo (2007), the present paper contributes a real-time monitoring system that is able to diagnose in advance different types of low quality cutting regimes in advance to wire breakage. The time since the diagnosis system raise the wire breakage alarm can be used to modify some of the machining parameters to overcome the degraded situation. The monitoring system is constructed from commercial off the shelf (COTS) hardware and software components. This constitutes a very flexible platform useful for research that allows to develop validation prototypes in a faster and simple manner. Moreover, the system can be easily employed under different experimental conditions.

The layout of the paper is as follows. In Section 2 the requirements that real-time monitoring system must meet are summarized. In Section 3, the design of the real-time monitoring system is described. In Section 4 a validation example is presented. Finally, in Section 5 the conclusions are drawn.

2. REAL-TIME REQUIREMENTS OF THE MONITORING SYSTEM

In previous works of the present authors, different types of degraded behavior were identified for different workpiece thicknesses (Cabanes, et al., 2008), (Portillo, et al., 2007). Considering the results of the identification process, an Electro-Discharge Machining Off-line Monitoring system was developed (see Fig. 2). Analysing the process history, it diagnoses the different types of low quality cutting regimes by triggering different levels of alarm (low, medium or high) depending on the degree of risk for occurring wire breakage. The system consists of two different parts. The first part is the *Virtual Instrumentation System* (VIS) that consists of virtual sensors that measure relevant magnitudes (in particular, related to the energy, the peak current and the ignition delay time of a sequence of discharges). The second part is the *Diagnostic System* (DS) that detects low quality cutting regimes and predicts wire breakage depending on the behaviour of the virtual sensors (a more detailed description of the DS module can be found in Cabanes, et al. (2008)). The system allowed the validation of the diagnosis rules proving that the detection in advance of instability tendencies was possible.

The next paragraphs summarize the generic mathematical expressions and the associated algorithms used to obtain the virtual measurements (VIS). A more detailed description can be found in (Portillo, et al., 2007):

1) For each basic window of size M, compute the total number of discharges (M_T), as well as the number of discharges whose basic variables (BV) exceeds or are lower than the reference value (RV) of each virtual sensor:

$$M(BV) = \sum_{j=1}^{M_T} p_j \text{ where } p = \begin{cases} 1, if\ BV \geq RV \\ 0, if\ BV < RV \end{cases} \quad (1)$$

2) In the first sliding widow of size N, compute the number of discharges N_T, as well as the total number of discharges that exceeds or are lower than the reference values (RV):

$$N_{BV} = \sum_{j=1}^{N/M} M(BV)_j \quad (2)$$

$$N_T = \sum_{j=1}^{N/M} M_{Tj} \quad (3)$$

3) For the following sliding windows of size M, compute the sliding computation:

$$N_{BV\,j+1} = N_{BV\,j} + M(BV)_{j+1} - M(BV)_{j+1-N} \quad (4)$$

$$N_{T\,j+1} = N_{T\,j} + M_{T\,j+1} - M_{T\,j+1-N} \quad (5)$$

$$MV_{j+1} = \frac{N_{BV\,j+1}}{N_{T\,j+1}} \quad (6)$$

However, the system did not considered real-time specifications. Consequently, the challenge is to design and develop a flexible real-time diagnosing system that could be used to improve the machine performance. Concerning this, the study of the distribution of the anticipation time is fundamental in order to know the available time period before wire breakage. Hence, the real-time detection and readjustment of the machine parameters has to be performed within the associated deadline so as to avoid wire breakage. The distribution of the anticipation time has been obtained from experimental tests in which wire breakage have occurred due to different disturbances. The results have shown that the detection strategy provides an anticipation time longer than 100 ms in approximately the 70% of the total wire breakage cases. Fig. 3 shows the distribution of different time intervals of the anticipation time for wire breakage occurred in workpieces 50 mm and 100 mm height, respectively. The results show that 95% of the wire breakage cases in workpieces 50 mm height have been predicted more than 100 ms before. The anticipation time in 41% of the cases ranges from 100 ms to 200 ms. In the case of workpieces 100 mm height, the results show that 75% of the wire breakage cases have been detected more than 100 ms in advance. Similar to the results obtained with workpieces 50 mm height, the anticipation time ranges from 100 ms to 200 ms in 39% of the cases. Among all the cases, the worst one has been approximately 15 ms. Thus, the challenge is to implement the VIS and the DS having a maximum response time of 15 ms. In order to have enough time to disconnect the power supply, a deadline of 12 ms has been selected.

3. DESIGN OF THE REAL-TIME MONITORING SYSTEM

In this section the design and development of the real-time prototype is presented. Based on a flexible approach, the main objective of the prototype is to demonstrate that is possible to read and process the samples, as well as perform a diagnostic in a time interval lower than the 80% of the worst case (12 ms). Once the objective is fulfilled, the industrial development of an embedded control system would be justified.

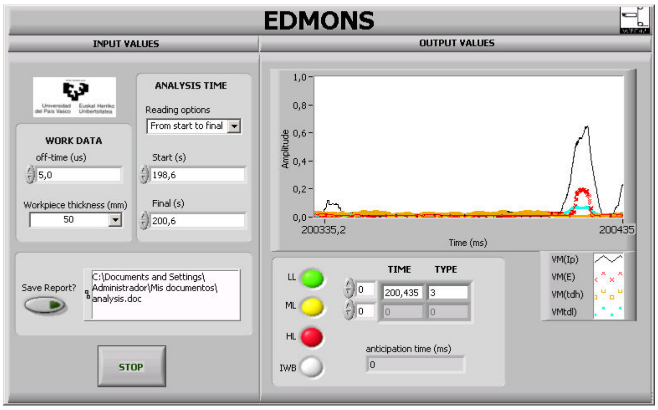

Fig. 2 Interface of the off-line monitoring system

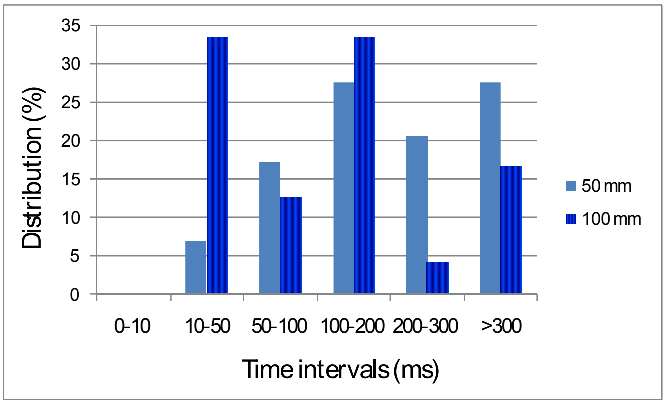

Fig. 3 Distribution of the anticipation time of wire breakage for workpieces 50 mm and 100 mm height, respectively

3.1 System architecture

Fig. 4 shows the system architecture of EDMONS-RT. The hardware platform is based on two PC's that follow the scheme *host-target*. The host allows the user to interact with the target, which is the real-time diagnosis system itself. The software platform is the LabView^{TM} real-time module, which uses the Pharlap Real Time Operating System (Ardence, 2001), (LabView^{TM}-RT, Help).

3.2 Definition of tasks

The target performs three main tasks:

1) Initialization and stop: this task deals with the initialization of the communication and synchronization mechanisms. It also finishes the other two tasks in case the host orders to finish the execution.

2) Communication: it reads and sends the host the triggered alarms, the type of degraded behaviour as well as the corresponding time stamp. This latter is used to determine the anticipation time when a high level alarm occurs.

3) Processing and diagnosing: basically, this task reads the process signals (current and voltage) at 5 MHz and processes the two modules mentioned above: VIS and DS. The processing performed by this task is periodic and consist of the following steps:

VIS: extraction of the basic variables of the discharges (energy, peak current and ignition delay time) from the current and voltage signals. The computational cost of this step depends mainly on the value of the off-time parameter. The lower the off-time, the higher the number of discharges during the computing interval M.

VIS: computation of the total number of discharges during a basic window of size M, as well as of the number of discharges that exceed (or are lower than) some predefined reference values (Cabanes, et al., 2008). The computational cost of this step increases when a degraded situation occurs since many discharges exceed (or are lower than) the reference values.

VIS: upload, download and displacement of the values computed in b. in a computing vector of size N/M. Thus, the computational cost is independent of the characteristics of the discharges.

DS: if necessary, it triggers alarms and identifies the associated type of degraded behavior. This algorithm is executed every computing interval M. Again, the computational cost depends on the characteristics of the discharges because the executed code differs.

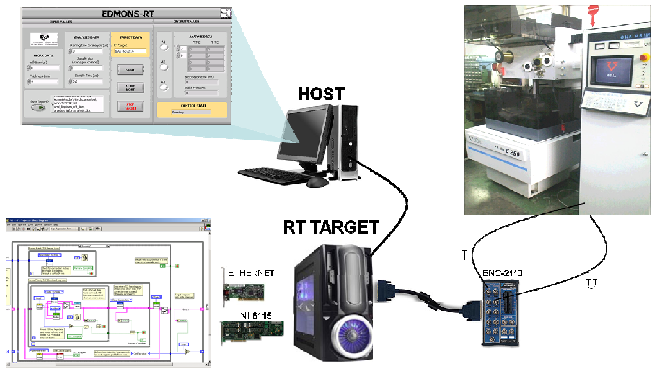

Fig. 4 System architecture

3.3 Implementation

In this sub-section, some structures and mechanisms available in the LabView^{TM} real-time module (LabView^{TM}-RT) are selected so as to provide the previously defined tasks with real-time features. In particular, the employed structures and mechanisms are the following:

1) Timed loop: this real-time structure is used to define periodic tasks. The timing source of this structure can be obtained from any properly configured hardware. Since

the processing and diagnosing task is periodic and critical, it will be implemented in a timed loop.

2) Real-Time FIFO (RTFIFO): it is a deterministic queue suitable to transmit data between threads. It is characterized by a predetermined size and by a parameter that indicates if overwriting has occurred during the execution. Considering these aspects, the data related to the alarms occurred during the cutting process will be transferred from the processing and diagnosing task to the communication task by means of a RTFIFO.

3) Functional Global Variable (FGV): this function (named *VI* in LabView^{TM}) is a shared resource that is not executed if another section of code is already using it. Similar to a RTFIFO; this mechanism is used to transmit data between threads. However, the FGV is addressed to not urgent data-transmissions. Since the request to stop the system established from the host is not considered urgent, it is manage in the target by a FGV.

4) Occurrence: it is a synchronization semaphore. In other words, it allows a section of code SC2 to execute in one thread only after another section of code SC1 is executed in another thread. Thus, when an alarm is triggered by the Diagnostic System, the communication task is activated by this mechanism.

Fig. 5 summarizes the relation of tasks and the associated real-time selected mechanisms.

As the priorities of the tasks are concerned, LabView^{TM}-RT provides 5 basic levels of priority which are, from minor to major: background, normal, above normal, high and time-critical. As the timed loops are concerned, they can be arranged in 128 levels of priority. The timed loops execute at a priority band between time-critical and high. Thus, LabView^{TM}-RT provides a total of 133 levels of priority.

Considering the characteristics of the defined tasks, the assignment of priority is established as follows: a) Initialization and stop: normal priority; b) Communication: high priority; c) Processing and diagnosing: timed loop priority.

3.4 Timing attributes

This sub-section is devoted to the specification of the timing attributes of the processing and diagnosing task, since it would be the only one to be incorporated into the final embedded system. Meeting the deadline is an ambitious challenge due to the fast dynamic of WEDM, and to the relative complexity of the processing (VIS and DS). In order to minimise computational time, mechanisms that may be time-consuming such as the dynamic memory manager have been avoided.

As for the other two tasks concerned, the stop request is read every 3 seconds (initialization and stop task). The communication task does not need timing attributes because it is not a real-time task as its function is to store the data related to alarms for further analysis.

The selection of the period of the processing and diagnosing task (executed in a timed loop) presents two main constraints:

a) The deadline of this task is 12 ms; b) The employed acquisition board (NI-6115) performs buffered acquisition instead of point by point acquisition.

Considering these constraints and particular aspects of the timed loops, some parameters have to be established:

a) Timing source: in order to synchronize the timed loop execution and the acquisition, the selected timing source is the 20 MHz clock available in the NI-6115 board.

b) Size of the acquisition buffer: there is a delay since the application activates the acquisition task and the actual execution of the task. Due to this reason, the diagnosis task must wait until the first block of samples is acquired. From now on it is called *initialization offset*. A total of 50000 activations of the timed loop initialization have been executed during a test phase in order to measure the mean and the standard deviation of the initialization offset. The mean is approximately 7.7 ms (considering the acquisition frequency of 5 MHz, 7.7 ms is equivalent to 38539 samples), and the standard deviation is 344 μs (equivalent to 1719 samples). Consequently, a buffer size of 40000 samples (equivalent to 8 ms) has been defined.

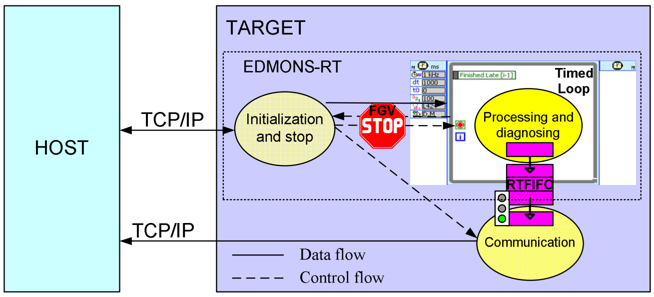

Fig. 5 Relation of tasks and the associated real-time mechanisms

c) Number of samples to be read and processed during each activation of the processing and diagnosing task: in order to determine it, it is necessary to know the maximum response time. The latter is the result of the sum of the following time intervals: the initialization offset, the time necessary to read the samples from the buffer (ReT), and the maximum computational time of the diagnostic algorithm (CoT). The *initialization offset*, which has been defined in the previous point, is 8 ms. As the ReT is concerned, on one hand, the number of samples to be read and processed should be high enough to reduce the time lag due to the transference operation. On the other hand, at the sight of the initialization offset, the number of samples should not exceed 35000 (equivalent to 7 ms). Since the exact transference time is not available for the user, statistical tests aimed at measuring the time necessary to read the samples generated in different time intervals (between 1 and 7 ms) are performed. In Fig. 6 the results of the reading time measurement (ReT) is shown during 50000 activations. The equivalent number of samples read per activation, the mean and standard deviation of the reading time, and the percentage of the reading mean time over the total available time T, are depicted per time interval. These experiments show that the lowest reading time is provided by the time interval of 4 ms. In order to measure the maximum computational time CoT, it is necessary to define the characteristics of the machining process samples that provoke the highest one. Based on the results of the analysis in Cabanes (2008), the worst case happens when a minimum off-time is adjusted (in this case, 5 µs), all the basic variables exceed (or are lower than) the predefined reference values, and the alarms are triggered. In order to reproduce the worst case, a low quality discharge has been obtained from the real experimental database. The discharge is repeated along time aimed at measuring the CoT during the different time intervals, that is, between 1 and 7 ms. It is remarkable that this analysis is pessimistic because such a sequence of discharges cannot exist: actually either the machine reacts, or the wire breaks down. Again, Fig. 6 shows the results of the measurement of the maximum computational time during 50000 activations. It can be noticed that, in all the cases except for the 1 ms time interval, the CoT involves the 79% of the total available time. Possibly, the slightly higher CoT in the 1 ms time interval is due to a more noticeable computational charge of the timed loop with smaller time intervals. In order to select the most appropriated number of samples to be read and processed during each activation of the task, the whole effect of both ReT and CoT can be analysed in Fig. 6. The lowest processor occupation is yielded by the time intervals of 4 and 5 ms. The criterion applied to rule out one of both is to select the time interval with the lowest Coefficient of Variation CoV, which corresponds to 4 ms.

d) In summary, the parameters of the timed loop are the following: period and deadline of 4 ms; the priority is irrelevant since only one timed loop is used; no offset is applied; and the late execution of the timed loop is handled by not processing any missed activations, and by defining a new schedule that starts at the deadline missing time. Both options can avoid provoking subsequent missing deadlines.

4. VALIDATION EXAMPLE

This section presents a validation example performed at an industrial WEDM machine (ONA PRIMA E-250). It reproduces a degraded situation consisting of cutting corners of 60º in a 50 mm height (AISI D2) tool steel work part. The value of the off-time parameter is the minimum one: 5 µs.

During the experiment, 50000 activations of the processing and diagnosing task have been executed (equivalent to 200 seconds), and the response time of each activation has been measured. The results show a mean response time of 3.25 ms with a standard deviation of 0.25 ms. These results involves a CPU occupation percentage of 81.25%, which is lower than the value obtained from the analysis (83%).

Table 1 shows some traces captured during the real-time experiment by the *Execution Trace Toolkit* of LabView^{TM}-RT. In the upper side of the figure, the Thread Events View is depicted. In the lower side, the VI Events View is shown. The traces display the timed loop priority, the high priority and the normal priority. The flags indicate that the deadline has been fulfilled.

In particular, in Table 1 the initialization offset is marked by a double side arrow between two cursors. As established in the previous section, the initialization offset is approximately 7.7 ms that correspond to 38500 samples (in this particular case, 7731.35). The other two cursors, which are provided by the Execution Trace Toolkit, delimit the ReT and CoT of one of the activations of the timed loop. The latter time interval is 3270.96 µs, which is displayed in the right upper side (see the circled area in Table 1.

CONCLUSIONS

The main conclusion of this paper is that the current HW/SW technologies make possible to diagnose in real-time tendencies to degraded operation working at frequencies of 5 MHz. This work has presented a flexible platform for research that allow to validate the results of the analysis of very high dynamics processes such it is the case in Wire Electro-Discharge Machining WEDM and Die Sinking Electro-Discharge Machining SEDM. The proposed system is supported by the use of a commercial data acquisition board that allow to capture the complete signals of the process, and by the establishment of virtual sensors in a versatile manner making use of LabView^{TM}-RT. The success of the design and development allows to justify a future industrial development of an embedded control system.

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Table 1 Time necessary to read the samples from the buffer (ReT), and maximum computational time of the diagnostic algorithm (CoT)

Time interval per activation T (ms)	Number of samples read per activation	ReT-Mean time (µs)	ReT-Standard deviation time (µs)	ReT/T (%)	CoT- Mean time (µs)	CoT- Standard deviation time (µs)	CoT/T (%)	(ReT+CoT)/T (%)
7	35000	362,48	6,72	5,17	5514,43	18,40	78,77	83,94
6	30000	265,04	5,69	4,41	4732,31	17,92	78,87	83,28
5	25000	209,51	2,50	4,19	3940,10	17,14	78,80	83
4	20000	163,55	1,18	4,08	3156,93	14,27	78,92	83
3	15000	128,29	1,91	4,27	2366,40	10,68	78,88	83,15
2	10000	89,98	0,90	4,5	1576,61	11,54	78,83	83,33
1	5000	57,46	1,75	5,74	805,27	8,12	80,52	86,26

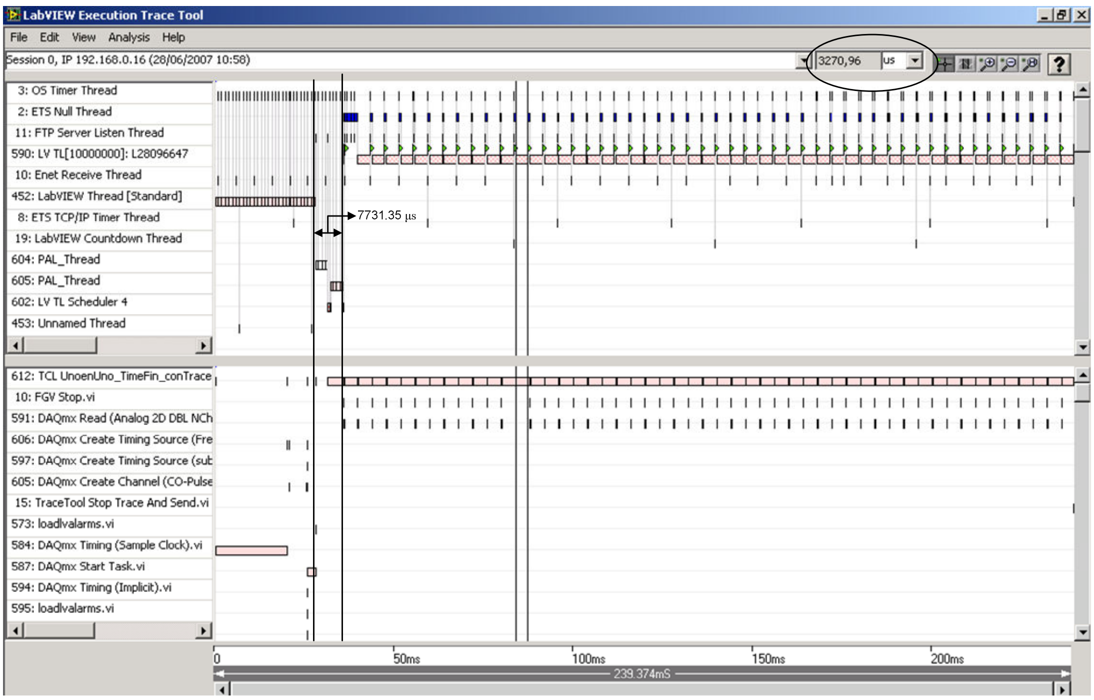

Fig. 6 Validation example: traces