FOR PUBLICATION
Brite/EuRam project
BRE2.CT92.0131
Proposal no: 92-5029

Synthesis Report
Report number 9
From 1st June 1993 to 30th September 1996

Ultrasonic resonance spectroscopy quality assurance testing of: concrete, aerospace and die-cast aluminium.

A project funded by the European Community under the Brite/EuRam programme

Co-ordinator
Instrumentation Innovation Ltd - GB
Church Farm Barn, Horse Ware, Over, CambridgeCB451WX, GB

Partners
Alcatel Espace SA - F
Taywood Engineering Ltd - GB
TechSonic SARL - F
Uppsala University - Sweden (U)

Associate partners
I So Test Engineering SRL - I
King's College London - GB (U)
High Point Rendel Management Consultants Ltd - GB

September 1996

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Proposal: 92-5029. Contract: BRE2.CT92.0131 For publication

Ultrasonic resonance spectroscopy for quality assurance testing of concrete, aerospace and other industrial components.

Authors:

Andrews, D.R., Instrumentation Innovation Ltd, Church Farm Barn, Horse Ware, Over, Cambridge CB4 5NX, GB.

Mathelin, D., Alcatel Espace SA, 26 Avenue JF Champollion, BP 1187,31037 Toulouse, France,

Fleischer, C., Vincent, N., Taywood Engineering Ltd, R&D Dept, 345 Ruislip Road, Southall, Middelsex UBl 2QX, GB.

Stepinski, T., Ericsson, L., University of Uppsala, Department of Technology, Teknikum, Box 534, 75121 Uppsala, Sweden

Castaldello, L., I So Test Engineering SRL, Via Roma 8, 10090 Reano (To), Italy.

Blakelock, R., Karbassi, A., High Point Rendel Management Consultants Ltd, 61 Southwark Street, London SE1 1 SA, GB.

Abstract

Continuous sine wave excitation is used to drive an ultrasonic transducer in contact with a test sample during a resonance spectroscope inspection, The response of the test sample is detected by a receiver at a second location on the surface, Both the amplitude and the relative phase of the received signal are recorded over a range of discreet test frequencies so that spectra of amplitude and phase are recorded. Test frequencies covering 100 Hz to 10 MHz have been used in experiments.

Ultrasonic resonance spectroscopy has application to inspecting the quality of a wide range of industrial components, for example: aerospace, concrete, and metallic. One of the advantages of the technique over pulse-echo examination is the ability to inspect a whole component with one test - virtually all other inspection methods require scanning of the surface which is relatively slow and expensive. It has been shown in this project that the combination of resonance spectroscopy, creating data (spectra), and an artificial neural network, deciding quality (using spectra), results in an inspection system with the following qualities:

- capable of inspecting whole components quickly,
- simple testing procedure - because only a single test is made,
- output of the neural network can be as simple as either Pass or Fail,
- operators do not make decisions about the quality of inspected samples - eliminating a source of error,
- the neural network is able to interpret spectra and decide correctly on quality when an operator is unable,
- the method has good potential for automation due to its simplicity,
- suitable for use in a mass-production environment at a low cost per inspection with 100% testing.

This way of applying resonance spectroscopy should find application where many identical components are to be tested, With further development it may be possible to use the technique on unique objects in the field.

The technique has been applied successfully, giving accurate assessments of the quality of a diverse range of test samples *when spectra have been interpreted using artificial neural network software - the* success-rate in correctly assessing quality has been encouragingly high (in the range 82% to 100%) - to be an attractive inspection method from a commercial point of *view* requires success-rates close to 100% but it is generally accepted that success-rates above 90% are good. Volumetric flaws in the range 0.04% to 3% were detected in tests on concrete paving slabs. When interpretation was un-aided, that is to say using human judgement alone, or when human judgement has been assisted by predictions using a finite element approach then interpretation has been mainly unsuccessful. This

lack of success was notable in the case of concrete components and structures, which possibly present an added difficulty due to the coarse-grained internal structure of concrete tested. However, a statistically significant number of finer-grained concrete paving slabs was successfully classified for quality using a neural network and aging experiments on coarse-grained concrete samples were partially successful so it is impossible at this stage to draw far-reaching conclusions because there is a need for more research. The range of success achieved on concrete samples serves not only to illustrate the difficulty of testing this material but also the importance of using a neural network to interpret experimental results. The main disadvantage of the neural network approach is the cost of creating *a* set of data with which to train the neural network - a network requires many different examples of spectra to represent all possible cases of both unacceptable and acceptable quality of samples.

By predicting a spectrum, using the finite element method, then comparing experimental and predicted spectra it should be possible to infer the condition or quality of individual test samples, This approach might be usefully applied to inspect samples that are only available individually, for example, concrete beams in a bridge. It has proved impossible to match predictions and experiments in this project and this has contributed to the lack of success in testing cons'ete structures and components. The reasons for this have been explored but it would seem that and the finite element software developed specifically for resonance spectroscopy as part of this work proved to be ineffective and unreliable. Another reason is that this approach needs more fundamental research into correcting for the influence of the test transducer on experimental spectra before the method can be used effectively.

Encouraging results were obtained using ultrasonic resonance spectroscopy covering a wide range of industrially important components including: forgings, pressings, brazings, bolts and (composites, Success-rates of 96% were typical for classifications using a neural network and in some cases 100% success was achieved (although this was for only a small number of samples).

Resonance spectroscopy has also been applied to Certain aerospace materials using welded aluminium and an aluminium honeycomb with surfaces made of woven carbon fibres. Whilst it has been possible to classify defective zones successfully, with a high success rate approaching 100%, an improvement in sensitivity to smaller flaws is needed ***before*** resonance spectroscopy meets the stringent requirements for aerospace quality inspection. There is optimism that this improvement is possible.

A novel lock-in amplifier has been designed and developed for this study, It has been used successfully with various transducers to collect spectra from all of the test samples, The lock-in amplifier principle has been well-established for many years and is known to be the optimum method of detecting a continuous sine-wave in noise. The novel features designed into this lock-in amplifier enable it to collect spectra quickly and with good accuracy.

Introduction and technical description

Quality assurance inspection is unsatisfactory for the following industrial] y important materials and components: concrete, concrete structures, certain aerospace materials and roller bearing cages. Improvements sought by industry include: introducing new methods to allow testing for the first time, reducing the cost of each test, increasing the sensitivity to flaws, in-service monitoring, feature selectivity and pass/fail decision making.

Two common characteristics of the materials of interest are:

. that they are all difficult or impossible to test by the ultrasonic pulse-echo method and

• that they all have fairly low acoustic attenuation at frequencies of interest.

Standing wave patterns can be established in these materials due to the latter characteristic and the method of ultrasonic resonance spectroscopy can be applied, however, the challenge remains to interpret spectra effectively.

The principle of operation of resonance spectroscopy is to excite a test sample into mechanical resonance with an ultrasonic transducer, driven by a continuous sine-wave excitation of constant amplitude, and to measure the amplitude and relative phase of a second transducer acting as a receiver. Spectra are built-up by testing at a constant frequency then stepping through a range of frequencies. The method can be considered as a refinement of the proven method of hammer-tapping. A lock-in amplifier[1] has been designed and built for this purpose which cannot be described in more detail in this communication since it is the subject of a patent application.

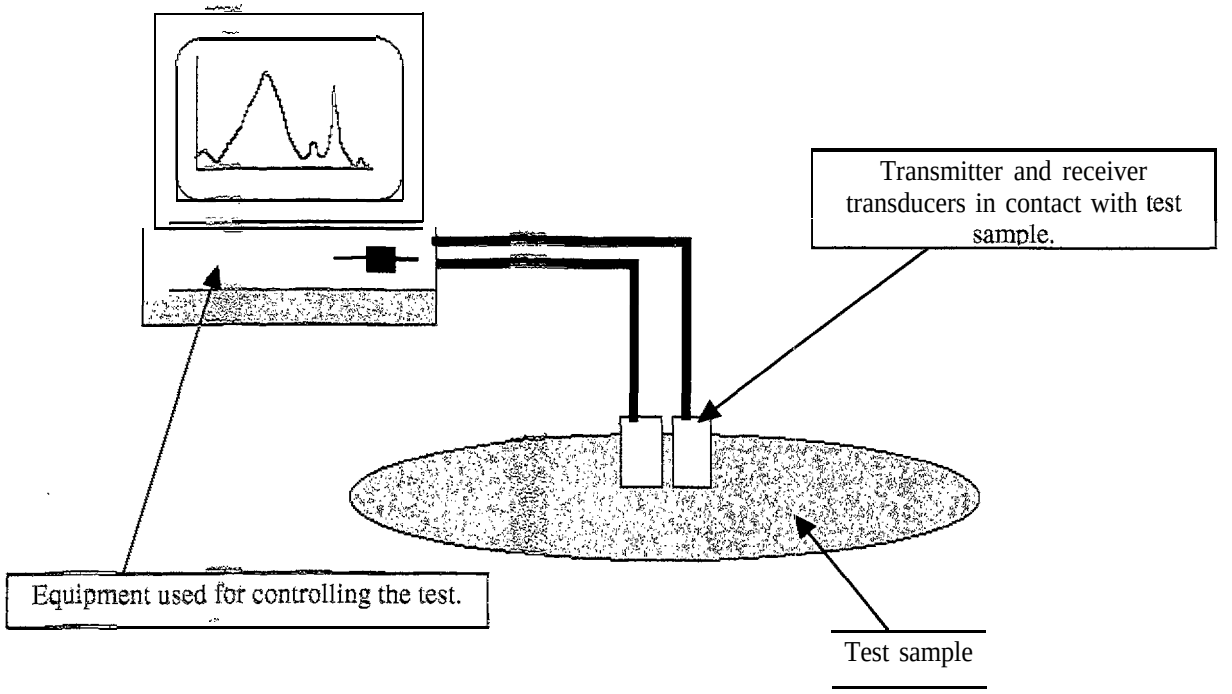

Figure 1

Sketch to show how a resonance ***experiment*** *is performed.*

Solid objects have many resonances or modes of vibration with peak frequencies that depend upon the mechanical properties of the object, its geometry and the presence of any flaws.

Two approaches to interpretation have been tried in the project:

1. Presented with many test samples an artificial neural network can be trained to identify flawed samples automatically - cm a production line for example. The main disadvantage of this method is the cost associated with training the network - possibly finding the classification of samples by destructive methods,
2. Presented with only one test sample it generally impossible to use a neural network approach but in principle it is possible to predict a spectrum, by numerical methods, and compare it with an experimental spectrum. The main disadvantage% are, firstly, the difficulty of creating an accurate model of the sample - it may be necessary to make assumptions about the number, position, size and type of possible defects therein and, secondly, the difficulty of removing or de-convoluting the frequency response {inherent spectrum) of the transducers used to collect the experimental spectrum.

Let us take this opportunity to make some qualifying remarks about the distinctions between the two approaches. Firstly, there is potential for using neural networks on single samples, such as a bridge beam, if the resonance spectroscopy test can be applied only locally to the transducers then the beam could be scanned and many nominally identical samples collected which could then be interpreted using a neural network, Secondly, spectra predicted using numerical methods could be used to help train a neural network. This might be quicker and more cost-effective than performing training tests, it might also ensure that the training set of experiments explored failure. types that might be difficult to reproduce under laboratory conditions,.

Impulse-resonance testing of concrete has achieved some success[2,3] but there are concerns about repeatability of spectra since workers frequently report a high degree of rejection of test data. Commercial pulse-echo does not work well on concrete although recent progress[4,5,6] has shown that research prototypes have been able to detect tendons, reinforcement bars honeycombing as well as measuring concrete thickness. In the case of aerospace

components there are already commercial resonance inspection instruments[7,8] available which can detect some defects in composites but better performance is required. For all of the above materials an ultrasonic test would be preferred for reasons of: speed of testing, reduced cost, portability on site and inherent safety.

Examples of resonance inspection systems include:
1. Low frequency (0.1 to 100 Hz) white noise vibro-testing of bridges[9].
2. Instrumented hammer tapping tests (frequency 10 Hz to 10 kHz).
3. DocTer impact-echo system[2,3] - neural network interpretation has been used for interpretation,
4. Grindo-sonic[7] (frequency up to 2 MHz).
5. Fokker[8] (typical frequency 2 MHz).
6. Schlumberger instrument[10] (1 Hz to 10 kHz).
7. Resonant ultrasonic inspection developed [1,12] at the Los Alamos Laboratory, USA,

The following technical limitations were identified in the above systems.

- Impulse excitation does not guarantee to establish steady-state resonance, making interpretation more difficult - figures 2 and 3 illustrate the point. Steady-state resonance is the limit of long times in numerical modelling and the eigen-modes predicted using finite element software are steady-state modes. If it is important to compare experiment and prediction then only steady-state results can be used.
- Test times are too short in many commercial frequency sweep systems Typically a set of 1000 test frequencies is swept in 20 ms in such systems (20 µs per test frequency) and displayed on a cathode ray tube (phosphor persistence time 20 ms) but the time to establish a steady-state resonance depends on the dimensions and slowest wave speed of the sample under test and it is inappropriate to use an arbitrary test time (of 20 µs - this might be suitable for a concrete sample no bigger than 10 x 10 x 10 cm).
- Most methods fail to record the phase angle spectrum (angle between the received signal and that of the transmitter) making it impossible to apply methods such as de-convolution,
- It is simpler for an operator to interpret a time-domain signal (pulse-echo) than a frequency domain spectrum (resonance spectroscopy). Most impulse-resonance systems collect information in the time-domain then convert them into the frequency-domain - making interpretation more difficult. One has to question the desirability of converting to the frequency-domain.
- Pass/fail decision making is frequently made by an operator who maybe subject to human error,

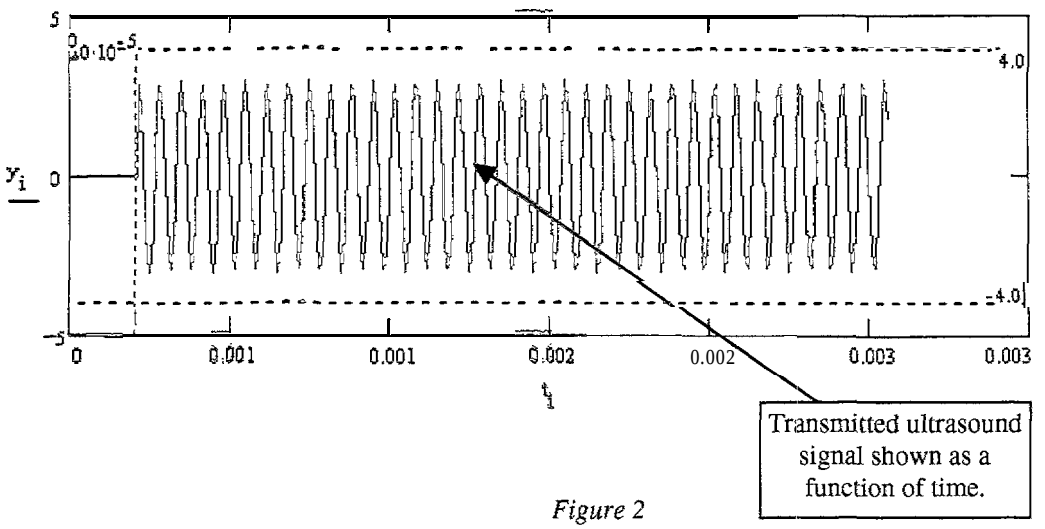

Figure 2

Continuous-wave excitation is first applied to a transmitter in a resonance spectroscopy test.

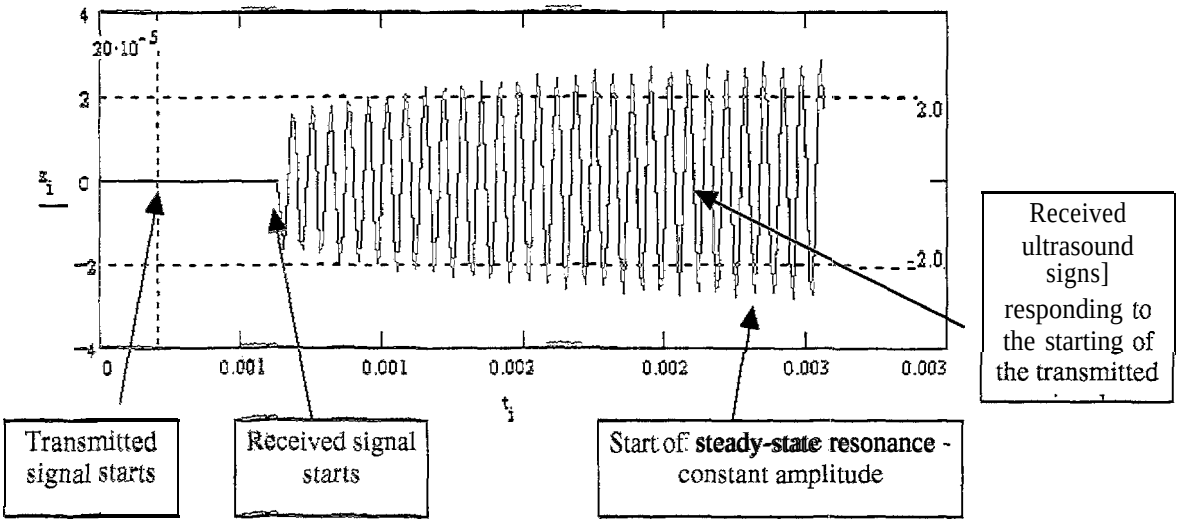

Figure 3

Sketch to illustrate the time taken to establish steady-state resonances in a test sample. Note that the received signal does not start until after the transmitted signal has started and it takes a further time before steady-state resonance has been established (constant amplitude).

Impulses used to excite resonances can be considered theoretically as solving the wave equation in 3-dimensions with suitable boundary conditions (commonly stress-free) and a Dirac-delta function impulse at one location. Theoretically the test starts at time. T=0 and one should continue recording until T=infinity. The solution can be found using either a Green's function solution and/or a Laplace transformation. **A** time-domain integral solution results. The main differences between theory and practice are that the impulse-excitation is a poor approximation to a Dirac-delta function (see figures 4 and 5) and that data collection lasts only a finite time.

An impact does not produce a Mac-delta impulse, instead the contact time depends upon the time it takes for an elastic wave to propagate through the impacter (typically a ball-bearing or hammer], Within that contact time plastic deformation processes can occur under the point of contact which substantially modify the elastic stress wave that is the source of the propagating wave in the sample. Precise control of test frequency range is difficult or impossible under these conditions and a degree of Variability is always present in results, Data collection usually stops when the signal disappears into noise and, consequently, low frequency information can be lost.

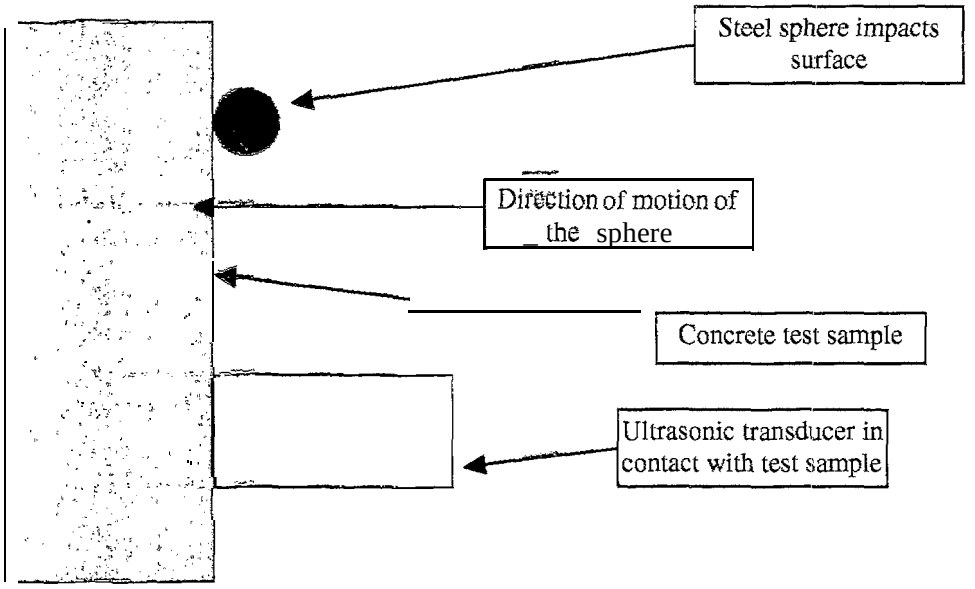

Figure 4

Sketch illustrating an impulse-resonance experiment in which a steel sphere strikes a concrete surface and a resonance spectroscopy experiment in which an ultrasonic transducer is used.

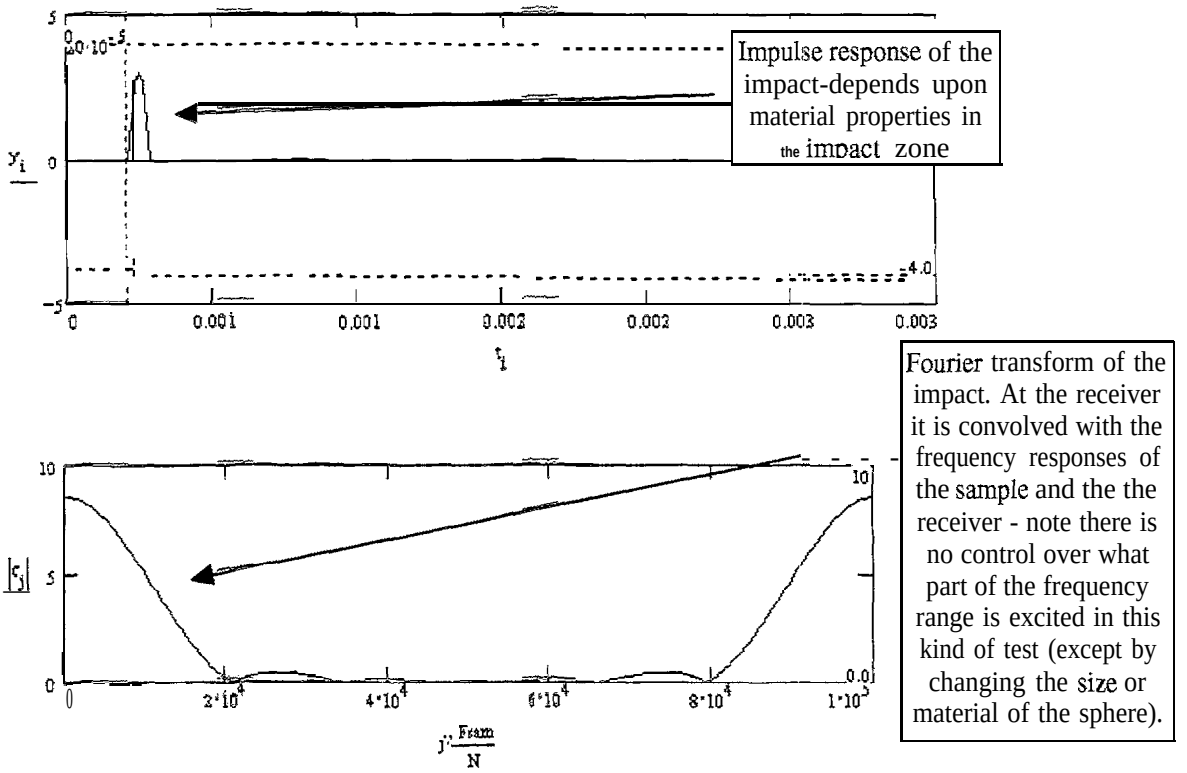

Figure 5

Time-domain (upper) and frequency-domain (lower) *representations of the force of an impact.*

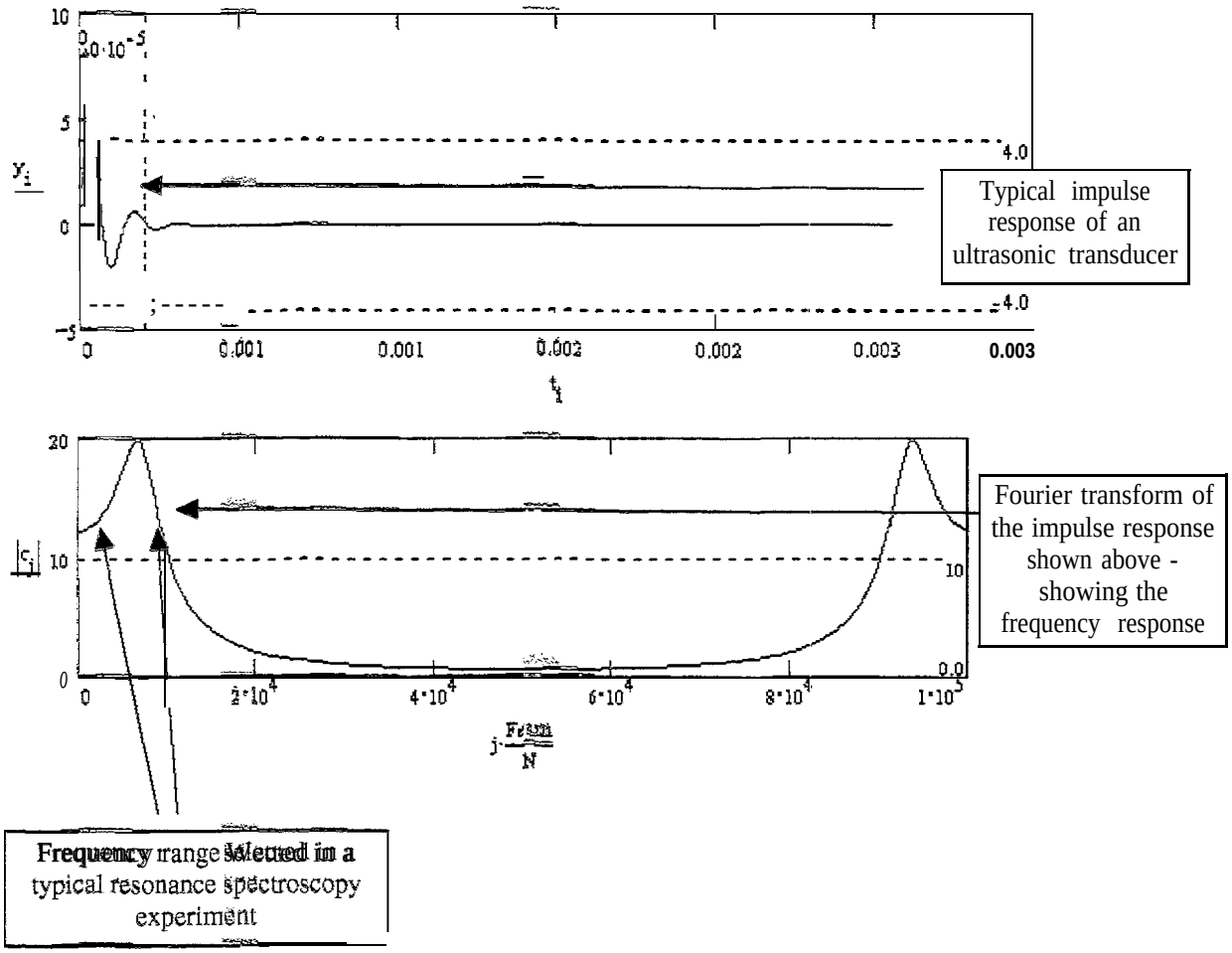

Figure 6

Sketch showing the impulse response (time-domain) and frequency response (frequency domain) of an ultrasonic transducer. Note the ability to select a range of frequencies in the test. It is also possible to de-convolute the frequency response of the transducer.

The approach in resonance spectroscopy is analogous to solving the wave equation, with the same boundary conditions as in impact test, but with a sine-wave driving function of constant frequency and amplitude. The frequency sweeping or stepping used 10 collect spectra corresponds to solving the problem repeatedly for each test frequency used. Theoretically the problem is very similar to the theory of the impact test, except that the driving function is a sine wave instead of a Dirac delta function. Theoretically there should be no difference in the final result for spectra.

Important practical differences are:

- Due to the use of narrow-band amplifiers in the stepping frequency method (lock-in amplifier) an arbitrarily low signal-to-noise ratio can be achieved - providing the operator with control over the quality (signal-to-noise ratio at any given frequency of test) of the spectrum at the time of collection. In an impact-echo test the operator cannot control the quality (signal-to-noise ratio) of the spectrum at the time of collecting the spectrum - this is decided by the input noise of the amplifier and sampling speed which are intrinsic parts of the design of the equipment.
- Ultrasonic transducers can operate reproducibly over controlled test frequency ranges - without random plastic deformation of the test sample.

These are the important differences, Stepping-frequency methods, as used in this study, can in principle collect spectra more accurately and reproducibly than impact methods. The testing transducers are also important in

determining the quality of the final spectrum, their Combined frequency response is convolved with the spectrum from the sample. Ideal transducers would have wide, flat frequency responses. It is possible to correct spectra for the frequency response of transducers by de-convolution in a resonance spectroscopy experiment but this is impossible in an impulse-resonance experiment.

An artificial neural network has been found to be the best way to interpret spectra in a resonance spectroscopy test. A network can make an interpretation that a human operator could not. Neural networks are used increasingly for classifying the quality of test samples - Tomlinson[13] has used a neural network for inspecting aerospace components and Sansalone[14] has used a neural network with an impulse-resonance approach for inspecting concrete structures. The advantages of using a neural network are:

- Data in the form of a spectrum is passed directly to the neural network - no operator is involved.
- Interpretation results in a probability of Pass, Don't Know and Fail.
- The interpretation/classification is made quickly {less than one second}.
- Spectra can be interpreted correctly that cannot be interpreted by a human operator.

Since it is unlikely that additional training examples could be provided after employing the neural network a version of the back-propagation algorithm has been developed which has an adaptive learning-rate and relies on cross-validation in order to avoid over-fitting. A multi-layer perceptron network was found to work best. The use of cross-validation is essential when the number of training spectra is small compared to the number of weights in the multi-layer perceptron. Other types of network that were tried but found to be unsuitable were: a matched network or correlation classifier and a multi-layer perceptron with a rational function pre-processor.

One of the major potential advantages of resonance spectroscopy is to test the whole sample with a single experiment - we term it global-testing in this communication. Provided acoustic energy has sufficient time to reach all parts of the sample and some of the energy returns to the receiver without too much attenuation then information about the whole sample is in the spectrum. Global-testing could reduce or eliminate the need for conventional scanning, which is time-consuming, Although it is sometimes possible to infer the type of flaw and its location with a single receiver from a resonance spectroscopy experiment in general one cannot. Global-testing is most simply used as a pass/fail test and in the present embodiment has not been used to locate the position of a fault. Tomlinson[13] and one of the authors[15] have investigated using artificial neural networks to classify the type of defect as well as the existence of a defect.

Local-testing, instead of global-testing, can be effected by testing over a higher range of frequencies. Since all materials increasingly attenuate ultrasound with increasing frequency, one can make energy from distant parts of a sample so weak, by increasing the frequency, that it becomes negligible compared to energy localised in the vicinity of the transducers. The distant energy can no longer affect the shape of the spectrum. Local resonance spectroscopy is more like conventional pulse-echo testing - the regions of the sample under test are similar and surface scanning can be used to localise any faults,

A mechanical or ultrasonic wave is intrinsically Well-suited to the task of inspecting the structural integrity of concretely. The principal difficulty is that of interpreting the resulting data. In all other respects, ultrasound is ideal for concrete: it is non-destructive; it is not an ionizing radiation, and is therefore inherently safe; it does not need high power - hence ultrasonic instruments catt be made portable, with consequent low capital cost,

The long established and widely used ultrasonic transmission test has resulted in BS 1881, part 203, a British Standard test, and is based largely on the work of Elvery[17]. It is limited, however, because it cannot be used in back-reflection. This is an important point because in many applications, particularly on-site, it is only possible to inspect at a single face of, say, a concrete beam and so a transmission testis impossible, It follows that a preferred testing method should be capable of use in back-reflection mode, for which a single surface is sufficient access. Resonance spectroscopy can be used in back-reflection.

Kroggel and co-workers[4,5,6] have developed an ultrasonic pulse-echo system for testing concrete in back-reflection. Kroggel's system has been used to locate a variety of targets in concrete, including: back-wall reflections, voids, honeycombing, reinforcement bars and tendon ducts. Kroggel's method presents signals to the operator that are essentially the same as those produced by conventional pulse-echo systems working on steel. The methods of testing used by inspection engineers working on steel are virtually the same and interpretation is closely related. Clearly there is great potential for the quick introduction of Kroggel's methods into the range of services offered by

existing inspection companies since there is little or no need for restraining. Pulse-echo signals are intrinsically easier to interpret by eye than resonance spectra - which is an advantage.

There is considerable interest in inspecting aerospace components *since these are* generally of higher value than found in other sectors of industrial activity and, consequently, it is more cost-effective to use inspection to achieve guaranteed performance. Other factors are the requirements for high reliability and safety which both necessitate often stringent testing regimes. A variety of inspection methods are used on aerospace materials but for certain composites and aluminium wave-guides there are needs to improve testing methods.

Results

Resonance tests on aluminium wave-guides and composites materials for antennas in the aerospace field have been fairly successful - showing that the technique is sensitive to flaws. Neural network software has achieved a success rate of between 82% and 100% in correctly classifying flaws in composite samples although the relatively small numbers of samples tested means that these percentage values are only rough indicators of the true performance on a large number of samples. A comparison of resonance testing has been made with other forms of inspection including scanning acoustic microscopy, microprobe X-radiography and conventional ultrasonic pulse-echo testing. Resonance testing has been shown to compare favourably with the other methods but none of them *is* entirely satisfactory, Only local testing has been evaluated - no work has been done on testing entire samples. It was not possible to apply finite element software to aerospace samples due to the complex structure of the samples. All non destructive test techniques evaluated in this project failed to detect flaws of very small sizes on aerospace components . given the very accurate requirements in the welding bead of aluminium wave-guide or in honeycomb composite parts. The best results were achieved with an acoustic microscope.

Resonance spectroscopy tests on roller bearing cages, with classification by an artificial neural network, have shown it is possible to find flawed samples with a success rate of approximately **93X0,** Tests on a range of other industrially important components have been made but interpretation with a neural network has not been tried, however, it was possible to excite resonances in all of them and there is good reason to expect that the method could also be used successfully on them.

Several feasibility demonstrations have been given; the most conclusive was made on a statistically significant number of pre-cast concrete paving slabs. Spectra Were collected from the samples before and after damage was introduced. A neural network was trained and in blind tests a multi-layer perception network was able to classify the paving slabs as either damaged or pristine with a Success rate of 87%. In this test each paving slab was tested at one position only - no surface scanning was used as in conventional ultrasonic testing. This demonstration also showed conclusively that an entire sample could be inspected with one test (global testing) - this is important because it makes the method simpler and faster than conventional testing and hence more cost-effective, The disadvantage is the effort needed 10 train the network. It is worth noting that it was impossible to classify the quality of these concrete samples by eye using the experimental spectra - only the neural network could correctly classify the quality. This serves to illustrate one of the findings of the project that classification of quality by eye is generally difficult or impossible and, so far, only a neural network has been able to do that interpretation successfully,

Ultrasonic resonance spectroscopy has been applied to various concrete components but without the benefit of a neural network. The technique shows difference?. by eye between good and rejected tunnel lining segments but significant variations between spectra from segments classified as good were also found. A correlation was also found between increasing strength and the early age of concrete - as was a shift in resonant frequency peaks (due to changes in the elastic modulus of the concrete), The technique did not prove sufficiently sensitive to permit an accurate estimate of concrete strength,

Resonance spectroscopy tests on structures and bridges, made without the benefit of a neural network, have shown that the technique is not suitable in this embodiment. It has not been possible to use a neural network for classifying spectra because of **the** difficulty in creating an initial training set of spectra. Resonance tests have been restricted to local testing. It was intended to use predictions from a finite element programme to assist an operator in classifying samples as either flawed or unflawed but the degree of agreement between experiment and prediction was not sufficiently good for this approach to be used with any confidence, The finite element software developed in the project is not suitable for predicting the spectra due to its limited ability and reliability.

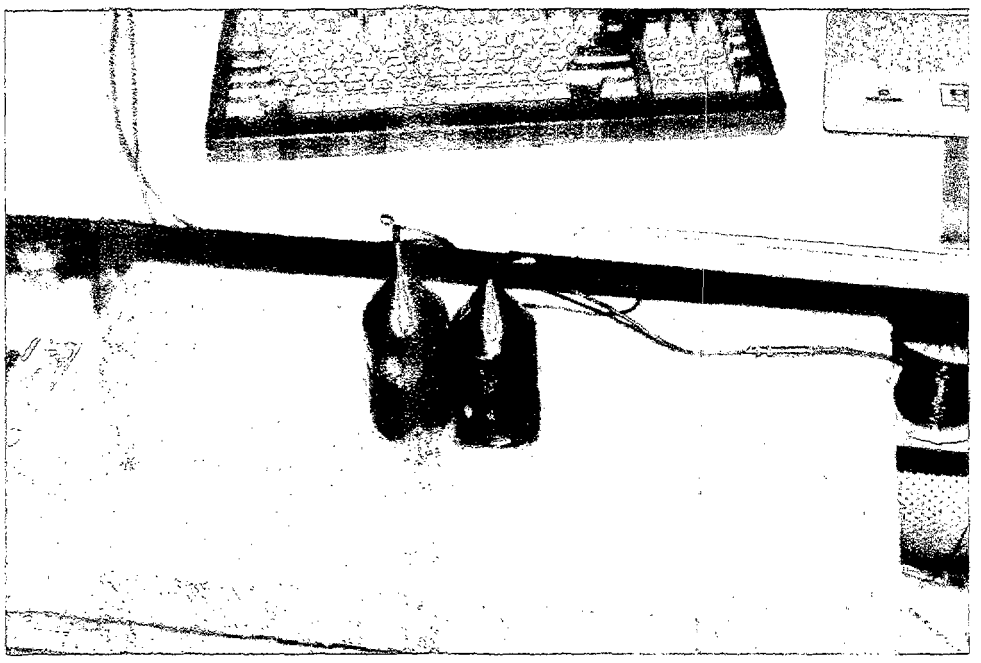

Figure 7

Two ultrasonic transducers are coupled to a pre-cast concrete paving slab to collect a spectrum.

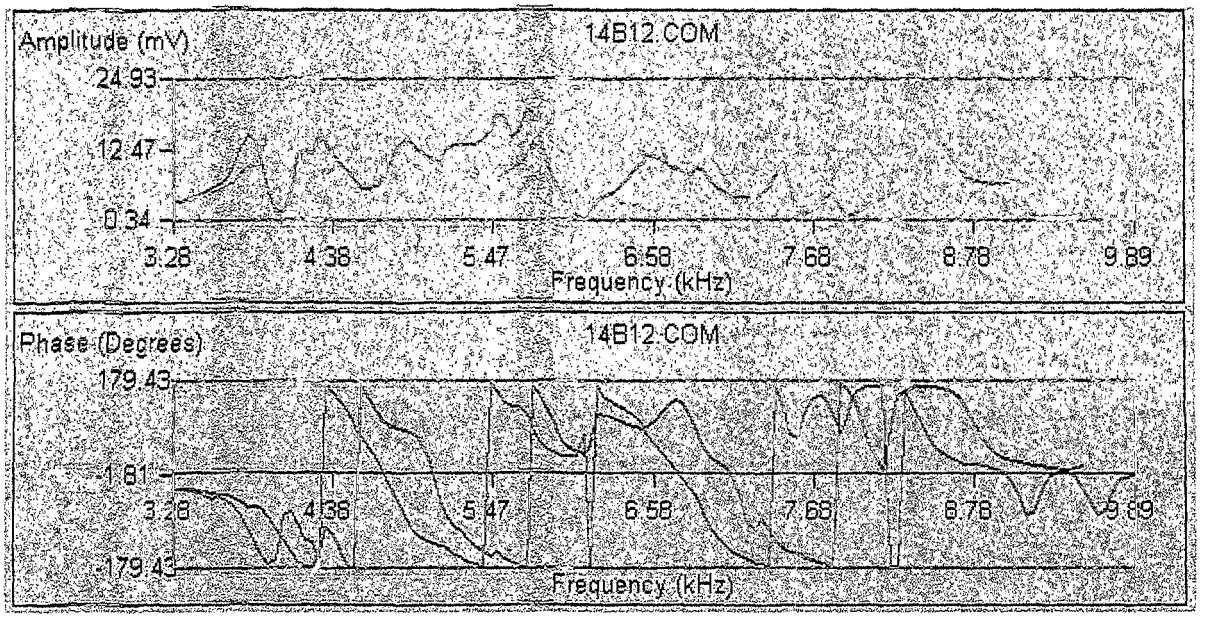

Figure 8

Spectrum compared for two nominally identical pre-cast concrete paving slabs showing differences due to material properties

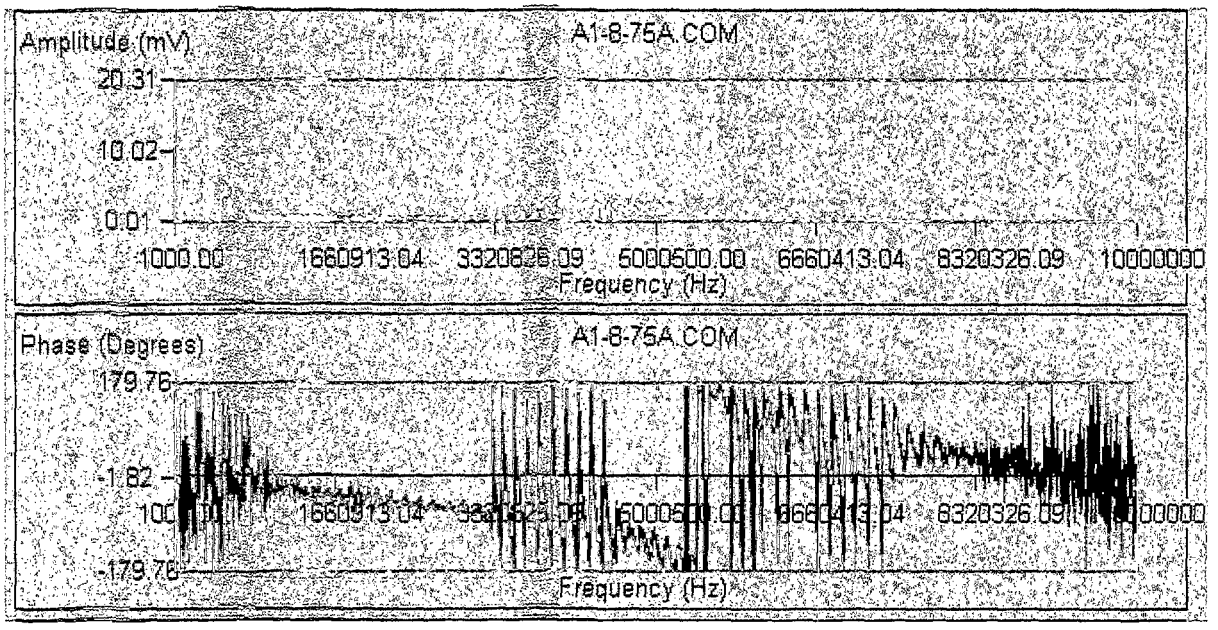

Figure 9

Comparison of spectra from aerospace wave-guides with and without flaws in the welding bead (red/blue = nominal, purple/green = welding bead to wide).

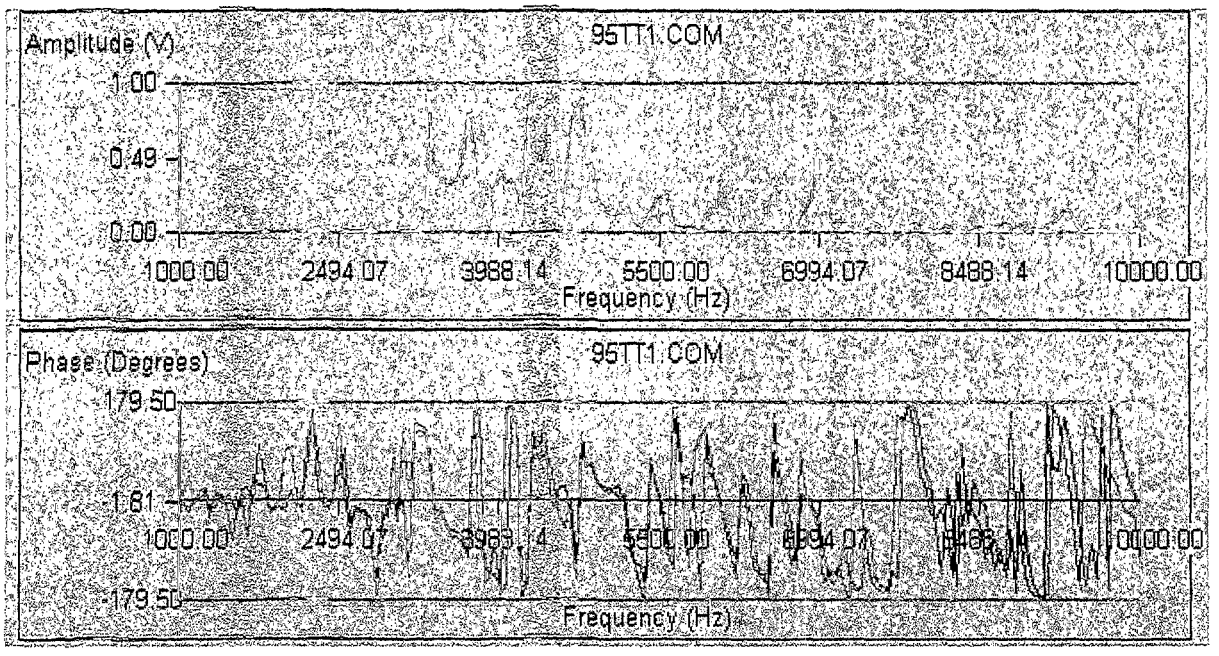

Figure 10

Comparison of the spectra collected from two rejected pre-cast concrete tunnel-wall segments having different defects - sand runs with surface blowholes compared to honeycombing alone.

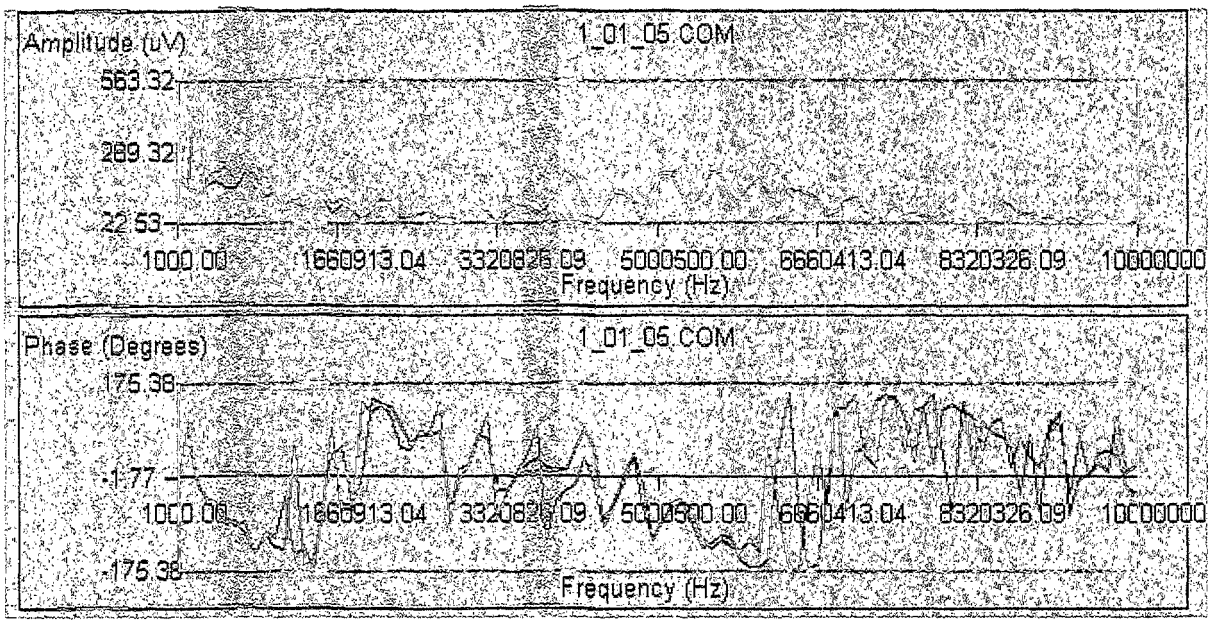

Figure 11

The comparison of the spectra from good and bad ball bearing cages (red/blue from the good sample, purple/green from the bad sample). A neural network achieved a 96.5% success-rate in correctly classifying ball bearing cages as either good or bad based upon these global spectra.

Conclusions

The two main technical challenges of the. project have been:

- To collect spectra accurately.
- To interpret spectra correctly,

One itern of electronic equipment (a lock-in amplifier cent.ded by custom software) used with various ultrasonic transducers has been developed to collect spectra - this has worked well for all of the materials evaluated, Two tools were developed for interpretation purposes:

- Artificial neural networks - to be used when many spectra are presented from nominally identical test samples.
- Finite element prediction - to be used when only a single spectrum is presented from a single lest sample.

The former, the neural network, has worked conspicuously well whenever it has been used but the latter, a specially developed finite element programme, has not been able to predict spectrums with good accuracy and it has also proved to be too unreliable to use with confidence.

The technique has been applied successfully, giving accurate assessments of the quality of a diverse range of test samples *when spectra have been interpreted using artificial neural network software - the* success-rate in correctly assessing quality has been encouragingly high (in the range 82% to 100%) - to be an attractive inspection method from a commercial point of view requires success-rates close to 100% but it is generally accepted that success-rates above 90% are good. When interpretation was un-aided, that is to say using human judgement alone, or when human judgement has been assisted by predictions using a finite element approach then interpretation has been mainly unsuccessful. This lack of success was notable in the case of concrete components and structures, which possibly present an added difficulty due to the coarse-grained internal structure of concrete tested. However, a statistically significant number of finer-grained concrete paving slabs was successfully classified for quality using a neural network and aging experiments on coarse-grained concrete samples were partially successful so it is impossible at this stage to draw far-reaching conditions because there is a need for more research, The range of success achieved on concrete samples serves not only to illustrate the difficulty of testing this material but also the importance of using a neural network to interpret experimental results, The main disadvantage of the neural network approach is the cost of creating a set of data with which to train the neural network - a network requires

many different examples of spectra to represent all possible cases of both unacceptable and acceptable quality of samples.

Encouraging results were obtained using ultrasonic resonance spectroscopy [covering a wide range of industrially important components including: roller bearing cages, forgings, pressings, brazings, bolts, sintered samples and composites, Success-rates of 96% were typical for classifications using a neural net work and in some cases 10(I% success was achieved (although this was for only a small number of samples). Not all of the materials listed above were evaluated with the neural network. To be an attractive inspection method from a commercial point of view requires success-rates close to 100% but it is generally accepted that success-rates above 90% are good. Ultrasonic resonance spectroscopy is potentially a very cost-effective technique if used for testing whole components and might be suitable for testing a range of industrial components. Artificial neural network software seems to be very useful for classifying manufactured parts quickly. The partner responsible for this work would very much like to exploit the findings commercially.

Quality inspection tests using resonance spectroscopy has been applied to certain aerospace materials made of either welded aluminium or an aluminium honeycomb with surfaces made of woven carbon fibres. Whilst it has been possible to classify defective zones successfully, with a high success-rate between 82% and 100%, an improvement in sensitivity to smaller flaws is needed before resonance spectroscopy meets the stringent requirements for aerospace quality inspection. There is optimism that this improvement is possible, Relatively small numbers of samples were tested and so the Percentage values are only a rough indicator of the possible performance on a large number of samples. Only local testing has been evaluated - no work has been done on global testing of samples. It was not possible to apply finite element software to aerospace samples due to the complex structure of the samples. An extensive range of inspection methods all failed to detect the smallest flaws of interest, including: scanning acoustic microscopy, microprobe X-radiography and conventional ultrasonic pulse-echo testing, Resonance testing has been shown to compare favorably with the other methods but none of them is entirely satisfactory, The best results were achieved with an acoustic microscope,

All non destructive test techniques evaluated in this project failed to detect flaws of very small sizes on aerospace c omponents - given the very accurate requirements in the welding bead of an aluminium wave-guide or bonding in honeycomb composite parts. The best results were achieved with an acoustic microscope which is probably the most accurate measurement technique in this range of application. Up to now, the frequency range of the resonance spectroscopy lock-in amplifier is too limited and might be increased up to 100 or even 200 MHz to reach the same performance as C-SAM techniques when used in local mode. On the other hand, Ultrasonic Resonance Spectroscopy is a very cost-saving technique when used in global mode and should be suitable for testing space composite antennas. Artificial neural network software seems to be very useful to classify manufactured parts quickly, It seems that this testing method is addressed more specifically to mass production. The finite element software developed in the project must be improved Before use in industrial applications.

A novel lock-in amplifier has been developed in the project that is well-configured for collecting ultrasonic resonance spectra. A patent application is in preparation. Spectra have been collected to high precision and with a quality that the authors believe marks a significant advance. The equipment has been used successfully to collect several thousands of spectra from test samples as diverse in range as concrete samples of eight tons in weight and low-density aerospace composites. The time to collect a spectrum depends upon the size of sample under test, its material properties, the number of frequency steps used to build-up the spectrum and other factors relating to accuracy and was found to range from about a few seconds (case of small metallic components with one hundred test frequencies) to several minutes (concrete samples with one thousand test frequencies), It was used by all of the end-user partners in the tests reported here - covering all of the materials. Tests performed by the developer of the lock-in amplifier have shown that the lock-in amplifier is performing better than its target specification in virtually all areas, Its electrical/software performance has not been directly confirmed by any other partner although considerable indirect evidence supports this assertion: (a) through the success of neural network classifications and (b) by agreement within the bounds of error between experimental spectra and theoretically predicted spectra for simple resonating systems.

Software has been developed based on an artificial neural network for the purpose of automatically classifying ultrasonic resonance spectra. It can be trained for detecting and rejecting components containing defects as well as distinguishing between different types of defects. The neural network engine is built on the well known multi-layer perceptron architecture and incorporates the concept of cross-validation in order to cope with limited numbers of

training spectra. The use of cross-validation is essential when the number of training spectra is small compared to the number of weights in the multi-layer perceptron. It has an adaptive learning-rate and relies cm cross-validation in order to avoid over-fitting. A multi-layer perception network was found to work best. Other types of network that were tried were: a matched network or correlation classifier and a multi-layer perception with a rational function pre-processor. The performance of the neural network engine has been one of the major successes in the project although it has not been possible to confirm the proper operation independently.

The classifier has been evaluated on ultrasonic resonance spectra collected from various samples, including concrete slabs, roller bearing cages and aluminium composites. In all cases the classifier adapted itself to the training spectra and could be used for classification of unknown spectra of similar origin, When testing roller-bearing cages and aerospace composites a large amount of training data was available, which enabled the classifier typically to classify about 95% of the samples correctly. When using the neural network classifier on pre-cast concrete paving slabs a success rate of 87% was achieved, The partners consider these results to be the major success of the project. For this method to be used commercially success-rates of close to 100% will be required.

Software has been written to predict the spectrum from samples using the finite element approach. It is intended to assist the end-user in applying ultrasonic resonance spectroscopy to single test samples, The software should also be of use in determining the best frequency range over which to collect a spectrum on a given sample (to optimize sensitivity to flaws of interest), choosing the best location on the test sample for the transducer-pair (to optimize sensitivity to flaws of interest) and predicting the effects of flaws in samples. Differences were found between predicted spectra for flawed and unflawed samples - the samples were also used in experiments. However, the size of the defect was rather large - the flaw that was modeled was relatively large (about 3% in volume of the sample) and there must be doubts about using the method on increasingly small volumetric flaws - there will be some cut-off in sensitivity. Experiments showed that an artificial neural network could detect flaws in the same class of samples down to the smallest flaws introduced, a volumetric ratio of 0.04%. It seems difficult to make a conclusion on the feasibility of using finite elements because of the large sizes of the flaws.

Several feasibility demonstrations have been given; the most conclusive was made on a statistically significant number of pre-cast concrete paving slabs. Spectra Were collected from the samples before and after damage was introduced. A neural network was trained and in blind tests a multi-layer perception network was able to classify the paving slabs as either damaged or pristine with a success rate of 87%. All attempts to classify the quality of the samples by eye alone failed and there were serious doubts initially that the neural network could be used successfully to classify the quality of these samples. The spectra contained variations indicating a high degree of variability between the samples, greater than had been expected, which appeared to be greater than the features introduced by damage, yet despite adverse conditions the multi-layer perception succeeded in correctly classifying the quality with a high success-rate - under blind-trial conditions. In these tests each paving slab was tested at one position only - no surface scanning was used as in conventional ultrasonic testing. This demonstration also showed conclusively that an entire sample could be inspected with one test (global. testing) - this is important because it makes the method simpler and faster than conventional testing and hence more cost-effective. The disadvantage is the effort needed to train the network but this kind of approach could be used to great advantage on a production-line. Finite element predictions confirmed that the spectra of damaged and pristine slabs should be different although it was not possible to predict the precise shape of the experimental spectrum. The volumetric ratio of flaw size to the size of the sample was normally in the range 0.04% to 3% with one sample of 100%.

Resonance spectroscopy tests on large pre-cast concrete tunnel lining segments were made without using artificial neural networks for classifying quality, Although spectra appeared by eye to show some sensitivity to quality the degree of variation in spectra due to concrete composition also appeared to be significant and commensurate with the degree of variation due to flaws. It should be pointed-out that given the observed diversity of response measured in the tunnel lining segments, even for ostensibly satisfactory ones, the number of segments available was not large enough to enable the variations to be fully characterised which would also contribute to a lack of success in using resonance spectroscopy, This was somewhat surprising as the production process offers a high degree of control over the end product as opposed to the in-situ methods used to produce some of the structural concrete elements tested in this project.

The finite element package 'was not able to assist in classifying a tunnel wall lining segment as damaged or undamaged with any degree of certainty and is considered to be of no practical assistance. The finite element software was not only found to be unreliable and difficult to use but seriously flawed in that predictions varied over

different frequency ranges on the same test sample. The cost of commercial finite element packages has fallen dramatically during this project and it is hoped that there is now a commercial finite element package that could be used more successfully to predict spectra.

A correlation between increasing early age strengths of concrete and the shift in resonant frequency peaks was demonstrated. The technique did not prove sensitive enough to be useful in respect of estimation of concrete strength for compliance with contractual requirements because the modulus is changing too slowly at the usual design strength age of 28 days and therefore, the resolution is insufficient at this age. However, this work shows that early age strength can be assessed but the controlling factors have not been fully identified,

The application of resonance spectroscopy to concrete structures in general and bridge structures in particular is limited in an embodiment in which interpretation is made by eye alone. On a typical set of bridges, it is unlikely that enough similar samples, which could tested by other means, could be found to train a neural network. From the start it was, therefore, seen as extremely unlikely that the neural network software could be applied to bridge inspections. The finite element software developed in the project was not suitable for predicting spectrums due to its limited ability and reliability. Further fundamental research work is needed in this area before the technique can be used for testing concrete structures. Currently, resonance spectroscopy without a neural network shows limited prospect for commercialisation on concrete without further development in the area of finite element predictions.

The conclusions from evaluation on concrete need to be carefully defined. On one hand tests on a large number of fine-grained concrete paving slabs were successful because a neural network was used - interpretation was impossible by eye - and aging tests on coarse-grained concrete samples were partially successful (only failing to achieve the required accuracy). On the other hand tests on a small number of coarse-grained tunnel-wall segments and a large number of tests on two large concrete Structures were unsuccessful - interpretation was only tried by eye. Important differences between the paving slab tests and the other concrete tests were that:

* the paving slabs were small and of fine-grained, unreinforced concrete,
- the paving slab tests were performed using a neural network for classification of quality,
- the other tests on concrete related to large specimens of reinforced concrete, with coarser grain structures and, possibly, significant numbers of fine cracks,
- the interpretation of results was done by eye for the other tests on concrete because neither the finite element prediction nor the neural network classifier could be applied in these instances.

The partner responsible for tests on the two concrete structures is confident that a neural network would almost certainly have failed to classify the quality of the concrete in the structures, The concision is made on the basis of painstaking examination by eye of the spectra showing an apparent sensitivity to unwanted factors such as weather condition, occasion of test, test position and an apparent lack of sensitivity to defects. On this basis it is only possible to conclude that:

1. Resonance spectroscopy can be successfully applied using a neural network to fine-grained, unreinforced concrete paving slabs.
2. Resonance spectroscopy might be applied to large reinforced concrete structures and pre-cast units but further fundamental study is heeded before any definitive conclusions will be possible.
3. Resonance spectroscopy, with a neural network, may be capable of successful application on coarse-grained concrete and concrete structures but this has not been tested in this study and more research will be needed to test the feasibility of this approach,

This project has shown that resonance spectroscopy, when used to test a whole sample (global testing) and when a neural network is used for interpretation is an intrinsically simple test and can be used successfully to assess the mechanical quality of industrial components. It involves no surface scanning and no operator is needed to interpret data. The project has also shown that resonance spectroscopy can be used successfully for local testing with a neural network for interpretation. The output of the neural network can 'be as simple as either Pass or Fail. The only manipulation of the object required is to place the transducer pair in contact with the sample for the test. For these reasons resonance spectroscopy has considerable potential to be a highly cost-effective tool for quality assurance of industrial parts made on a production-line. Resonance spectroscopy has been much less successful when it is used without an effective aid to interpretation - when that the. operator is substantially responsible for deciding the quality of the inspected component and it cannot be recommended for use in this particular way. However, resonance spectroscopy when aided by a neural network has proved to be a highly effective tool for inspecting a range of industrial components,

Acknowledgments

The partners are grateful for the financial support of the Commission of the European Union, Instrumentation Innovation would also like to thank the Petroleum Science and Technology Institute for its financial support.

References

1. "Ultrasonic resonance spectroscopy for NDT - optimizing spectrum collection," Andrews, D.R., Blanchard, J.E., Castaldello, L., Proc Italian NDT Sot, Turin October (1995).
2. "Impact-echo method" Sansalone, M., Carino, N.J., Concrete Int April (1988)
3. "Transient impact response of thick circular plates" Sansalone, M., Carino, N. J., J Res Nat Bureau Standards (USA, Gaithersburg) (1987)
4. "Comparison of pulse-echo methods for testing concrete" Kroggel, O., et al Int Symp on NDT in Civil Engineering (NDT-CE) September (1995) BAM, Berlin.
5. "Detection of tendon ducts with the ultrasonic impulse echo method in interlaboratory tests at BAM" Kroggel, O., et al, Dramstadt Concrete 10(1995]305-17.
6. "Detection of corroded reinforcement utilising ultrasound back-scatter technique" Kroggel, O., et al, Dramstadt Concrete 10(1995)295-305.
7. Grindo-Sonic: J.W.Lemmens, Leuven 13-3001, Belgium.
8. Fokker, Netherlands,
9. "Identification of structural properties using dynamic techniques" Geigrich, G., Kroggel, O., Ötes, A., Darmstadt Concrete 2(1987) ISSN 0931-11881 also EC Brite project 1353-4-85.
10. Solartron/Schlumberger 1209 and 1210 instrument, UK.
11. "Crystals and ultrasound" Migliori, A., Fisk, Z., Los Alamos Science 21(1993) 182-194
12. "The use of resonances to sort spherical and tapered rolling elements" Quatrosonics Inc., Rhodes, G.W., Thomas, D, E.,
13. "Neural networks involving new signal processing procedures for fault assessment in civil engineering structures" Tomlinson, G.R., et al Brite/EuRam project BE 4618-90 Contract BREU-526(WB) European Commission (1994).
14. "Non-destructive materials testing apparatus and technique for use in the field" Sansalone, M.J., US Patent 5,165,270 (1992)
15. "Flaw classification of aerospace sandwich components using artificial neural networks" Stepinski, T., Private communication 1996.
16. "Future prospects of ultrasonic inspection of concrete" Andrews, D.R., Proc Instn Civ Engrs Structs & Bldgs (1993) 99 Feb., 71-73.
17. "Non-destructive testing of concrete and its application to specifications" Elvery, R.H., Concrete (1971) May, 137-141,