Progress in Nuclear Energy 99 (2017) 140–146

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

Localization of loose part impacts on the general 3D surface of the nuclear power plant coolant circuit components

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ARTICLE INFO

Article history:
Received 15 December 2016
Received in revised form
19 April 2017
Accepted 12 May 2017
Available online 30 May 2017

Keywords:
Monitoring
Loose part
Signal processing
Time-frequency analysis
Localization
Nuclear power plant

ABSTRACT

A fundamental monitoring system in nuclear power plants is the so called loose part monitoring system (LPMS) detecting, localizing and specifying the loose parts (such as rivets, nuts, ...) within the reactor coolant system. The loose parts could drift along the coolant flow and cause damage to the coolant system components, leading to power plant failure. One of the main tasks is a precise localization of the loose part impacts in order to identify the loose part and trace its motion in the system. Current localization methods are based on the time-of-arrival evaluation of mechanical waves travelling through mostly metal components from the impact place to the sensor positions. Diverse methods have been proposed, such as hyperbola or circle intersection methods, which are more or less analytical methods with a low grade of algorithmization, thus requiring a portion of manual effort. The proposed 3D localization method is flexible and efficient based on an algorithm for computing the shortest path along a general surface of components. This paper also presents a deeper insight into the mechanisms of the 3D localization method by analyzing its error and structural limitations. In the end, results obtained in an experiment on a real reactor vessel are presented.

1. Introduction

The problem treated in this paper is loose part localization in the reactor coolant system of a nuclear power plant (NPP). If the loose part changes its location in time, the localization problem can easily be turned into a tracking problem. Due to the drag force of the circulating coolant, the loose part can start to move. This uncontrollable motion is a safety hazard to the operation of the NPP, possibly causing damage to the inner boundary of the coolant system or blockage of the control rods. There is therefore a natural demand to obtain as much information about the loose part as possible including the exact location of that part.

The loose part monitoring system (LPMS) detects loose part motion on the basis of sensing vibration signals, which propagate in the metallic parts of the system (see for example Mayo, 1994; Olma, 1985). The major limitation of all loose part monitoring systems is that detectors can be placed only on the outer boundary of the coolant system and not inside where the loose part is found. Today, a common indirect way to detect the loose part is to measure vibrations using accelerometers placed on the outer boundary of the coolant system. The loose part impacts during its motion to the inner wall of the coolant system and initiates transient mechanical waves (also called structure borne sound, see Cremer et al., 2005). These waves propagate along the boundary of the coolant system and are sensed by the accelerometers.

A lot of effort has already been made in the field of loose part localization. As a starting point of all the algorithms, the times of arrival of the mechanical wave to particular accelerometers are determined. This can effectively be solved in time-frequency domain (Kim et al., 2003; Olma, 1985, 2003) or with the use of wavelet transformation (Figedy and Oksa, 2005). For the localization itself, diverse methods have been proposed, such as hyperbola intersection method or circle intersection method (Szappanos and Por, 1999). These are analytical methods with a low grade of algorithmization, thus requiring a portion of manual effort.

The proposed 3D localization method can be characterized as flexible and efficient. The flexibility relates to the algorithmic nature of the 3D localization method, as opposed to the conventional approach. It has certain inputs and an output which makes it easy recalculable if the sensor positions change or if different resolution of the result is desired. Efficiency is achieved by an ingenious breakup of the algorithm in an offline and online part. The offline part is

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http://dx.doi.org/10.1016/j.pnucene.2017.05.004
0149-1970/

computationally more expensive, however it is executed only once. The output of the offline part is then stored in the memory and used as an input for the online part which is executed every time a new impact has to be localized, but with relatively low computational costs as it is a simple $O(n)$ algorithm.

The following text of the paper is structured as follows. Section 2 provides a technical background to the problem and defines some assumptions for the 3D localization method. Sections 3 and 4 introduce two subsidiary algorithms necessary for the 3D localization method. Namely a time-frequency method for computing the time of arrival of a transient in a signal is introduced in section 3 and an algorithm for computing the shortest path along a general surface is discussed in section 4. The algorithm of the proposed 3D localization method is described in section 5. Section 6 provides a deeper insight into the mechanisms of the 3D localization method by analyzing its error and structural limitations. Section 7 presents the results of the 3D localization on a real reactor vessel. The most important findings are briefly summarized in the Conclusion.

2. Technical background and preliminaries

If a loose part impacts against the inner boundary of the coolant system, a mechanical transient wave is generated. It is supposed that the wave propagates along the boundary of the coolant system with a constant speed which is independent on the actual location and direction. As a consequence, the wave propagation time between two points on the surface is uniquely determined by the length of the shortest path along the surface between these points.

The generated wave is measurable with accelerometers placed on the outer boundary of the coolant system. These accelerometers are mounted perpendicularly to the surface and thus measure transverse waves. As the anti-symmetric mode of the wave is being detected the wave speed considered in the objective frequency band is 3100 m/s. Detailed information on mechanical waves can be found in (Rose, 1999).

The time between the wave initiation and its detection on a sensor depends on the distance between the impact location and the sensor location. If more than one sensors were used, each sensor will detect the wave in a generally different time as the distance from the impact to respective sensors is generally different. It can be assumed, that each possible impact location yields a unique combination of detection times. Conversely, measured detection times uniquely determine the impact location. This is the key principle of the proposed 3D localization method.

For simplicity, the term ‘detection time’ will denote an N-dimensional vector of detection times obtained on all N sensors.

3. Time-frequency methods for impact detection

Impact detection is a standalone problem requiring advanced signal processing methods. The goal is to determine the first time of a burst in the signal. There is no general method for burst detection. Instead, the detection algorithm and its parameters have to be tuned to gain the best performance in a particular situation. For the proposed 3D localization method, thresholding of the k-value computed from the stochastically normalized short-time Fourier spectrogram (Bechtold and Ocelik, 2004) proved to be a good choice.

In Fig. 1, a measured burst signal corresponding to the transient wave initiated by an impact is shown.

At first, the signal has to be transformed from the time domain to the time-frequency domain. For this purpose, the short-time Fourier transform (STFT) is applied. The spectrogram obtained for the signal from Fig. 1 is shown on the left hand side of Fig. 2. Because the time information is more important than the frequency

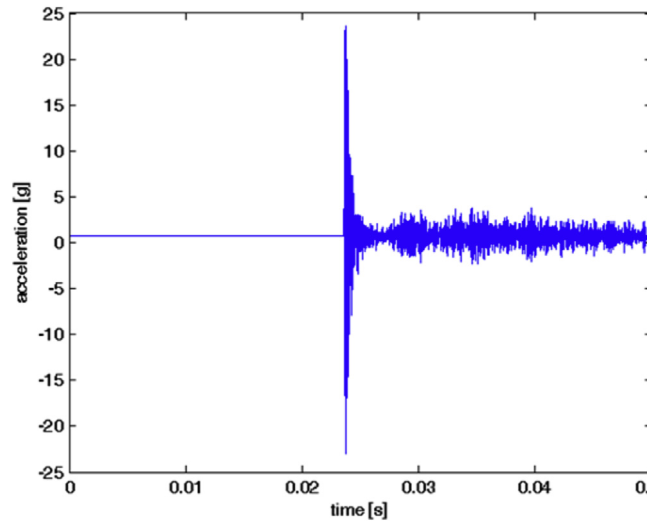

Fig. 1. Burst signal.

information, the stochastic normalization of the spectrogram can be executed. This process normalizes the mean amplitude and variance of each frequency line of the spectrogram. As a consequence, the burst gets more contoured as seen on the right hand side of Fig. 2.

Subsequently, the k-value is computed by summing all the values of individual columns of the normalized spectrogram. The transient wave time of arrival is determined as the time where k-value exceeds a threshold. The value of the threshold is a matter of choice. A value of 200 has been proven to be a good choice in our case as it is half the height of an average peak. In Fig. 3, the red point depicts the time when the k-value exceeds the threshold.

4. Computing the shortest path along a surface - application of the Chen and Han algorithm

In the offline part of the 3D localization method, there is a need for computing the shortest path between two vertices along a triangulated surface of a general shape.

One possibility is to use the discrete Dijkstra's algorithm (Cormen et al., 2009) for finding the minimal path in a weighted graph. In this case, the vertices of the mesh are assumed to be the nodes of the graph and the lengths of the edges of the mesh are assumed to be the weights of the graph. Dijkstra's algorithm is easy to implement, however its results are not satisfactory. In particular, if the triangulated mesh contains faces of an unsuitable shape, the nature of the minimal path being a sequence of edges becomes limitative. The shortest path found by the Dijkstra's algorithm for two different meshes representing the same object is shown in Fig. 4.

To compute the exact shortest path along a surface, the Chen and Han algorithm (Chen and Han, 1990; Xin and Wang, 2009) can be used. It is named after its inventors who proposed the use in the field of motion planning. However, their algorithm can advantageously be used in 3D localization method as it gives the exact shortest path independent of the actual triangulation of the model.

This algorithm makes use of the fact that the shortest path turns into a straight line if all the faces it intersects are unfolded into a single plane. It considers the actual shape of the object compared to the Dijkstra's algorithm which considers only the lengths of the edges. A detailed analysis of this algorithm is out of the scope of this paper and can be found in the references.