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REPORT

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LOGIC BASED FEATURE DETECTION ON INCORE NEUTRON SPECTRA

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Logic Based Feature Detection on Incore Neutron Spectra

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ABSTRACT

A general framework for detecting features of incore neutron spectra with a rulebased methodology is presented. As an example, we determine the meaningful peaks in the APSD-s. This work is part of a larger project, aimed at developing a noise diagnostic expert system.

Keywords: rule-based systems, Bayesian inference, knowledge engineering, linguistic variables, incore detectors.

Bende-Farkas S., Kiss S. és Rácz A.: Incore neutronspektrumok jellemzőinek logikus felismerése
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KIVONAT

Egy szabályokon alapuló eljárást mutatunk be incore neutronspektrumok jellemzőinek felismerésére. Illusztrációként meghatározzuk a jellemző csúcsokat egy APSD-n. Jelen munka része egy, jelenleg kifejlesztés alatt álló, reaktordiagnosztikai szakértői rendszernek.

Kulcsszavak: szabályokon alapuló rendszer, Bayes-i döntéshozatal, knowledge engineering, lingvisztikai változók, incore detektorok.

Introduction

Extracting information from neutron spectra could be regarded as a kind of art. It is a *difficult* task involving knowledge of reactor as well as a complicated (though unconscious) visual image processing. On the other hand, it is *important* because helps to reveal the changes of the underlying system [1].

Neutron spectra interpretation demands both experience, fantasy, intuition as well as good eyes since the features in the neutron spectra are usually not too salient. Due to the above criteria, hardly can two experts be found, reaching the *same* conclusion when investigating the *same* spectrum. Although the disagreement can explore unbelievable depth of knowledge it would be better if the common background could be seen more clearly.

Nowadays we have arrived the border line. In one hand there are enough information as well as both theoretical and experimental knowledge about neutron spectra. On the other hand this knowledge is not consistently organized. Certainly ample important articles appear answering particular questions. However, even if these works refer to different viewpoints of other authors, it is almost impossible to see if

- there are any differences at all
- these differences are real or only virtual
- the mentioned differences could really cause the final disagreements

The list can be continued up to infinity. Certainly, these problems are not attached only to neutron spectrum interpretation. It can be said for each field of any sciences, human and/or natural. We do not intend to find the final answer (since even the final question is covered). Our goal is very "simple". We *only* would like to computerize (algorithmize) the neutron spectrum interpretation. In order to do it the first step is to find out what kind of information can be get from *human experts* at all. Afterwards a *language* must be defined by which this knowledge can be fed to the computer.

To handle the above problems a new area of sciences is being developed, the so-called *knowledge-engineering*. Let us consider the following "simple" but important question: "What is the probability of a double-peak in an APSD, if ...?". It is almost impossible to get *definite* answer from an expert for it. A definite answer can be expressed as a number, i.e. $p = 0.3$ (where p is the probability in the above sentence). However a typical answer rather is "well, it is quite sure" or "it depends" or "not big" or "almost impossible", etc. These are not definite answers, and it is better to consider the probability as a *linguistic variable* taking some "values" like

$$p \overset{\text{def}}{=} (\text{impossible}, \text{small}, \text{medium}, \text{large}, \text{almost sure})$$

There are special programming languages (e.g. PROLOG) to treat this kind of variables [2]. In this work we show how a system can be built up using these new tools and methods. We propose a methodology for recognition elementary features (peaks, linear segments, ascending and descending lines, etc.) in neutron spectra. In this paper we are concentrating only on recognition *physically relevant peaks* in an APSD.

Let us summarize why *automatic* neutron spectrum interpretation is *principally new*. (The reason, why it is *important*, has already been mentioned.)

- It leads to a systematization of knowledge.
- A useful training systems can be developed using it.
- It applies the rules consistently, unlike the humans.
- The completeness of the rule system can be checked relatively easily.
- The rule system can be easily modified whenever it is necessary.

Recognition of a real peak is a two-step process. [Henceforth "real peak" is meant for those peaks which have physical significance according to a given (and hopefully complete and consistent) rule system.] First every *peakish* part of the spectrum is detected and collected without attaching any physical significance to them. They are referred to as *elementary peaks*. Afterwards the *real peaks* (or *peaks* for brevity) are selected from them. A *confidence level* is calculated and assigned to every peak measuring the significance (or the trust of an expert in the relevance) of the peak. The confidence level is calculated via *Bayesian logic*.

The *peakishness* will be defined in a self-consistent way keeping in mind that there are many possibilities to choose peaks from a spectrum. The situation is the same during attaching physical significance to every elementary peak. The rule system is applied here only one way to recognize real peaks in a neutron spectrum. However, the method is general and any other rule system can be implemented following the proposed way.

As a matter of fact, there has been several attempts to make the spectrum interpretation *automatic*. However, our method is superior to them in that sense that it offers a bridge over the discontinuity between machine algorithms and the human thinking schemes.

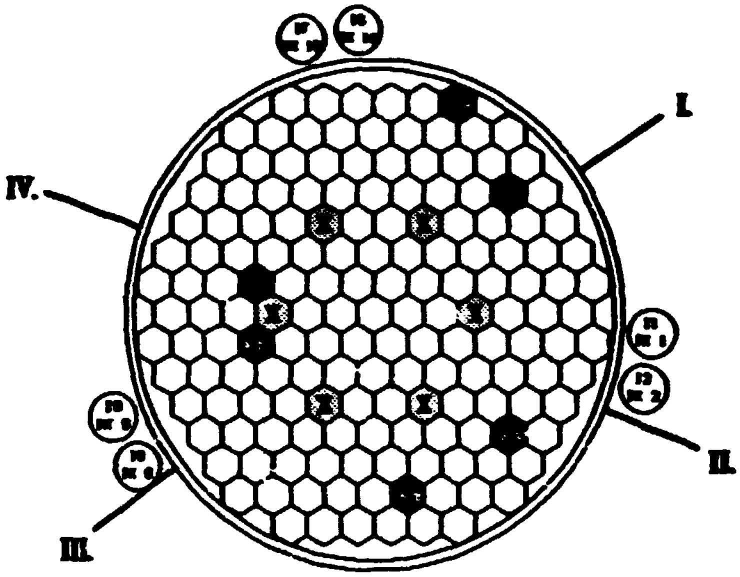
This article represents only the starting point of a large diagnostic expert system under development. Our main point is to *demonstrate* how a new methodology can support experts not only to save their time performing repetitive and boring (mechanical) tasks but also to open a principally new line to compare and check different viewpoints.

The organization of the paper is the following. In Section 2 we overview both the theoretical and experimental background of getting neutron spectra. The rule system to recognize real peaks is presented in Section 3 while Section 4 is devoted to the Bayesian decision methods. The methodology is applied on real signals. An illustrative example for detection peaks in an APSD is shown in Section 5. The discussion, open problems and near future researches are summarized in the Conclusions.

2. Evaluating incore neutron detector signals

In this Section the main points of noise diagnostics based on neutron signal investigation are surveyed. There is no *direct way* to map the inside of a reactor core because of the extrem conditions ($p \approx 120\text{bar}, T \approx 270°\text{C}$ at a WWER-440 NPP) and the very high radioactivity. Therefore only *indirect* information is available. The most popular method is applying self-powered neutron detectors (SPNDs) to observe the neutronic processes going on the core. For orientation the intersection of the core can be seen in Figure 1.

Figure 1



The core map of a WWER—1000 reactor used for noise diagnostics
black hexagones — strings of SPND detectors
shadowed hexagones — clusters of the tenth group of control rods
I.–IV. — inlet/outlet tubes
circles — ionization chambers

Besides the incore detectors, the following devices are also used in noise diagnostic evaluations;

- thermocouples (for only low frequency [< 0.5Hz] thermic fluctuations)
- ionization chambers (for the motion of the core barrel)
- vibration detectors (for the global motion of the reactor vessel and inside vibration phenomena)
- inlet and outlet pressure detectors

In the following we are concentrating on *neutron detectors.*

The major part of the signal obtained from SPN detectors can only be used to determine the *steady–state* power since these detectors have very long response time (about 10 min.). Only 5–7% of the DC signal is *prompt*; this part is used to investigate the high frequency behaviour (for noise diagnostics). In addition, the SPN detectors have other drawbacks, namely:

i) The neutron detector has a relatively large (≈ 30cm) linear size.
ii) Mechanical vibrations can be detected only *indirectly*.
iii) Long wires are necessary to carry signals; the relevant information may be suppressed by the background noise.

After having separated the fluctuating part in the detected signal by high-pass (≈ 0.1Hz) filters, the second task is to explore the relevant information. It can be done by the familiar FFT (Fast Fourier Transformation) methods. Since the most important time-dependent processes have a relatively low characteristic frequency (usually less than 50Hz), the sampling frequency is about 100Hz. In order to avoid the so-called *aliasing* of the higher components, the signals must be pre-filtered by a low-pass (≈ 40 – 50Hz) filter.

Mutual investigation of the *phases* and *coherences* of different signals recorded from different detector positions helps to understand both the *spatial* and the *collective* behaviour of the underlying mechanisms. In theory, *local* changes have *global* effects. In practice, it means that a pointwise perturbation influences the detectors which are situated in the neighborhood of the changes. The extent of the influence depends on the scale and the type of the local effect. For the problem in hand, it has a major advantage. In fact, having detected something unusual only by *one* detector while there is no trace of the effect in any other signal, suggests *measurement failure*. In contrary, a real physical event modifies almost all detected signals. This knowledge is built into the rule system which is applied to separate physical events from unphysical ones.

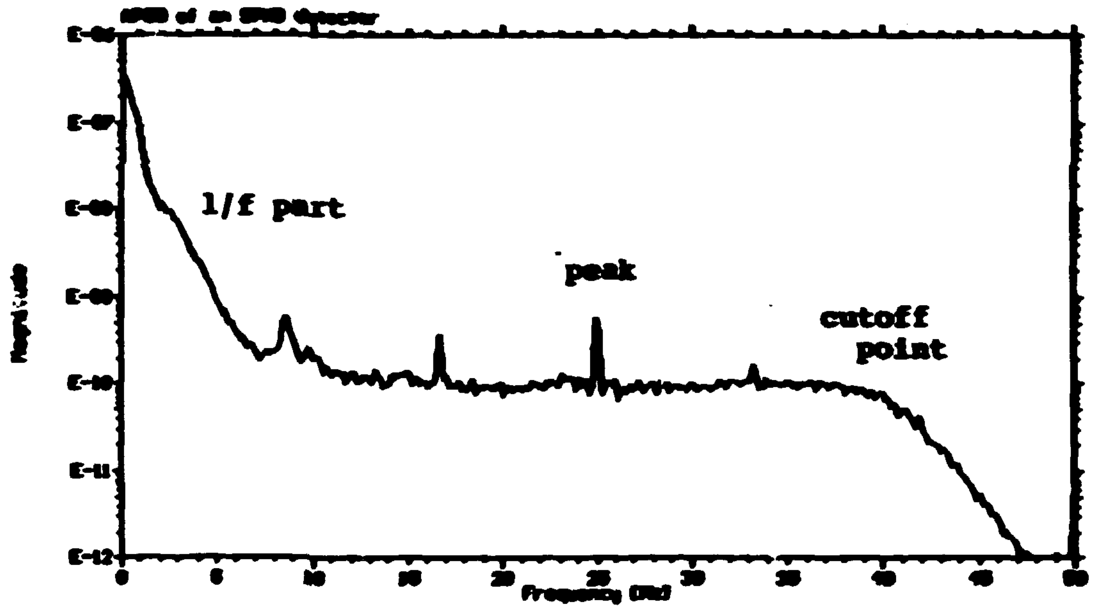
Figure 2 shows a typical spectrum. Knowing the characteristic of the applied low-pass/high-pass filters and the sampling frequency during the A/D conversion, the general shape of the spectrum can be predicted. Thus certainly exist

- an exponentially decreasing part in the low frequency band
- wideband peaks
- a cutoff point

Some of the above features are well known and thoroughly investigated. As an example, in the WWER-1000 NPPs a peak at 16Hz is assigned to the main pump. On the other hand, the most important features are those that can *not be predicted*. These peaks have the most important information about some changes in the underlying system therefore these peaks must be reliably recognized. However, even a well-trained expert could overlook some unusual phenomena. In fact, some new peaks are not too significant (they are hidden by the background noise) and can only be recognized via a *systematic search*. Although *theoretically* a systematic search is an *easy* task, in practice it is almost impossible to perform because of the large amount of signals. If the appearance of a new peak is predicted (or expected) in a restricted frequency range, then the peak is recognizable; on the other hand, without any expectation, there is almost no chance to find anything. On the other hand, the neutron detectors provide *only indirect* information about the vibration mechanisms. Therefore the peaks are *smashed* and usually suppressed by the background noise. Human recognition could easily overlook it. In the following we will show how a compact rule system can be applied to

- find the predicted peaks
- find peaks without any prior expectation.

Figure 2



A spectrum with its characteristic points and features (details in the text).

3. Peak recognition

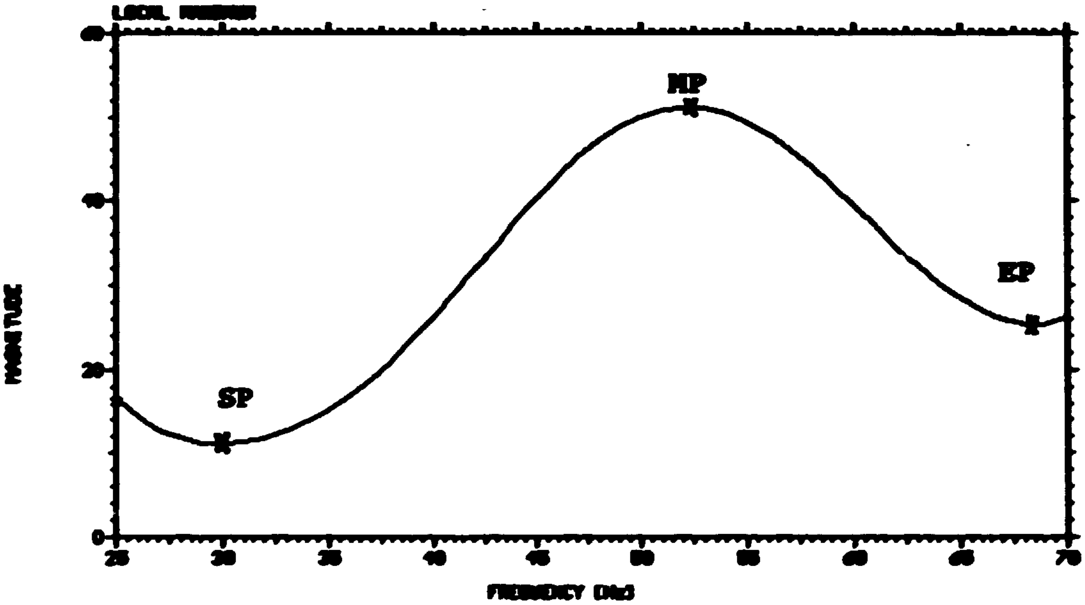
We would like to follow the thinking of human experts when separating physical peaks in a spectrum. Usually an (unconscious) visual prepocessing selects "peakish" things. Sometimes these features are called *visual peaks*. Every part of the spectrum satisfying a simple condition (*local properties*) listed below is regarded as a visual peak. In the second stage *additional* properties and conditions are introduced to *narrow* the set of the found visual peaks in order to pick out the *real peaks* from them. During the separation process every element of the final set containing the real peaks has a *weight* or a *confidence level* showing its significance. It is possible to separate different classes exploring the differences in the confidence levels. It helps e.g. to recognize new phenomena since the well-known peaks (with high confidence level) can be in a separated class. Therefore the weights have double-role:

- Imitates a real (human based) selection process.
- *Makes further classifications possible.*

In this work the following conditions are used for preselection as well as further classification.

Preselection: Visual peaks are the *local* maxima of the spectrum. During the calculation a *simple gradient method* is applied to create a *list* containing local maxima. *Four* attributes are assigned to a visual peak, namely its *start* (SP), *middle* (MP) and *endpoint* (EP) as well as its *relative height* (RH). (See Figures 3 and 4). The function $H(\cdot)$ measures the magnitude of the APSD.

Figure 3



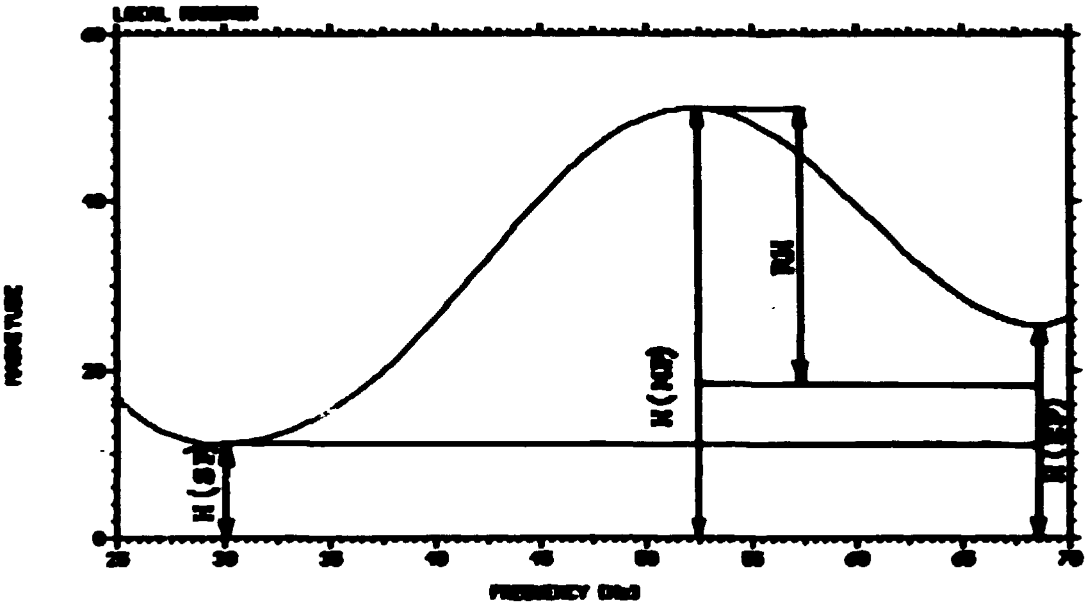
Start point (SP), middle point (MP) and
end point (EP) of a local maximum.

$$\mathrm{RH} \overset{\mathrm{def}}{=} H(\mathrm{MP}) - 0.5 \times [H(\mathrm{SP}) + H(\mathrm{EP})]$$

After constructing the list of visual peaks, further selection is done. This step begins with a *filtering* when those local maxima, whose relative height are *less* then a *threshold value* are *discarded*. Obviously the choice of the threshold value is arbitrary. There is no way to decide the best value. Usually it is set by so-called *ex chatedra* methods, or at least the determination of the threshold value comes from certain *compromise*.

Confidence level is calculated using the Bayesian decision method. The general rules are the following:

Figure 4



Relative height (RH) of a local maximum

i) *If* there are local maxima at a given frequency in more then one spectrum calculated from the neighboring detector signals *then* the confidence value *increases.*
ii) *If* there is a maximum in the coherence in the neighborhood of a frequency *then* the confidence value *increases*
iii) *If* the frequency is higher then the cutoff frequency of the filters *then* the confidence value *decreases.*
iv) *If* the relative height is greater than a threshold value *then* the confidence value *increases*
v) *If* a physically meaningful peak *was* found at a frequency in previous measurements *then* the confidence value *increases.*

Rule v) is implementable only in special circumstances, i.e. when previous results are also available. Here only the general rules are listed since the next part of the article gives the details of the Bayesian decision methods.

Sometimes a *final selection* is performed when the confidence levels are compared to a threshold value.

In the following these rules are applied to detect physical peaks. First the expressions (increasing, decreasing) are related to numerical values (linguistic variables). Afterwards it will be shown, how confidence level (or likelihood) can be related to physical significance (Bayesian reasoning).

4. Bayesian decision methods

Here we show how the general rules listed in the previous Section can be formulated in order to calculate the confidence levels. The inference procedure must be able to evaluate conditional probabilities. Let H denote the hypothesis that the find local maximum is a real peak and let e be an event listed in the rules. For example, rule ii) says that there is a maximum in the coherences. Thus the conditional probability $P(H|e)$ measures the likelihood that a local maximum is a real peak *if* on other spectra real peaks were found at neighboring frequencies. The final task is to determine the $P(H|e)$ probabilities. However, it is easier to calculate $P(H|e)$ indirectly, i.e. through the $P(e|H)$ probabilities. In fact, if we know that a local maximum is a real peak, then both experiments and theory can predict the probability $P(e|H)$ that there is a real peak in the neighborhood frequencies at other spectra. Having known $P(e|H)$ values the Bayes theory gives the tool to determine $P(H|e)$ probabilities [3]. The familiar *Bayes formula* is the following:

$$P(H|e) = \frac{P(e|H)P(H)}{P(e)} \tag{1}$$

where $P(\cdot|\cdot)$ denotes the *conditional probability*; $P(H|e)$ is the probability of hypothesis H upon obtaining event e; $P(H)$ is the *a priori* probability of hypothesis H; $P(e|H)$ is the probability of occurrence event e if hypothesis H is true; $P(e)$ is the probability of an event e. The changing of the confidence level is proportional to the calculated $P(H|e)$ conditional probability. As it can be seen, some previous information is necessary to evaluate $P(H|e)$, namely the probabilities $P(e|H)$ and $P(H)$. The probability of event e is out of interest. In fact, the following two constraints hold:

$$P(H) + P(\bar{H}) = 1 \tag{2}$$

$$P(H|e) + P(\bar{H}|e) = 1 \tag{3}$$

where $\bar{H}$ is the *negation* of hypothesis H. After applying the Bayes rule for $\bar{H}$

$$P(\bar{H}|e) = \frac{P(e|\bar{H})P(\bar{H})}{P(e)} \tag{4}$$

and taking advantage of Eq.(3), the probability $P(e)$ reads

$$P(e) = P(e|H)P(H) + P(e|\bar{H})P(\bar{H}) \tag{5}$$

After substituting Eq.(5) into Eq.(1) and utilizing Eq.(2), the conditional probability $P(H|e)$ takes the final form:

$$P(H|e) = \frac{P(e|H)P(H)}{P(e|H)P(H) + P(e|\bar{H})[1 - P(H)]} \tag{6}$$

The interpretation of the above formula is the following. In order to calculate the probability of a hypothesis H conditioned in the event e, the *a priori* probability $P(H)$ must be known. Here $P(H)$ is calculated as the *relative frequency* of the occurrence H, i.e.

$$P(H) \overset{\text{def}}{=} \frac{\text{expected number of real peaks}}{\text{average number of local maxima}}$$

From experience, $P(H)$ was set to $P(H) = 0.1$. In additional. the probability $P(e|H)$ must be known (or guessed) also, i.e. the likelihood that the event e would happen *if* hypothesis H is true. On the other hand, event e could also happen *if* hypothesis H is not true. The conditional probability is quantified by the likelihood $P(e|\bar{H})$.

In our case, $P(e|\bar{H})$ measures the probability that, for example, there is a maximum in the coherence *but* there is no physical peak at the given frequency. In the following Eq.(6) is applied to determine the confidence levels.

First the probabilities are translated into *linguistic variables* denoted by LV. By definition, the following linguistic "values" are introduced:

$$LV \overset{\text{def}}{=} \begin{pmatrix} \textit{surely not} \\ \textit{small} \\ \textit{medium} \\ \textit{large} \\ \textit{sure} \end{pmatrix}$$

Afterwards *numerical values* are assigned to them. The numerical values originate either from *well-trained* experts or computer simulation results. Here the following matching seemed to be appropriate:

$$\begin{pmatrix} \textit{surely not} \\ \textit{small} \\ \textit{medium} \\ \textit{large} \\ \textit{sure} \end{pmatrix} \Longleftrightarrow \begin{pmatrix} 0.0 \\ 0.2 \\ 0.5 \\ 0.8 \\ 1.0 \end{pmatrix}$$

Obviously, there is no *theoretical* limitation of the number of LV variables and values. However, practice confirmed that it is not worth to use more LV values. The reason is that the more values are introduced the harder to get definite answer from experts about their numerical representation.

As it has been outlined, the merit of using Bayes rules is that it is easier to predict the $P(e|H)$ probabilities than the $P(H|e)$ values. An expert can guess the likelihood that *if* there is a real peak in the spectrum then it has the trace in the coherence as well. For illustration, Table I shows the probabilities $P(e|H)$ and $P(e|\bar{H})$ determined using both experimental and theoretical knowledge about neutron spectra.

The events e are related to the rules mentioned previously. The notation H stands for the hypothesis that there is a real peak at the given frequency, while $\bar{H}$ denote the *negation* i.e. that no real peak is in the given frequency.

Table I

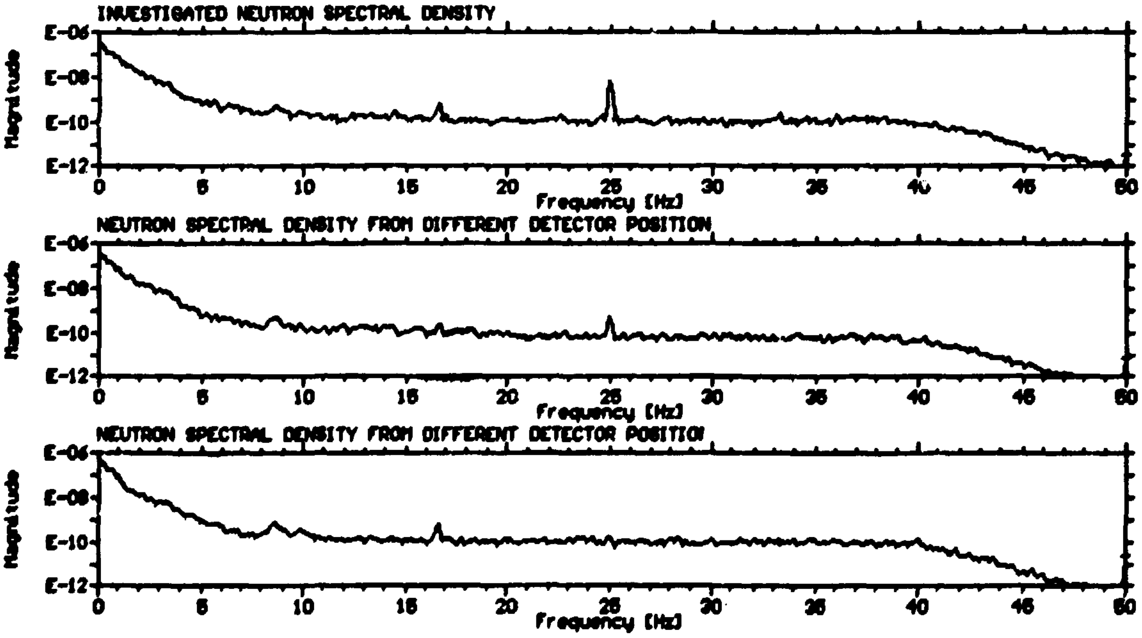
event e	$P(e\|H)$	$P(e\|\bar{H})$
rule i)	*large*	*small*
rule ii)	*large*	*medium*
rule iii)	*large*	*small*
rule iv)	*large*	*small*
rule v)	*small*	*medium*

The conditional probabilities expressed through *linguistic variables.*

5. An example

Here we show an example to demonstrate the capability of the method. *Three* neutron detector signals were co-analyzed.

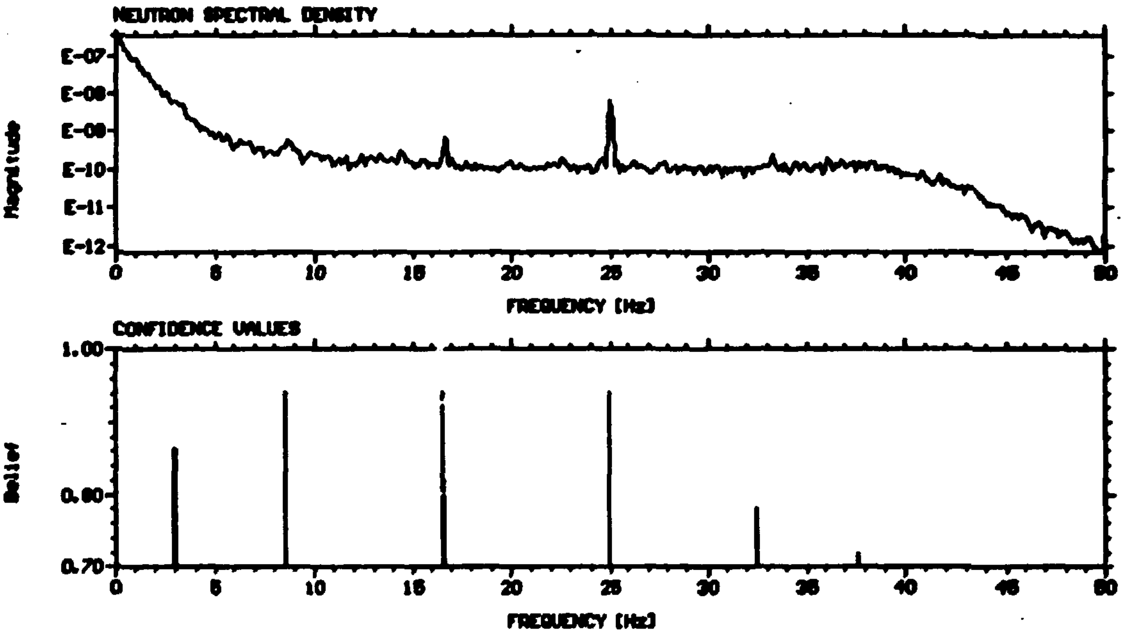
Figure 5



The three different spectra

The three SPN detectors were located at different points. The peak detection procedure was performed at only one APSD; the additional two signals were used to get further information (coherences) about the significance of certain *elementary peaks*. Figure 5 shows the three APSDs. They are calculated by conventional signal processing methods (FFT).

Figure 6



The analyzed spectra (upper part) and the peaks with the confidence levels (lower part).

Since *no* previous analysis was performed, rule v) cannot be applied here. The real peaks were recognized using only rules i) – iv). As it has been mentioned in Section 3 a final selection can be performed if necessary. For the problem in hand, that peaks which have smaller confidence level than 0.7, were not included in the final list. The result is given in Figure 6. The upper part shows the spectrum; the lower part displays the locations of the real peaks and the calculated confidence levels.

Considering the final result it can be seen that the method is able to recognize significant peaks. It is easy to check since experts know characteristic peaks in the APSDs. Namely,

- ≈ 8.5Hz: standing waves in the primary loop
- ≈ 16Hz: main coolant pump
- ≈ 33Hz: second harmonics of the main coolant pump

These peaks are found here too. However, other peaks ***almost hidden*** by the background noise are also selected. In fact, the peaks at $\approx$ 3Hz and $\approx$ 25Hz are really a mistery for experts [4]. To understand the meaning of these peaks needs further theoretical investigation [5].

Conclusions

In the present paper we proposed a methodology to investigate neutron spectra in such a way which is similar to human thinking. The goal was to save experts from tedious, mechanical tasks, namely browsing a huge amount of signals in order to recognize changes of the underlying mechanisms. Ancient methods are based on visual image processing supported by the gained knowledge of long practice. This knowledge can only be expressed by linguistic variables. During the spectrum interpretation usually an unconscious hypothesis test is also performed relating confidence level to the found features. In our method Bayesian inferencing plays the role of decision making.

In order to apply the developed algorithm first a rule system must be defined which contains the knowledge of the experts in a convenient form. The form is an IF—THEN—ELSE structure expressed in PROLOG syntax.

Having obtained the output the consistency of the rule system is easy to check. In additional, changing the rule system to another one gives the possibility to contradict different viewpoints. These points are one of the major advantages of the proposed method.

The procedure was applied to peak detection in the APSDs. As a conclusion, the method recognized those peaks with high confidence level, which have also been selected by human experts. In addition, no significant peak was missed. However, a few seemingly unphysical peaks were also chosen. The reason for that could be either the inappropriateness of the applied rule system or the trace of some new, real, yet uncovered physical phenomena. The answer demands further investigation.

The peak detection was used only for illustration. Any other feature can be detected without any major modification. In fact, the rule system is built up using simple words (small, sure,...) and if-then-else conditions. Since experts have different knowledge, a library can be created containing and reflecting these different believes. The library would make it easy to compare the different rule systems. To collect the necessary information and compile them into the a library need further work.

Certainly the method is not restricted to APSDs and/or neutron spectra. Any other signal processing task which needs feature detection, can also be performed in a similar way.

The automatic feature detection procedure is going to be integrated into a larger automatic diagnostic system [6]. On the other hand it is a very powerful tool for researchers to test new hypotheses and develop more complete and consistent databases.

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