AN EXPERT SYSTEM FOR ULTRASONIC MATERIALS CHARACTERIZATION AND NDE

Ming-Shong Lan and Richard K. Elsley

Rockwell International Science Center
P.O.Box 1085, Thousand Oaks, CA 91360

INTRODUCTION

Science, engineering, and manufacturing all depend on accurate measurements. These measurements can be made either by a human or by an automated system. In both NDE and materials characterization, there are numerous evaluations and decisions which must be made based on the experience and judgment of an operator or engineer. Current automated systems are not capable of making these judgments. Instead, typically, the operator or engineer evaluates the results after the measurements have been made. Expert systems provide a method for building the expertise of the human into the measurement apparatus, thereby causing all decisions made during the measurement process to be made with the skill of expert operators.

A human operator can have expert level skill or less than expert skill. A number of differences in approach and performance can be observed between an expert human, a less than expert human, and conventional automated measurement systems. Table 1 lists a number of steps that a measurement process can include and whether or not these steps are typically performed by each of the three types of operators. All measurement systems must perform at least steps 1 and 2. Most automated measurement systems do not go much beyond these two. Human operators usually add a number of steps that evaluate the validity of the data and results. The difference between an expert and a nonexpert is whether and how well he performs these steps. Finally, only the expert will decide what measurements ought to be performed or will discover new methods.

Expert systems technology provides a means of implementing, in an automated system, the qualitative and judgmental reasoning used by experts and has been widely applied[1] to problems that do not involve direct processing of sensor data. In addition, a growing number of expert systems are addressing the interpretation of sensor data.[2-3]

The objective of this project is to develop an automated measurement system that will perform ultrasonic measurements and provide expert interpretation of them without the need for an operator who is himself an expert in these measurements. The resulting system is a hybrid that uses the methods and tools of expert systems to flexibly manipulate the symbolic aspects of the problem and uses numerical algorithms for experiment control, data acquisition and signal processing.

Table 1. Steps of the measurement process that are performed by experts, non-experts and automated systems

	Step	Expert	Non-expert	Automated system
1.	Measurement of the raw data	yes	yes	yes
2.	Calculation of the result	yes	yes	yes
3.	Verification that the apparatus is working correctly	yes	sometimes	sometimes
4.	Direct estimation of the accuracy of the raw data	yes	sometimes	sometimes
5.	Error propagation	yes	sometimes	
6.	Inference of validity of data from nondata features	yes	sometimes	
7.	Evaluation of validity and usefulness of the results	yes	sometimes	
8.	Selection of apparatus for the measurement	yes	sometimes	
9.	Selection of appropriate measurement methods	yes		
10.	Discovery of new measurement methods	yes		
11.	Should the measurement have been made at all?	yes		

In operation, MCES first presents the operator with a menu of the properties that it can measure. He selects one or more and MCES evaluates each of a number of measurement methods in turn to determine applicability. This process includes asking the operator if he can provide required external information. Once MCES has selected applicable methods, the operator is instructed to place the ultrasonic transducer on the sample in a desktop water tank. When this has been done, MCES fires the transducer, measures the echoes and does the required signal processing and calculations. The results are presented to the operator along with heuristic judgments as to the accuracy of the results.

During this project, several new measurement methods were discovered, and a method for automatic method discovery was developed. Work is in progress to implement this and the other steps from Table 1 into the system.

MEASUREMENT METHODS

Figure 1 illustrates several requirements for a measurement to be performed successfully. First, for a given method to be applicable, certain conditions must be true about the specimen. For example, a method may require that the specimen have two flat parallel surfaces. The method may also require that certain data be obtained from sources external to the measurement process. For example, it may be necessary to know the thickness of the specimen in order to calculate its velocity. Finally, it may be necessary to make measurements on reference specimens in order to obtain calibration information. Once it is decided that a method is applicable, the actual measurements are performed. This involves operating the ultrasonic pulser/receiver and data acquisition equipment and performing signal processing on the results. Finally, the calculations that give the desired answers are performed and the data and results evaluated.

In the initial version of MCES, each method is stored as a single entity, including the measurements that must be made, the series of calculations used and the operator interfacing required to get external data. An approach in which the components that make up all of the methods are stored separately and MCES links them together to form new methods in response to the operator's requests has been developed (see Method Discovery section below).

ULTRASONIC MEASUREMENTS

Figure 2 shows the measurement geometry used for this preliminary version of MCES. Normal incidence, unfocussed waves are incident on the sample. Echo u_1 returns from the front surface of the specimen. If the specimen has a parallel back surface, echoes u_2 and u_3 may also be present. However, due to noise considerations, echo u_3 may not be detectable.

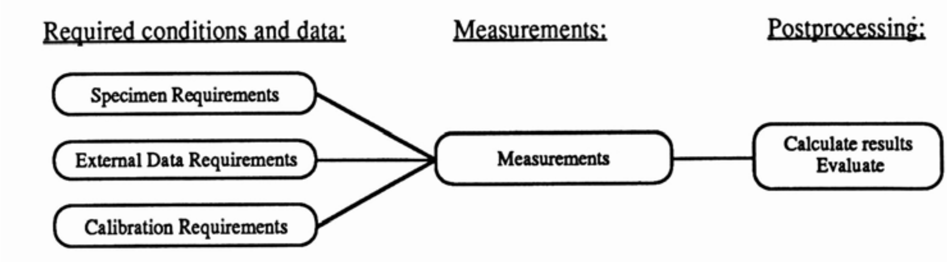

Fig. 1. A measurement method includes conditions and data required for its use, execution of the measurements, calculation of results and evaluation of the data and results.

For some measurement methods, only a front surface echo is required, although these tend to be less accurate because of their dependence on absolute amplitude measurements. For some methods, a measurement from a reference specimen of known properties (echo u_0) is required. The expert system must take all of these considerations into account.

The features of the measured signals that are used for interpretation can be simple ones such as the peak amplitude and arrival time of pulses, or the frequency spectrum may be used as a signature of the properties of the specimen. This initial version uses the amplitude and arrival time of the video pulses of the echoes. More sophisticated features can readily be added.

DESCRIPTION OF MCES

Architecture

Unlike conventional expert systems, MCES performs not only symbolic (rule-based) computations, but also performs data acquisition and numeric computations (signal processing). This is accomplished via the architecture shown in Figure 3. Symbolic processing is performed on an LMI Lambda 2X2 computer whose native language is LISP. The software is written in KEE (Knowledge Engineering Environment) by Intellicorp, Inc., which is a software tool that provides an object oriented programming environment and a production system that supports both forward and backward chaining mechanisms.[4] Numeric processing (data acquisition and signal processing) is performed in a VAX 11/780 using ISP, a high-level signal processing language developed by Rockwell International. Ultrasonic data acquisition is performed under control of the VAX using a Data Precision D/6000 transient recorder and Panametrics ultrasonic transducers and electronics. The symbolic processor controls the system and contains a knowledge base, an inference engine, and an operator interface.

Fig. 2. Ultrasonic measurements. Normal incidence, unfocussed ultrasound pulses produce one or more echoes.

	Symbolic Processor	Numeric Processor	Measurement Apparatus
Function:	Operator Interface, Method Selection, Measurement Control, Evaluation	Data Acquisition, Signal Processing	Ultrasonic Measurement, Transient Recording
Hardware:	LMI Lambda 2X2 Lisp Machine	VAX 11/780	D/6000 Panametrics
Software:	KEE	ISP	

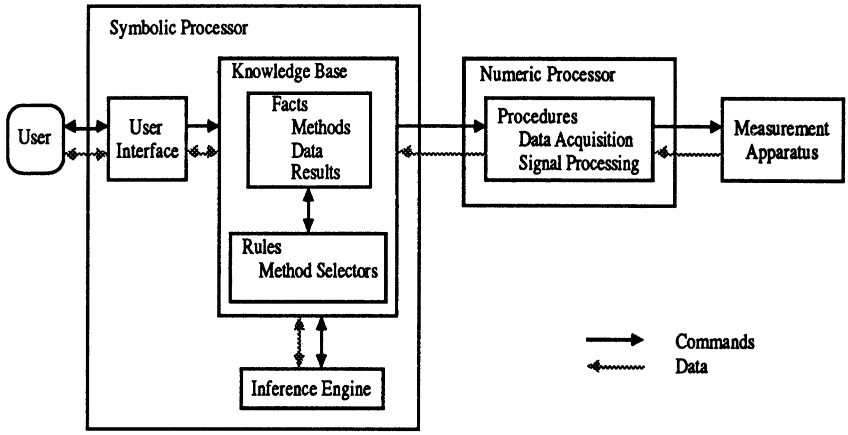

Fig. 3. Architecture of the MCES system.

Knowledge Base

The knowledge base (see Figure 3) includes several classes of facts and a set of rules. The facts include properties of reference materials, features extracted from the measurements, the current state of knowledge of the specimen at any time during the measurement process, and the procedures to be used in executing the methods. The rule set includes rules for selecting applicable methods and will soon include rules for detecting invalid data and evaluating the accuracy of the results.

The measurement methods included in MCES are listed in Table 2. MCES can measure ultrasonic velocity, ultrasonic attenuation, density, and specimen thickness. These quantities were chosen because they are the building blocks that will be used to determine a range of other material properties in the next version of the system. The system knows two methods for measuring each of the four measurable quantities.

Table 2. MCES Measurement Methods

Method	Quantity Measured	Geometry Required	Echoes Required	Data Required	Expected accuracy
SV1	velocity	-	u_1, u_0	density	Medium
SV2	velocity	parallel faces	u_1, u_2	thickness	Good
SA2	attenuation	parallel faces	u_1, u_2, u_0	thickness	Medium
SA3	attenuation	parallel faces	u_1, u_2, u_3	-	Good if atten is low
ST1	thickness	parallel faces	u_1, u_2, u_0	density	Comparable to SV1
ST2	thickness	parallel faces	u_1, u_2	velocity	Comparable to SV2
SD1	density	-	u_1, u_0	velocity	Comparable to SV1
SD2	density	parallel faces	u_1, u_2, u_0	thickness	Comparable to SV1

For each method, the knowledge base contains rules that describe the requirements for its applicability (third, fourth and fifth columns of Table 2). These requirements are encoded in method selector rules (see Figure 3) and are used to determine which methods can be used for a given specimen. Also included are the a-priori accuracy estimates (last column of Table 2). They are derived from the experience of an expert and are used to determine the order in which methods are applied (best first) if more than one method is applicable. For each method selected, a sequence of operations needs to be performed to execute the method. This sequence is implemented in the method selector rules.

The diverse sources of data that are used by MCES are stored in objects (units) in KEE for use in the calculation of results and their evaluation. The collection of measured features are stored in an object that contains attributes (slots) including the values of measured features, quantitative estimates of their uncertainty, and a qualitative measure of their validity. Data derived from the operator dialog are stored in objects that describe the material and specimen properties. The properties of the reference specimen are stored in another object.

Knowledge Acquisition

The knowledge base used by MCES was developed through a series of interviews between an expert and a knowledge engineer. This knowledge includes measurement methods, operational procedures, signal processing methods and calculation methods. The project involved three people: a knowledge engineer (MSL) familiar with the required programming techniques and also familiar with the basics of ultrasonics; Expert #1 (RKE), who is the source of the expertise, and Expert #2 (LAA), against whose measurements MCES was tested. The structure of the system evolved as experience with the knowledge base accumulated.

Operation of MCES

MCES offers the operator a menu of properties that it can measure. After he has chosen one or more properties, MCES applies the method selector rules to determine if any methods are applicable to this specimen. This process includes asking the operator if the specimen has the required geometry and if he can provide the necessary external data. If one or more methods are applicable, the measurements are begun. MCES instructs the operator to position the specimen and the transducer. It then instructs the VAX computer to perform the data acquisition and signal processing.

For each method in the knowledge base, companion ISP procedures in the VAX acquire data and perform the signal processing necessary to identify the required pulses and extract their features. The signal processing consists of searching the measured waveform for the appropriate ultrasonic pulses and then extracting from the pulses the features needed to calculate the required results. Two types of features can be extracted. The first and simplest type is scalar features of the pulses, such as peak amplitude and arrival time. The second approach to feature extraction is to measure the full frequency dependence of the measured quantities. This approach can provide additional information, but requires more extensive computation and more subtle interpretation. This first version of MCES uses only scalar features extracted from the video envelope of the pulse. Their simplicity makes them preferable to frequency-dependent features and their accuracy is often quite adequate. Future work will incorporate frequency-dependent methods as well.

The features extracted from the measured data by ISP are then passed to KEE for result calculation and evaluation. The properties selected by the operator are reported to him, after which he can choose to perform other measurements.

Data Evaluation

A human expert performs two types of evaluation of the measurement results. One is a quantitative a-posteriori estimate of the accuracy of the result based on measured accuracies of the data. The other is a qualitative, often heuristic, evaluation of whether anything is seriously wrong with the result and whether it may be of questionable accuracy. Approaches to these methods of evaluation have been developed and are currently being implemented.

Each piece of numeric data in the system consists of numbers:

x_i, the expected value of the quantity,

σ_i^2, the variance of x_i,

ν_i , the number of degrees of freedom associated with the measurement, and

c_i , a qualitative confidence factor.

The a-posteriori accuracy estimate will be performed by propagating through the calculations estimates of the variance of each variable and of the number of degrees of freedom of that estimate. For a function $f(\{x_i\})$, the variance σ_f^2 of f in terms of the variances σ_i^2 of the x_i is given by

$$\sigma_f^2 = \sum_i (\partial f/\partial x_i)^2 \cdot \sigma_i^2 \qquad (1)$$

and the number of degrees of freedom ν_f of f in terms of the number of degrees of freedom ν_i of the x_i is given by

$$\nu_f = \sigma_f^4 / \sum_i [(\partial f/\partial x_i)^4 \ \sigma_i^4 / \nu_i] \qquad (2)$$

In order to use this method, estimates of σ_i^2 and ν_i for the measured features and the operator supplied data are required. For measured features, several repetitions of the measurement can be made quickly. From them, σ_i^2 and ν_i can be estimated. For user-supplied data, the user will be asked if he knows σ_i^2, and if so, how sure he is of it. If he does not know σ_i^2, a reasonable value from the knowledge base will be substituted, assuming one degree of freedom. If he gives a value of σ_i^2, a value of ν_i will be supplied based on his degree of certainty of the value.

The confidence factors c_i can take on four values:

Good data,
Adequate, but perhaps not highly accurate,
Suspect,
Probably bad.

The confidence factors for experimental data will be determined from several sources: unusual characteristics in the data (such as the presence of unexpected pulses, unexpected feature values and lower than expected signal to noise ratios), or a-priori prejudice on the part of the expert. The confidence factors will be propagated through the calculations as follows. The confidence factor resulting from a calculation will be equal to the worst confidence factor of any of the inputs to the calculation. This is a pessimistic philosophy, but remember that the purpose of the confidence factor is not to say quantatively how accurate the measurement is. The variance and degrees of freedom serve this purpose. The purpose of the confidence factor is to give qualitative warning that something unusual has happened.

Discovery of New Measurement Methods

As mentioned above, the current version of MCES groups the measurements, calculations, and external information requests that compose a method into one entity. During codification of the knowledge, it was observed that if these components were rearranged, new measurement methods could be created. As a result, methods for measuring the density of a specimen or the thickness of a plate purely ultrasonically were discovered. Neither expert #1 nor #2 was previously aware of these methods, although in retrospect any expert would probably have discovered them if he had asked himself the right questions. This points up one of the advantages often cited for the knowledge codification process: that thinking systematically about the knowledge often yields new insights.

An approach was therefore developed to allow the version of MCES currently under development to discover new methods. In this approach, the knowledge base contains tables of all raw data that can be measured and all equations which express useful relationships between measured data and calculable quantities. When the operator requests measurement of a given quantity, the expert system searches in turn all equations which contain that quantity. It then chains through all other equations, attempting to establish one or more methods that link available measurements and external data to the desired quantity. This capability would discover all of the methods that MCES currently contains.

RESULTS

A test was performed in which four specimens of widely varying acoustic properties were measured by MCES and by Expert #2. The specimens were made of Lucite, aluminum, Inconel and beryllium. They were chosen for their wide range of density and ultrasonic velocity. MCES and the human expert used methods and apparatus of their own choosing. Hence, the methods used were not identical. The results were evaluated in terms of the accuracy of the measurements and how long the measurements took to perform. Handbook values (not measured on the same specimens) were also compared where appropriate. The results are presented in Table 3. They are grouped by methods that are approximately equivalent.

The time required for MCES to make measurements consists primarily of the user dialog and the manual positioning of the specimen in the water tank. Typical time is 3 minutes per measurement. The human operator required 1 hour to measure velocity and attenuation for one sample. This time was 75% setup and 25% measurement and analysis. These numbers are not directly comparable because different methods were used, but they clearly show the speed advantage of the expert system.

Velocity measurements: The more accurate method (SV2) gave results that were 1.5-5% higher than handbook values, probably due in part to a systematic error in the simple signal features used. Method SV1, which is generally less accurate because it depends critically on absolute amplitude measurements, had errors of 7-15%. The human expert's results were within 2% of handbook values.

Attenuation measurements: Attenuation is inherently more difficult to measure accurately than velocity. Methods SA2 and SA3 gave values that were within a factor of two of one another and of reasonable magnitude. This represents an acceptable level of agreement The expert's measurements were of the same order of magnitude in two cases, but were clearly invalid (negative attenuation) in another. Hence, in this case, MCES's measurements appear to be more stable than the expert's.

Thickness and density measurements: At the beginning of the project, Expert #2 did not know a method for ultrasonically measuring these quantities. Hence, no measurements are reported. The accuracy of MCES's measurements are directly related to the accuracies of methods SV1 and SV2, on which they are based, and are in the 5-12% range.

CONCLUSIONS

The Materials Characterization Expert System (MCES) is designed to ultrasonically measure a number of material properties. It knows several methods for measuring each one. The user is presented with a list of properties and is asked to select one or more for MCES to measure. MCES then carries on a dialog with the user to determine which of the methods are applicable in this case and which are likely to give the most accurate results. It then performs the measurements, analyzes the data, and reports the results to the user.

Table 3. Results comparing human expert and MCES.

Measurement	Method	Material: Lucite	Aluminum	Inconel	Beryllium
Velocity:	SV1	2.92	6.75	5.15	15.11
(mm/μs)	SV2	2.80	6.40	5.90	13.51
	Expert (1)	2.72	6.31	5.62(2)	12.62
	Handbook	2.68	6.32-6.50	5.72	12.90
Attenuation:	SA2	0.57	0.092	0.091	0.194
(dB/mm)	SA3	0.59	0.143	0.172	0.265
(at 5 MHz)	Expert (3)	0.75	0.19	1.85(4)	(5)
Thickness:	ST1	5.97	10.50	2.53	10.09
(mm)	ST2	5.47	9.84	2.81	8.61
	Expert (6)	-	-	-	-
	Micrometer	5.72	9.96	2.90	9.02
Density:	SD1	1.276	2.87	7.23	2.14
(g/cc)	SD2	1.22	2.84	7.01	2.04
	Expert (6)	-	-	-	-
	Direct Meas.	1.171	2.691	8.028	1.827

Notes:
1. Expert's method similar to SV2, except visual pulse overlap is used to measure time delay.
2. 15 MHz transducer used.
3. Expert calculated attenuation as function of frequency and read off value at given frequency.
4. Measured at 15 MHz; cannot be compared to 5 MHz measurements.
5. Measurement gave unreasonable (negative) value. Expert advised against its use.
6. Expert did not know a method for making this measurement.

Developing MCES involved the following: 1) development of a knowledge representation for ultrasonic measurement methods and data; 2) codification of ultrasonic measurement knowledge; 3) discovery of new ultrasonic measurement methods; 4) integration of symbolic data processing, numeric data processing and ultrasonic measurements in one system; 5) automatic selection of measurement methods; 6) automatic identification of ultrasonic pulses in a measured signal and extraction of features from them. Work currently in progress to improve MCES includes: 1) automatic evaluation, by both quantitative and heuristic methods, of the quality of measured data and the calculated results; and 2) automatic discovery of new measurement methods.

ACKNOWLEDGEMENTS

This paper is dedicated to the memory of Lloyd Ahlberg, colleague and friend. This work was supported by the Rockwell International Independent Research and Development Program.

REFERENCES

1. **Building Expert Systems**, F. Hayes-Roth, D. A. Waterman, D. B. Lenat, eds., Addison-Wesley, 1983.
2. L. D. Erman, F. Hayes-Roth, V. R. Lesser, D. R. Reddy, "The Hearsay-II Speech-Understanding System: Integrating Knowledge to Resolve Uncertainty", **Computing Surveys** 12 (2) June 1980, pp. 213-253.
3. H. P. Nii, E. A. Feigenbaum, "Rule-based Understanding of Signals", **Pattern-Directed Inference Systems**, D. A. Waterman, F. Hayes-Roth, eds., Academic Press, 1978, pp. 483-501.
4. KEE Software Development System Reference Manual, Document R-2.0-1.0, Intellicorp, Menlo Park, CA, March 1985.