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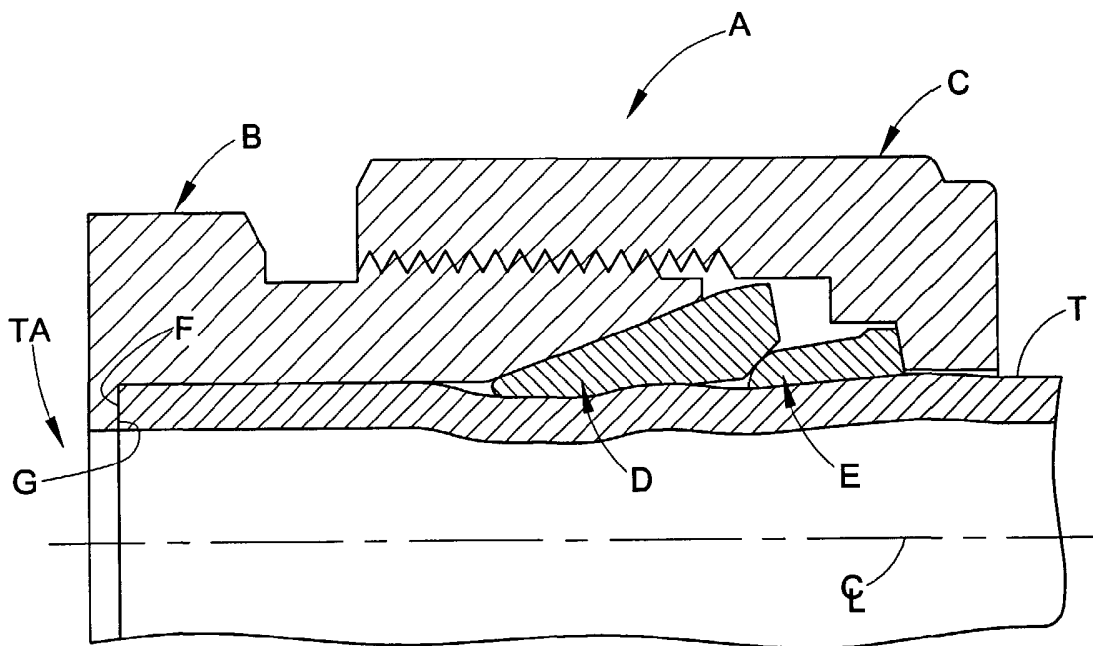
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(54) Title: ULTRASONIC TESTING OF FITTING ASSEMBLY



(57) Abstract: Apparatus and method for determining relative and/or absolute axial position of a conduit end within a fluid coupling includes application of input ultrasonic energy in the form of transient shear waves and analyzing the reflected energy. Application of the input energy collected at different radial positions about a first axial location is used with wavelet based correlation techniques to better analyze the reflected energy signals. Quality of the abutment between the conduit end and a surface associated with the coupling may also be determined as a separate or combined feature of the axial position determination.



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## **ULTRASONIC TESTING OF FITTING ASSEMBLY**

### **Related Application**

This application claims the benefit of United States Provisional patent application serial no. 60/389,394 filed on June 17, 2002 for ULTRASONIC FITTING ASSEMBLY VALIDATION, the entire disclosure of which is fully incorporated herein by reference.

### **Technical Field Of The Invention**

The invention relates generally to apparatus and methods for non-destructive evaluation of fitting assemblies after assembly is completed. More particularly, the invention relates to using mechanical energy to make evaluations of the fitting assembly.

### **Background of the Invention**

Fluid handling equipment, whether the fluid is gas, liquid, combination of gas and liquid, slurries and so on, may use many fluid control devices that are connected together with the use of fittings. Typical fluid control devices include valves, regulators, meters and so on that are interconnected in a fluid circuit with either tube or pipe. The fittings may take on a wide variety of designs, including but not limited to single ferrule and multi-ferrule tube fittings, various clamping arrangements using elastomeric seals, gripping rings and so on. For purposes of this disclosure we refer to tube and pipe as "conduit" because the present invention may be used with either tube or pipe.

Common to nearly all fluid circuits that use fittings to connect conduit to a flow control device or process is the desire to verify in a non-destructive manner that a fitting has been fully assembled. Most connections via fittings involve the positioning of a conduit within a fitting body or other structure associated with a fluid coupling (referred to herein as a fitting assembly of a conduit and coupling) such that an end of the conduit abuts a shoulder or wall of the fitting body or other structure. This abutment or "bottoming" as we also refer to it herein, is usually desirable as it allows that gripping device, such as a ferrule, to be installed onto the conduit without the conduit moving axially.

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Inherent in the assembly process, however, is the practical circumstance that once the fitting is installed there is no cost-effective non-destructive way, known to date, to determine that the conduit is fully bottomed. For example, it is known to use x-rays to observe the fitting condition, however, this is a very expensive process and simply not practical for many if not most assemblers. Various techniques are known that are used to verify proper installation of the fitting components, or to verify proper pull-up based on the number of turns of a fitting nut or axial displacement of the conduit relative to the nut. For example, the fitting may be disassembled after pull-up, visually inspected and then reassembled, but such steps are time consuming and costly. In another known technique, the tubing may be pre-marked in an appropriate manner prior to assembly, but this technique is subject to error in the marking or interpretation process. None of these techniques can absolutely determine in a final assembled fitting that the conduit is bottomed, and also determine the nature or quality of the contact or abutment between the conduit and the associated structure.

The need exists therefore to provide process and apparatus for non-destructive analysis and evaluation of whether a conduit is properly bottomed within a fitting.

### Summary Of The Invention

The invention contemplates in one aspect determining position of a conduit end using input energy applied to the conduit. In one exemplary embodiment, ultrasonic energy emitted from a shear wave transducer is applied to the conduit and propagates through the conduit as mechanical waves. Alternatively or in combination, the input energy may be applied through one or more of the fluid coupling components such as the fitting body, for example. Reflected energy (also sometimes referred to herein alternatively as return signals, return energy, return energy signals, reflected signals or reflected energy signals) is converted into electrical signals by the transducer and these electrical signals are analyzed to determine position of the conduit end. In a specific exemplary application the invention may be used to determine the position of an end of

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the conduit within a fluid coupling installed thereon. In alternative applications, the invention may be used to determine proper assembly of one or more of the ferrules in a single or multi-ferrule tube fitting by detecting a characteristic of the tube bite or indentation typically associated with ferrule-type tube fittings, such as, for example, the axial location thereof or the presence/absence thereof.

In accordance with another aspect of the invention, correlation techniques are used to more clearly discriminate the reflected energy signals. In one exemplary embodiment, ultrasonic energy is applied to the conduit at different radial positions about a first location of the conduit that is axially spaced from the conduit end. Reflected energy signals are correlated to determine relative axial position of the conduit end. Noise reduction may also be applied to the return signals.

In accordance with another aspect of the invention, the quality and/or nature of contact between the conduit and a surface associated with a fluid coupling installed on the conduit end may be determined. In one exemplary embodiment, ultrasonic energy is applied to the conduit and the amplitude of reflected energy is analyzed to determine the quality of the contact or bottoming of the conduit end against the surface associated with the fluid coupling, such as, for example, whether the conduit end is fully bottomed, partially bottomed or not bottomed. Correlation analysis may also be used in connection with this aspect of the invention.

These and other aspects and advantages of the present invention will be readily appreciated and understood from the following detailed description of the invention in view of the accompanying drawings.

### **Brief Description Of The Drawings**

Fig. 1 is a prior art two ferrule flareless tube fitting as an exemplary fluid coupling that the present invention may be used with, illustrated in half-view longitudinal cross-section;

Fig. 2 is an elevation of a fluid coupling assembly and the present invention;

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Fig. 3 is a functional block diagram of an analyzer in accordance with the invention; and

Fig. 4 is an end view of an optional configuration for an ultrasonic transducer location in accordance with another aspect of the invention.

## Detailed Description Of The Invention

### 1. INTRODUCTION

The present invention is directed to apparatus and methods relating to determining position of a conduit within a fluid coupling installed on the conduit. This determination may include, separately or combined, determining the axial position of an end of the conduit within a fluid coupling, and determining the quality of contact between the conduit and a surface associated with the fluid coupling.

Determining the axial position of a conduit within a fluid coupling is particularly useful, for example, with tube fittings of the type that have a threadably coupled nut and body and at least one ferrule that is used to provide a fluid tight coupling between the tube end and the body. Although the invention is described herein with particular reference to its use with a two ferrule flareless tube fitting, those skilled in the art will readily appreciate that the invention may be used in many other applications, and generally to any application wherein it is desired to determine the relative and/or absolute axial position of an end of a conduit, such as tubing or pipe, whether the conduit end is positioned with a fluid coupling, a fluid flow device or so on.

Determining the nature or quality of contact is also particularly useful, for example, with the aforementioned tube fittings. In particular, the fitting body includes a generally radial shoulder against which the tube end is preferably abutted after a complete pull-up of the fitting. By "pull-up" is simply meant the final assembly and tightening of the coupling nut (beyond the initial finger tight assembly) and body so as to secure the one or more ferrules onto the tube end in a seal-tight manner. The quality of this abutting relationship is affected by many factors, including but not limited to, the facing operation of the tube end, such as the degree of flatness

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and square alignment of the tube end, the nature of the radial shoulder in the body including its flatness and square alignment, the amount of tube deformation that may occur during pull-up, the amount of compressive load between the tube end and the body shoulder, and so on. The quality of the bottoming is therefore a general reference to the completeness of the bottoming and the  
5 load between the abutting surfaces, as exhibited by the nature of the contact in terms of the amount of contact area, the characteristics of the abutting surfaces and so on. The particular characteristics of quality and nature of the abutment may be selected as required for a particular application. Again, the invention will find application beyond two ferrule flareless tube fittings, and may be used in many applications wherein it is desired to determine the quality of the  
10 abutment between a conduit end and a surface in a fluid element such as a tube fitting, a flow control device and so on. In many coupling applications, simply knowing the quality of the conduit end insertion, for example whether the conduit end is fully bottomed, partially bottomed or not bottomed, is the most useful information, regardless of the ability to detect axial position of the conduit end.

15 In the exemplary embodiments herein, the invention is realized using ultrasonic energy as an input energy signal. The more specific, but not necessarily required, characteristics of the ultrasonic energy in the exemplary embodiments is ultrasonic energy in the form of a generally continuous mechanical wave or waves having one or more discontinuities. In other words, the input energy may be applied as a series of one or more transient waveforms. The input energy  
20 signal in the exemplary embodiments therefore is in the form of one or more packets or pulses of the energy waveform. By "pulse" or "packet" we do not intend to restrict the waveform of the input signal to any particular or required waveform shape or characteristic either in the time, frequency, wavelength or amplitude domains. In the exemplary embodiments, the input energy signal is realized in the form of a transient signal having one or more harmonic waveforms with  
25 decreasing amplitudes over the time duration of the transient signal. The input waveform characteristics may be selected to facilitate analysis of the return signals, such as by the

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correlation techniques described herein. Alternatively, the applied waveform may be any Fourier series waveform for example, including an impulse harmonic waveform, a square wave, and so on. Those skilled in the art will appreciate that the invention may be used with any conveniently available form of reflectable mechanical energy, as distinguished from electromagnetic energy such as x-rays, that is transmitted by pressure waves in a material medium, such as, for example, the conduit or one or more parts of a fluid coupling, and detected therefrom.

While the invention is described and illustrated herein with particular reference to various specific forms and functions and steps of the apparatus and methods thereof, it is to be understood that such illustrations and explanations are intended to be exemplary in nature and should not be construed in a limiting sense. For example, the present invention may be utilized with any fluid coupling between a conduit and a fluid flow member including but not limited to another conduit. The term fluid coupling therefore is used in its broadest sense to refer to any mechanical connection between a conduit end and an abutment surface of another fluid flow element. Furthermore, while the invention is described herein with reference to stainless steel tubing and tube fittings, the invention will find application with many other metals and indeed non-metal applications such as plastics, as well as to tubing, pipe and so on.

Additionally, various aspects of the invention are described herein and are illustrated as embodied in various combinations in the exemplary embodiments. These various aspects however may be realized in alternative embodiments either alone or in various other combinations thereof. Some of these alternative embodiments may be described herein but such descriptions are not intended to be a complete or exhaustive list of available alternative embodiments or modifications. Those skilled in the art may readily adopt one or more of the aspects of the invention into additional embodiments within the scope of the present invention even if such embodiments are not expressly disclosed herein. Additionally, even though some features and aspects and combinations thereof may be described herein as having a preferred form, function, arrangement or method, such description is not intended to suggest that such

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preferred description is required or necessary unless so expressly stated. Those skilled in the art will readily appreciate that the invention may be used with additional modifications, improvements and equivalents either known or later developed as substitute or alternatives for the embodiments described herein.

## 2. DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

With reference to Fig. 1, there is illustrated a highly successful two ferrule tube fitting A. This fitting A is described in United States Patent No. 3,103,373 owned by the assignee of the present invention and fully incorporated herein by reference. The illustration of Fig. 1 shows only one half of the fitting, it being recognized by those skilled in the art that the other half of the view is identical about the centerline CL.

The fitting A includes a body B, a nut C that is threadably engaged with the body B during finger-tight assembly and pull-up, a front ferrule D and a back ferrule E. The fitting A is illustrated installed on a conduit, in this case in the form of a tube end T. The tubing T may carry a media such as liquid, gas, slurry and so on. The assembly in Fig. 1 is illustrated in the pulled-up condition, with the ferrules D and E plastically deformed so as to provide a fluid tight seal and strong grip on the tube end T.

It is desirable that the inner end F of the tube end T abut at the region TA defined at a radial shoulder G formed in the body B. This abutment is referred to as "bottoming" the tube end T and is desirable to provide a strong mechanical assemblage, including forming a good seal and having a strong tube grip, that can withstand environmental conditions such as temperature variations and vibration effects. A seal may but need not be formed at the abutment between the surfaces F and G. Whether a seal is formed there or not, it would be advantageous to be able to determine that the tube end is bottomed and the quality, nature or completeness of the contact. A tube end could be partially or incompletely bottomed by virtue of the assembler failing to properly insert the tube end sufficiently into the body B in accordance with the manufacturer's instructions.

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A fully bottomed conduit end would be a condition in which there was substantial surface to surface contact between the conduit end and the body shoulder and good solid mechanical contact or compression therebetween. A partially bottomed conduit end would be a condition in which, for example, there is not substantial surface to surface contact due to poor end facing of the conduit end, a cocked or tilted conduit, or simply a lack of strong compression between the two abutting surfaces. A conduit end that is not bottomed would be a condition of little or no surface to surface contact or the presence of an actual axial gap between the non-abutting surfaces. Therefore, as used herein, the nature or quality of the contact between the conduit end and the abutting surface refers generally but not exclusively to various features either alone or in various combinations including the amount of surface area where contact is made, the force or load between the conduit end and the abutting surface, presence of a gap therebetween, lack of square alignment of the abutting surfaces, and so on.

With reference to Fig. 2 we illustrate a first embodiment of the invention. An input energy source or input device 12 is coupled to the conduit T so as to apply mechanical input energy into the conduit T, wherein a portion of the applied input energy is reflected back or returned. The source device 12 may be, for example, a transducer that converts an electrical drive signal into vibration or mechanical energy. One example is an ultrasonic transducer that emits a high frequency signal which may be reflected or otherwise returned to the source 12 by a variety of conditions including but not limited to inclusions, micro-structural deformations, voids, the tube end F, and tubing deformations or indentations such as the ferrule bite or compression. The source 12 is used as a transmitter as well as a receiver or sensor and converts the reflected energy that reaches the source 12 into a corresponding electrical signal. Alternatively, the transmitter and receiver may be separate or different devices. The source 12 is coupled via a cable 14 or other suitable connection to an electronics arrangement 16. The electronics 16 includes appropriate circuitry that generates the drive signal for the source device 12 and that receives the electrical signals from the source device 12.

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We have found that--although a surface wave transducer or a delay line transducer may be used to determine the bottomed condition of a tube end, as well as proper assembly of the tube fitting, and that either of these transducers is a useful alternative to the exemplary embodiment herein--a preferred technique and device is to use a shear wave transducer to apply the input energy to the conduit T. A shear wave transducer is distinguished from a delay line transducer in that the shear wave transducer applies energy into an object generally longitudinally or along the direction of the surface of the object, whereas a delay line transducer applies energy generally normal to the surface, and thus may be used to determine wall thickness. The shear wave transducer is thus able to produce a better return reflection or echo of the end of the conduit, particularly when the conduit is only partially bottomed or completely not bottomed.

A suitable and exemplary transducer is a Phoenix-ISL shear wave transducer model SSW-4-70 that is resonant at 4 Megahertz. Other transducers commercially available or later developed will also be suitable for the present invention, and the invention is not limited to the use of ultrasonic energy waves. Non-ultrasonic wave frequencies may be used provided that adequate and detectable energy is reflected back from the tube end. It is also possible to use a tuned frequency that provides the strongest echo from the conduit end depending on the conduit dimensions, material, temperature, the fluid coupling associated therewith, and so on.

It is worth noting at this time that a particular advantage of the present invention is that it may be used to determine the bottoming condition of a conduit within a fluid coupling in a non-destructive manner, even while the fluid is present in the conduit. Thus there is no need to necessarily purge the system or disassemble any components, although such may be desirable in some circumstances.

We have further found that easily interpreted data can be obtained after noise filtering and performing correlation analysis to the reflected energy. We have moreover found that a Morlet wavelet function, well known to those skilled in the art as to its mathematical form, aids the filtering function with the invention, however, the present invention is not limited to using such a

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Morlet wavelet function. For example, other types of exponential sinusoidal wavelet functions, or other filtering functions, may be alternatively useful in some applications.

With reference to Fig. 3, we illustrate a detailed functional block diagram of the electronics arrangement 16 in the form of an analyzer. It is desirable that the invention be realized in the digital analysis domain, however, such is not required and it may be suitable in some applications to perform analog or hybrid analog/digital analysis.

Fig. 3 also illustrates additional aspects of the invention relating to the mounting of the source 12. In this example, the source 12 is a shear wave transducer and is firmly supported on a base 20 that can be suitably attached to or placed in contact with the conduit surface TS. The base 20 preferably is made of a high transmission material, such as acrylic resin, so that the energy emitted from the transducer face 22 is coupled with good efficiency into the conduit T. The use of a base 20 or other suitable structure enhances the coupling because the base 20 can be provided with a surface 24 that conforms to the surface profile of the conduit surface TS. This usually will be an improvement over simply trying to position the typically flat transducer face 22 against a cylindrical surface TS, however, in some applications, especially large diameter conduits, such a direct mounting may be useable. A suitable low attenuation coupling material may also be applied between the base surface 24 and the conduit surface TS. A suitable low attenuation liquid couplant may be water for example, however other coupling material such as solid or paste may be used, such as for example, latex or silicone rubber or AQUALENE<sup>TM</sup> available from R/D Tech. The use of a coupling material may be omitted in cases where the signal coupling between the conduit and the transducer does not adversely attenuate either the drive signal into the conduit or the reflected energy back into the transducer.

Fig. 3 illustrates that the base 20 may be configured so that the transducer face 22 is angled away from normal towards the conduit longitudinal axis CL. In this manner, the input energy enters the conduit structure at an angle  $\theta_R$ . We have found that a suitable range for  $\theta_R$  is from about greater than 0° to about 90°, more preferably about 45° to about 85°, and most

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preferably about 65° to about 75°. However, the selected angle for  $\theta_R$  in any particular application may be selected based on the angle that produces the best or most useful return energy profiles. Materials having appropriate indices of refraction may be selected to allow refraction to assist in the input energy entering the coupling assembly at the desired angle  $\theta_R$ .

5        With continued reference to Fig. 3, the analyzer 16 may be realized in the form of any suitable digital processor including but not limited to DSP, microprocessors, discrete digital circuits and so on. The analyzer processor 16 may conveniently be any commercially available or later developed circuit that is programmable in accordance with programming techniques well known to those skilled in the art, to carryout the functions described herein. The analyzer  
10    processor 16 thus includes a signal generator 26 that produces a suitable drive signal that is coupled to the transducer 12 via a suitable cable or wire 28. The analyzer processor 16 further includes a filter function 30 that may be used for noise reduction, since the electrical signal from the transducer 12 will typically include a substantial amount of background undesired noise. Any suitable filter design in circuitry or software well known to those skilled in the art may be  
15    used. Note that in Fig. 3 the noise filtering function is performed on the analog signal from the transducer 12. Alternatively, digital filtering may be performed in cases when the transducer signal has been digitized. Still further, a filter function may be included in the transducer itself, and special shielding on the cables and transducer assembly may be used as required to further reduce noise.

20        The filter function 30 receives the electrical output signal from the transducer 12 via a cable or other suitable connection 32 (note that the wire 32 and the wire 28 are part of the aforementioned cable 14 of Fig. 2).

      The filtered signal from the transducer 12 is then input to a conventional analog to digital (A/D) converter 34. The A/D converter 34 converts the electrical signal from the transducer 12  
25    into a digitized signal that can be conveniently stored in a storage device such as a memory 36.

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The memory 36 may be volatile or non-volatile memory or both depending on the type of data analysis to be performed.

5 In some applications, the reflected energy signal may have a very pronounced and easily discernible signal level that corresponds to the axial position of the conduit end relative to the energy source 12. Note that the axial position of the conduit end relative to the transducer may be determined either as an absolute number or a relative number, and is computed based on knowing the propagation speed of the energy through the conduit, as is well known in the art of ultrasonic analysis. If the reflected energy provides an easily discernible signal stored in the memory 36, then the controller 16 can simply be programmed to determine the characteristics of  
10 the signal to ascertain the axial position of the conduit end.

In accordance with another aspect of the invention, the relative strength of the reflected energy is an indication of the quality of the bottoming. We have found that when there is good or complete bottoming, very little energy is returned from the conduit end because the energy passes through into the fitting body material (and/or other contacting structures) and there is thus  
15 a substantial attenuation in the reflected or returned energy. Thus interestingly, the absence of a strong reflected energy level actually indicates excellent bottoming. For an un-bottomed conduit end, a high and sharply pronounced reflected energy level is returned due to reflection at the gap interface between the conduit end and the body shoulder. For a partially bottomed conduit end, the reflected energy will be somewhere in between a fully bottomed conduit end and an un-  
20 bottomed conduit end. Test samples and empirical data may be used to calibrate the system 16 as required.

We have further found through experimentation, however, that the mechanical complexity of a typical fluid coupling and conduit micro-structure renders a nice clean easy-to-detect reflected energy signal to not be a practical reality. Instead, all sorts of false or non-  
25 repeatable echoes may arise. Furthermore, we have found that for a single axial location of the transducer relative to the conduit end, the circumferential position of the transducer may

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significantly influence the nature of the reflected energy. For example, the reflected energy from the conduit end may not always appear at the same time delay marker when the transducer is moved about different circumferential positions, even at the same axial location, on the conduit.

We attribute this to micro-variations in the conduit and the fluid coupling structure, but whatever the causes may be, the practical consequence is that they typically will be present.

In accordance then with another aspect of the invention, the energy applied into the conduit T is done at two or more circumferential positions about the selected axial location of the source transducer 12. This is illustrated in Fig. 4 wherein reflected energy data is collected and stored for two or more circumferential positions of the source transducer 12 about the conduit at the axial location selected. This can be performed using a plurality of transducers positioned at different positions about the conduit T, or more simply by repositioning a single transducer 12 and then collecting data at each location as indicated by the dashed lines in Fig. 4. The different positions may be but need not be evenly spaced about the conduit.

Each application of input energy at a particular circumferential position produces reflected or return energy that is converted into an electrical signal, filtered and stored as previously described herein. Data is collected for two or more, and preferably about three, different circumferential positions at the selected axial location of the transducer (which in the exemplary embodiment is just behind the nut C of the fitting assembly A.) A correlation function 40 is then applied to the set of data from the plurality of circumferential positions. The correlation analysis substantially eliminates or "filters" the random return energy signals from the micro-variations in the conduit because their positions relative to the applied energy transducer source 12 changes as the transducer is repositioned about the conduit T. The conduit end relative position, however, does not, and correlation analysis distinctly discriminates the corresponding signal. The correlation analysis may be conventional, such as for example but not limited to, the analysis disclosed in Correlation Analysis of Spatial Time Series Datasets: A Filter and Refine Approach, Zhang, Huang, Shekhar and Kumar, University of Minnesota, Technical Report

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Abstracts, 2001, the entire disclosure of which is fully incorporated herein by reference. We have found that the selected signal correlation analysis may be significantly facilitated by optionally but preferably using the wavelet based correlation method disclosed in Complex Wavelet Analysis of Ultrasonic Signals, Hull, Yang, and Seymour, to be published in IMechE (Institution of Mechanical Engineers, London), June, 2003, the entire disclosure of which is fully incorporated herein by reference, and which may be implemented/programmed in software or firmware using conventional and well known techniques. The analyzer 16 can thus produce an output 42, in any suitable form including but not limited to a visual output, printed output and so on, of the quality of the conduit end bottoming and, if so desired or alternatively separately desired, the absolute or relative axial position of the conduit end as a function of the axial location of the source 12.

The present invention contemplates not only the structure of the aforementioned apparatus, but also the methods embodied in its use, and furthermore a method for determining position of a conduit end within a fluid coupling and a method for determining the quality of the bottoming of a conduit end against a structural surface. Such a method includes the steps of applying energy into the conduit structure, detecting reflected or returned energy from the conduit end and determining the position of the conduit end as a function of the location of the source. In another method, the quality of the bottoming of a conduit end is determined by applying energy into the conduit structure, detecting reflected or returned energy from the conduit end and determining the quality of bottoming of the conduit end as a function of the reflected energy signal strength. Both methods may be used alone or in combination with each other or other analysis, and both methods may optionally utilize the above-described noise filtering and correlation techniques.

As some of the many available alternatives, the electronics 16 may be incorporated into any suitable package for use in the desired application and environment. For example, the electronics 16 including the source 12 may be incorporated into a device or tool that also is used

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as a conventional gap gauge. The electronics 16 may produce an output of any desired format, and for example, could simply be a light that indicates a go/no go result of the bottoming of the tube end. The electronics may also incorporate intelligent rules based software such as neural nets for calibration and/or analysis and may include the above described noise filtering and correlation techniques.

The source 12 may alternatively be configured to apply the input energy into a component of the fluid coupling, rather than or in addition to the conduit. This would only require a simply reconfiguration of the interface geometry of the base 20 for example. Depending on the surface for mounting, the base 20 may even be unnecessary. For example, the source 12 may apply the input energy into the fitting body B, such as at the head or neck of the fitting body.

Still further, the present invention may be used to determine, separately or in combination with the conduit end position, other evaluations of the fitting assembly. As described herein above, the present invention may be used to determine the position and abutment characteristics of the conduit end. The invention may also be used to determine the position and characteristics of other normal deformations and structural variations of the conduit such as are associated with the fluid coupling, as such conditions may also produce reflected energy. For example, but not limited thereto, the invention may be used to detect the presence and/or location of the bite or tube indentation or compression caused by one or more of the ferrules. By determining that the selected condition is positioned properly and has the desired quality, the user may know that the fitting assembly has been properly completed, such as knowing that the ferrules are correctly installed and pulled up. Absence of such signals may indicate improper assembly or pull-up.

The invention has been described with reference to the preferred embodiment. Modifications and alterations will occur to others upon a reading and understanding of this specification. It is intended to include all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.

## Correlation Analysis of Spatial Time Series Datasets: A Filter-and-Refine Approach

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**Abstract.** A spatial time series dataset is a collection of time series, each referencing a location in a common spatial framework. Correlation analysis is often used to identify pairs of potentially interacting elements from the cross product of two spatial time series datasets. However, the computational cost of correlation analysis is very high when the dimension of the time series and the number of locations in the spatial frameworks are large. The key contribution of this paper is the use of spatial autocorrelation among spatial neighboring time series to reduce computational cost. A filter-and-refine algorithm based on coning, i.e. grouping of locations, is proposed to reduce the cost of correlation analysis over a pair of spatial time series datasets. Cone-level correlation computation can be used to eliminate (filter out) a large number of element pairs whose correlation is clearly below (or above) a given threshold. Element pair correlation needs to be computed for remaining pairs. Using experimental studies with Earth science datasets, we show that the filter-and-refine approach can save a large fraction of the computational cost, particularly when the minimal correlation threshold is high.

### 1 Introduction

Spatio-temporal data mining [14, 16, 15, 17, 13, 7] is important in many application domains such as epidemiology, ecology, climatology, or census statistics, where datasets which are spatio-temporal in nature are routinely collected. The development of efficient tools [1, 4, 8, 10, 11] to explore these datasets, the focus of this work, is crucial to organizations which make decisions based on large spatio-temporal datasets.

A spatial framework [19] consists of a collection of locations and a neighbor relationship. A time series is a sequence of observations taken sequentially in

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time [2]. A spatial time series dataset is a collection of time series, each referencing a location in a common spatial framework. For example, the collection of global daily temperature measurements for the last 10 years is a spatial time series dataset over a degree-by-degree latitude-longitude grid spatial framework on the surface of the Earth.

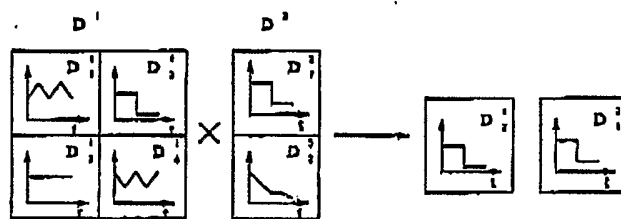


Fig. 1. An Illustration of the Correlation Analysis of Two Spatial Time Series Datasets

Correlation analysis is important to identify potentially interacting pairs of time series across two spatial time series datasets. A strongly correlated pair of time series indicates potential movement in one series when the other time series moves. For example, El Nino, the anomalous warming of the eastern tropical region of the Pacific, has been linked to climate phenomena such as droughts in Australia and heavy rainfall along the Eastern coast of South America [18]. Fig. 1 illustrates the correlation analysis of two spatial time series datasets  $D^1$  and  $D^2$ .  $D^1$  has 4 spatial locations and  $D^2$  has 2 spatial locations. The cross product of  $D^1$  and  $D^2$  has 8 pairs of locations. A highly correlated pair, i.e.  $(D_2^1, D_1^2)$ , is identified from the correlation analysis of the cross product of the two datasets.

However, a correlation analysis across two spatial time series datasets is computationally expensive when the dimension of the time series and number of locations in the spaces are large. The computational cost can be reduced by reducing time series dimensionality or reducing the number of time series pairs to be tested, or both. Time series dimensionality reduction techniques include discrete Fourier transformation [1], discrete wavelet transformation [4], and singular vector decomposition [6].

The number of pairs of time series can be reduced by a cone-based filter-and-refine approach which groups together similar time series within each dataset. A filter-and-refine approach has two logical phases. The filtering phase groups similar time series as cones in each dataset and calculates the centroids and boundaries of each cone. These cone parameters allow computation of the upper and lower bounds of the correlations between the time series pairs across cones. Many All-True and All-False time series pairs can be eliminated at the cone level to reduce the set of time series pairs to be tested by the refinement phase. We propose to exploit an interesting property of spatial time series datasets, namely spatial auto-correlation [5], which provides a computationally efficient method to determine cones. Experiments with Earth science data [12] show that the filter-and-refine approach can save a large fraction of computational cost, especially

when the minimal correlation threshold is high. To the best of our knowledge, this is the first paper exploiting spatial auto-correlation among time series at nearby locations to reduce the computational cost of correlation analysis over a pair of spatial time series datasets.

**Scope and Outline:** In this paper, the computation saving methods focus on reduction of the time series pairs to be tested. Methods based on non-spatial properties (e.g. time-series power spectrum [1, 4, 6]) are beyond the scope of the paper and will be addressed in future work.

The rest of the paper is organized as follows. In Section 2, the basic concepts and lemmas related to cone boundaries are provided. Section 3 proposes our filter-and-refine algorithm, and the experimental design and results are presented in Section 4. We summarize our work and discuss future directions in Section 5.

## 2 Basic Concepts

In this section, we introduce the basic concepts of correlation calculation and the multi-dimensional unit sphere formed by normalized time series. We define the cone concept in the multi-dimensional unit sphere and prove two lemmas to bound the correlation of pairs of time series from two cones.

### 2.1 Correlation and Test of Significance of Correlation

Let  $x = \langle x_1, x_2, \dots, x_m \rangle$  and  $y = \langle y_1, y_2, \dots, y_m \rangle$  be two time series of length  $m$ . The correlation coefficient [3] of the two time series is defined as:

$$\text{corr}(x, y) = \frac{1}{m-1} \sum_{i=1}^m \left( \frac{x_i - \bar{x}}{\sigma_x} \right) \cdot \left( \frac{y_i - \bar{y}}{\sigma_y} \right) = \hat{x} \cdot \hat{y}$$

where  $\bar{x} = \frac{\sum_{i=1}^m x_i}{m}$ ,  $\bar{y} = \frac{\sum_{i=1}^m y_i}{m}$ ,  $\sigma_x = \sqrt{\frac{\sum_{i=1}^m (x_i - \bar{x})^2}{m-1}}$ ,  $\sigma_y = \sqrt{\frac{\sum_{i=1}^m (y_i - \bar{y})^2}{m-1}}$ ,  $\hat{x}_i = \frac{1}{\sqrt{m-1}} \frac{x_i - \bar{x}}{\sigma_x}$ ,  $\hat{y}_i = \frac{1}{\sqrt{m-1}} \frac{y_i - \bar{y}}{\sigma_y}$ ,  $\hat{x} = \langle \hat{x}_1, \hat{x}_2, \dots, \hat{x}_m \rangle$ , and  $\hat{y} = \langle \hat{y}_1, \hat{y}_2, \dots, \hat{y}_m \rangle$ .

A simple method to test the null hypothesis that the product moment correlation coefficient is zero can be obtained using a Student's t-test [3] on the t statistic as follows:  $t = \sqrt{m-2} \frac{r}{\sqrt{1-r^2}}$ , where  $r$  is the correlation coefficient between the two time series. The freedom degree of the above test is  $m-2$ . Using this we can find a  $p$ -value or find the critical value for a test at a specified level of significance. For a dataset with larger length  $m$ , we can adopt Fisher's Z-test [3] as follows:  $Z = \frac{1}{2} \log \frac{1+r}{1-r}$ , where  $r$  is the correlation coefficient between the two time series. The correlation threshold can be determined for a given time series length and confidence level.

### 2.2 Multi-dimensional Sphere Structure

In this subsection, we discuss the multi-dimensional unit sphere representation of time series. The correlation of a pair of time series is related to the cosine measure between their unit vector representations in the unit sphere.

**Fact 1 (Multi-dimensional Unit Sphere Representation)** Let  $x = \langle x_1, x_2, \dots, x_m \rangle$  and  $y = \langle y_1, y_2, \dots, y_m \rangle$  be two time series of length  $m$ . Let  $\hat{x}_i = \frac{1}{\sqrt{m-1}} \frac{x_i - \bar{x}}{\sigma_x}$ ,  $\hat{y}_i = \frac{1}{\sqrt{m-1}} \frac{y_i - \bar{y}}{\sigma_y}$ ,  $\hat{x} = \langle \hat{x}_1, \hat{x}_2, \dots, \hat{x}_m \rangle$ , and  $\hat{y} = \langle \hat{y}_1, \hat{y}_2, \dots, \hat{y}_m \rangle$ . Then  $\hat{x}$  and  $\hat{y}$  are located on the surface of a multi-dimensional unit sphere and  $\text{corr}(x, y) = \hat{x} \cdot \hat{y} = \cos(\angle(\hat{x}, \hat{y}))$  where  $\angle(\hat{x}, \hat{y})$  is the angle of  $\hat{x}$  and  $\hat{y}$  in  $[0, 180^\circ]$  in the multi-dimensional unit sphere.

Because the sum of the  $\hat{x}_i^2$  is equal to 1:  $\sum_{i=1}^m \hat{x}_i^2 = \sum_{i=1}^m \left( \frac{1}{\sqrt{m-1}} \frac{x_i - \bar{x}}{\sigma_x} \right)^2 = 1$ ,  $\hat{x}$  is located in the multi-dimensional unit sphere. Similarly,  $\hat{y}$  is also located in the multi-dimensional unit sphere. Based on the definition of  $\text{corr}(x, y)$ , we have  $\text{corr}(x, y) = \hat{x} \cdot \hat{y} = \cos(\angle(\hat{x}, \hat{y}))$ .

**Fact 2 (Correlation and Cosine)** Given two time series  $x$  and  $y$  and a user specified minimal correlation threshold  $\theta$  where  $0 < \theta \leq 1$ ,  $|\text{corr}(x, y)| = |\cos(\angle(\hat{x}, \hat{y}))| \geq \theta$  if and only if  $0 \leq \angle(\hat{x}, \hat{y}) \leq \theta_a$  or  $180^\circ - \theta_a \leq \angle(\hat{x}, \hat{y}) \leq 180^\circ$ , where  $\theta_a = \arccos(\theta)$ .

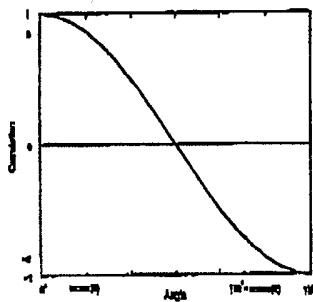


Fig. 2. Cosine Value vs. Central Angle

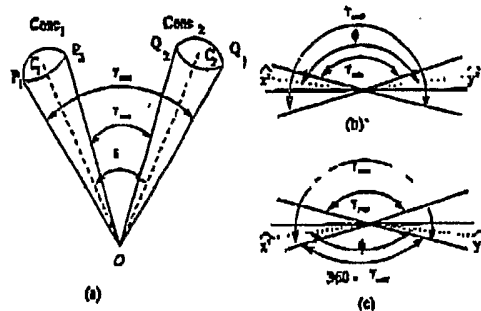


Fig. 3. Angle of Time Series in Two Spherical Cones

Fig. 2 shows that  $|\text{corr}(x, y)| = |\cos(\angle(\hat{x}, \hat{y}))|$  falls in the range of  $[\theta, 1]$  or  $[-1, -\theta]$  if and only if  $\angle(\hat{x}, \hat{y})$  falls in the range of  $[0, \arccos(\theta)]$  or  $[180^\circ - \arccos(\theta), 180^\circ]$ .

The correlation of two time series is directly related to the angle between the two time series in the multi-dimensional unit sphere. Finding pairs of time series with an absolute value of correlation above the user given minimal correlation threshold  $\theta$  is equivalent to finding pairs of time series  $\hat{x}$  and  $\hat{y}$  on the unit multi-dimensional sphere with an angle in the range of  $[0, \theta_a]$  or  $[180^\circ - \theta_a, 180^\circ]$ .

### 2.3 Cone and Correlation between a Pair of Cones

This subsection formally defines the concept of cone and proves two lemmas to bound the correlations of pairs of time series from two cones. The user specified

minimal correlation threshold is denoted by  $\theta$  ( $0 < \theta \leq 1$ ), and  $\arccos(\theta)$  is denoted by  $\theta_a$  accordingly.

**Definition 1 (Cone).** A cone is a set of time series in a multi-dimensional unit sphere and is characterized by two parameters, the center and the span of the cone. The center of the cone is the mean of all the time series in the cone. The span  $\tau$  of the cone is the maximal angle between any time series in the cone and the cone center.

We now investigate the relationship of two time series from two cones in a multi-dimensional unit sphere as illustrated in Fig. 3 (a). The largest angle ( $\angle P_1 O Q_1$ ) between two cones  $C_1$  and  $C_2$  is denoted as  $\gamma_{\max}$  and the smallest angle ( $\angle P_2 O Q_2$ ) is denoted as  $\gamma_{\min}$ . We prove the following lemmas to show that if  $\gamma_{\max}$  and  $\gamma_{\min}$  are in specific ranges, the absolute value of the correlation of any pair of time series from the two cones are all above  $\theta$  (or below  $\theta$ ). Thus all pairs of time series between the two cones satisfy (or dissatisfy) the minimal correlation threshold.

**Lemma 1 (All-True Lemma).** Let  $C_1$  and  $C_2$  be two cones from the multi-dimensional unit sphere structure. Let  $\hat{x}$  and  $\hat{y}$  be any two time series from the two cones respectively. If  $0 \leq \gamma_{\max} \leq \theta_a$ , then  $0 \leq \angle(\hat{x}, \hat{y}) \leq \theta_a$ . If  $180^\circ - \theta_a \leq \gamma_{\min} \leq 180^\circ$ , then  $180^\circ - \theta_a \leq \angle(\hat{x}, \hat{y}) \leq 180^\circ$ . If either of the above two conditions is satisfied,  $\{C_1, C_2\}$  is called an All-True cone pair.

**Proof:** For the first case, it is easy to see from Fig. 3 that if  $\gamma_{\max} \leq \theta_a$ , then the angle between  $\hat{x}$  and  $\hat{y}$  is less or equal to  $\theta_a$ . For the second case, when  $180^\circ - \theta_a \leq \gamma_{\min} \leq 180^\circ$ , we need to show that  $180^\circ - \theta_a \leq \angle(\hat{x}, \hat{y}) \leq 180^\circ$ . If this were not true, there exist  $\hat{x}' \in C_1$  and  $\hat{y}' \in C_2$  where  $0 \leq \angle(\hat{x}', \hat{y}') < 180^\circ - \theta_a$  since the angle between any pairs of time series is chosen from 0 to  $180^\circ$ . From this inequality, we would have either  $\gamma_{\min} \leq \phi = \angle(\hat{x}', \hat{y}') < 180^\circ - \theta_a$  as shown in Fig. 3 (b) or  $360^\circ - \gamma_{\max} \leq \phi = \angle(\hat{x}', \hat{y}') < 180^\circ - \theta_a$  as shown in Fig. 3 (c). The first condition contradicts our assumption that  $180^\circ - \theta_a \leq \gamma_{\min} \leq 180^\circ$ . The second condition implies that  $360^\circ - \gamma_{\max} < \gamma_{\min}$  since  $180^\circ - \theta_a \leq \gamma_{\min}$ . This contradicts our choice of  $\gamma_{\min}$  as the minimal angle of the two cones.  $\square$

Lemma 1 shows that when two cones are close enough, any pair of time series from the two cones is highly positively correlated; and when two cones are far enough apart, any pair of time series from the two cones are highly negatively correlated.

**Lemma 2 (All-False Lemma).** Let  $C_1$  and  $C_2$  be two cones from the multi-dimensional unit sphere; let  $\hat{x}$  and  $\hat{y}$  be any two time series from the two cones respectively. If  $\theta_a \leq \gamma_{\min} \leq 180^\circ$  and  $\gamma_{\min} \leq \gamma_{\max} \leq 180^\circ - \theta_a$ , then  $\theta_a \leq \angle(\hat{x}, \hat{y}) \leq 180^\circ - \theta_a$  and  $\{C_1, C_2\}$  is called an All-False cone pair.

**Proof:** The proof is straightforward from the inequalities.  $\square$

Lemma 2 shows that if two cones are in a moderate range, any pair of time series from the two cones is weakly correlated.

### 3 Cone-based Filter-and-Refine Algorithm

Our algorithm consists of four steps as shown in Algorithm 1: Pre-processing (line 1), Cone Formation (line 2), Filtering i.e. Cone-level Join (line 4), and Refinement i.e. Instance-level Join (lines 7-11). The first step is to pre-process

Input: 1)  $S^1 = \{s_1^1, s_2^1, \dots, s_n^1\}$ :  $n_1$  spatial referenced time series  
 where each instance references a spatial framework  $SF_1$ ;  
 2)  $S^2 = \{s_1^2, s_2^2, \dots, s_n^2\}$ :  $n_2$  spatial referenced time series  
 where each instance references a spatial framework  $SF_2$ ;  
 3) a user defined correlation threshold  $\theta$ ;  
 Output: all pairs of time series each from  $S^1$  and  $S^2$  with  
 correlations above  $\theta$ ;  
 Method:  
 Pre-processing( $S^1$ ); Pre-processing( $S^2$ ); (1)  
 $CN_1 = \text{Cone\_Formation}(S^1, SF_1)$ ;  $CN_2 = \text{Cone\_Formation}(S^2, SF_2)$ ; (2)  
 for all pair  $c_1$  and  $c_2$  each from  $CN_1$  and  $CN_2$  do { (3)  
    $\text{Filter\_Flag} = \text{Cone\_level\_Join}(c_1, c_2, \theta)$ ; (4)  
   if ( $\text{Filter\_Flag} \neq \text{ALL\_TRUE}$ ) (5)  
     output all pairs in the two cones (6)  
   else if ( $\text{Filter\_Flag} \neq \text{ALL\_FALSE}$ ) { (7)  
     for all pair  $s_1$  and  $s_2$  each from  $c_1$  and  $c_2$  do { (8)  
        $\text{High\_Corr\_Flag} = \text{Instance\_level\_Join}(s_1, s_2, \theta)$ ; (9)  
       if ( $\text{High\_Corr\_Flag}$ ) output  $s_1$  and  $s_2$ ; (10)  
     } (11)  
   } (12)

Algorithm 1: Correlation Finder

the raw data to the multi-dimensional unit sphere representation. The second step, cone formation, involves grouping similar time series into cones in spatial time series datasets. Clustering the time series is an intuitive approach. However, clustering on time-series datasets may be expensive and sensitive to the clustering method and its objective function. For example,  $K$ -means approaches [9] find globular clusters while density-based clustering approaches [9] find arbitrary shaped clusters with user-given density thresholds. Spatial indexes, such as  $R^*$  trees, which are built after time series dimensionality reduction [1, 4] could be another approach to group similar time series together. In this paper, we explore spatial auto-correlation for the cone formation. First the space is divided into disjoint cells. The cells can come from domain experts, such as the El Nino region, or could be as simple as uniform grids. By scanning the dataset once, we map each time-series into its corresponding cell. Each cell contains similar time series and represents a cone in the multi-dimensional unit sphere representation. The center and span are calculated to characterize each cone.

*Example 1 (Spatial Cone Formation).* Fig. 4 illustrates the spatial cone formation for two datasets, namely land and ocean. Both land and ocean frameworks consist of 16 locations. The time series of length  $m$  in a location  $s$  is denoted as  $F(s) = F_1(s), F_2(s), \dots, F_i(s), \dots, F_m(s)$ . Fig. 4 only depicts a time series

for  $m = 2$ . Each arrow in a location  $s$  of ocean or land represents the vector  $\langle F_1(s), F_2(s) \rangle$  normalized to the two dimensional unit sphere. Since the dimension of the time series is two, the multi-dimensional unit sphere reduces to a unit circle, as shown in Fig. 4 (b). By grouping the time series in each dataset into 4 disjoint cells according to their spatial proximity, we have 4 cells each for ocean and land. The ocean is partitioned to  $L_1 - L_4$  and the land is partitioned to  $O_1 - O_4$ , as shown in Fig. 4 (a). Each cell represents a cone in the multi-dimensional unit sphere. For example, the patch  $L_2$  in Fig. 4 (a) matches  $L_2$  in the circle in Fig. 4 (b).

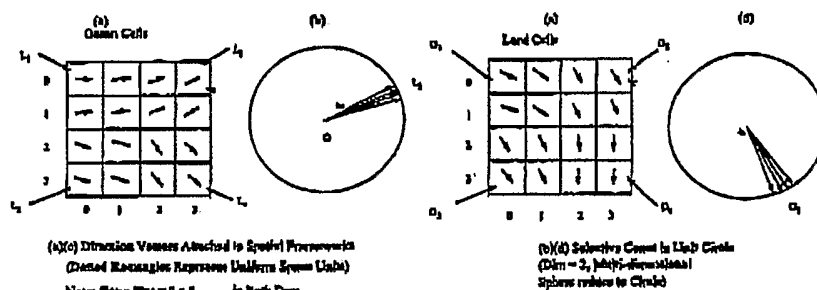


Fig. 4. An Illustrative Example for Spatial Cone Formation

After the cone formation, a cone-based join is applied between the two datasets. The calculation of the angle between each pair of cone centers is carried out, and the minimum and maximum bounds of the angles between the two cones are derived based on the spans of the two cones. The All-False cone pairs or All-True cone pairs are filtered out based on the lemmas. Finally, the candidates which cannot be filtered are explored in the refinement step.

**Example 2 (Filter-and-refine).** The join operations between the cones in Fig. 4 (a) are applied as shown in Table 1. The number of correlation computations is used in this paper as the basic unit to measure computation costs. Many All-False cone pairs and All-True cone pairs are detected in the filtering step and the number of candidates explored in the refinement step are reduced substantially. The cost of the filtering phase is 16. Only pairs  $(O_1, L_1)$ ,  $(O_3, L_4)$ , and  $(O_4, L_4)$  cannot be filtered and need to be explored in the refinement step. The cost of the refinement step is  $3 \times 16$  since there are 4 time series in both the ocean and land cone for all 3 pairs. The total cost of filter-and-refine adds up to 64. The number of correlation calculations using the simple nested loop is 256, which is greater than the number of correlation calculations in the filter-and-refine approach. Thus when the cost of the cone formation phase is less than 192 units, the filter-and-refine approach is more efficient.

**Completeness and Correctness Based on the lemmas in Section 2,** All-True cone pairs and All-False cone pairs are filtered out so that a superset of results

is obtained after the filtering step. There are no false dismissals for this filter-and-refine algorithm. All pairs found by the algorithm satisfy the given minimal correlation threshold.

| Ocean-Land Filtering Refinement |           |    | Ocean-Land Filtering Refinement |          |    |
|---------------------------------|-----------|----|---------------------------------|----------|----|
| $O_1 - L_1$                     | No        | 16 | $O_3 - L_1$                     | All-True |    |
| $O_1 - L_2$                     | All-False |    | $O_3 - L_2$                     | All-True |    |
| $O_1 - L_3$                     | All-False |    | $O_3 - L_3$                     | All-True |    |
| $O_1 - L_4$                     | All-False |    | $O_3 - L_4$                     | No       | 16 |
| $O_2 - L_1$                     | All-False |    | $O_4 - L_1$                     | All-True |    |
| $O_2 - L_2$                     | All-False |    | $O_4 - L_2$                     | All-True |    |
| $O_2 - L_3$                     | All-False |    | $O_4 - L_3$                     | All-True |    |
| $O_2 - L_4$                     | All-False |    | $O_4 - L_4$                     | No       | 16 |

Table 1. Cone-based Join in Example Data

#### 4 Performance Evaluation

We wanted to answer two questions: (1) How does the spatial auto-correlation based inexpensive grouping algorithm affect filtering efficiency? In particular, how do we identify the proper cone size to achieve better overall savings? (2) How does the minimal correlation threshold influence the filtering efficiency? These questions can be answered in two ways: algebraically, as discussed in section 4.1 and experimentally, as discussed in section 4.2.

Fig. 5 describes the experimental setup to evaluate the impact of parameters on the performance of the algorithm. We evaluated the performance of the algorithm with a dataset from NASA Earth science data [12]. In this experiment, a correlation analysis between the East Pacific Ocean region (80W - 180W, 15N - 15S) and the United States was investigated. The time series from 2901 land cells of the United States and 11556 ocean cells of the East Pacific Ocean were obtained under a 0.5 degree by 0.5 degree resolution.

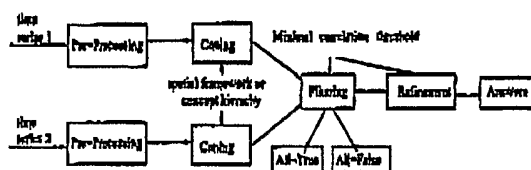


Fig. 5. Experiment Design

Net Primary Production (NPP) was the attribute for the land cells, and Sea Surface Temperature (SST) was the attribute for the ocean cells. NPP is the net photo-synthetic accumulation of carbon by plants. Keeping track of NPP is important because NPP includes the food source of humans and all other organisms and thus, sudden changes in the NPP of a region can have a direct impact on the regional ecology. The records of NPP and SST were monthly data from 1982 to 1993.

#### 4.1 Parameter Selections

In this section we investigate the selective range of the cone spans to improve filtering efficiency. Both All-False and All-True filtering can be applied in the filtering step. Thus we investigate the appropriate range of the cone spans in each of these filtering categories. Here we define the fraction of time series pairs redacted in the filtering step as  $FAR$ , i.e.  $FAR = \frac{N_{\text{time series pairs}} - f_{\text{cleared}}}{|D_1| \times |D_2|}$ . Thus  $FAR$  in the cone level is represented as  $FAR_{\text{cone}}$ .

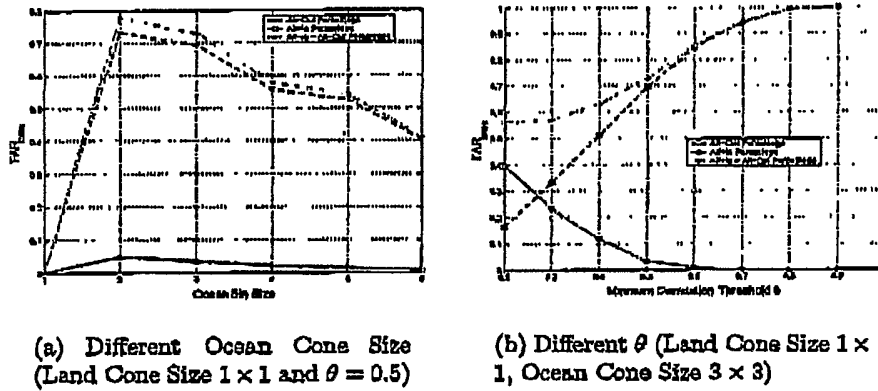


Fig. 6. All-True and All-False Filtering Percentages for Different Parameters

Fig. 6 demonstrates the  $FAR_{\text{cone}}$  is related to the cone size and minimal correlation threshold. The proper cone size and larger minimal correlation threshold improve the filtering ability. Given a minimal correlation threshold  $\theta$  ( $0 < \theta < 1$ ),  $\gamma_{\max} = \delta + \tau_1 + \tau_2$  and  $\gamma_{\min} = \delta - \tau_1 - \tau_2$ , where  $\delta$  is the angle between the centers of two cones, and the  $\tau_1$  and  $\tau_2$  are the spans of the two cones respectively. For simplicity, suppose  $\tau_1 \approx \tau_2 = \tau$ .

**Lemma 3.** Given a minimal correlation threshold  $\theta$ , if a pair of cones both with span  $\tau$  is an All-True cone pair, then  $\tau < \frac{\arccos(\theta)}{2}$ .

**Proof:** Assume that a cone pair satisfies the All-True Lemma, i.e., either  $\gamma_{\max} < \arccos(\theta)$  or  $\gamma_{\min} > 180^\circ - \arccos(\theta)$  is satisfied. In the former scenario, the angle  $\delta$  is very small, and we get  $\delta + 2\tau < \arccos(\theta)$ , i.e.,  $\tau < \frac{\arccos(\theta) - \delta}{2}$ . In the latter scenario, the angle  $\delta$  is very large, and we get  $\delta - 2\tau > 180^\circ - \arccos(\theta)$ , i.e.,  $\tau < \frac{\arccos(\theta) + \delta - 180^\circ}{2}$ . The  $\tau$  is less than  $\frac{\arccos(\theta)}{2}$  in either scenario since  $\tau < 180^\circ$ .  $\square$

**Lemma 4.** Given a minimal correlation threshold  $\theta$ , if a pair of cones both with span  $\tau$  is an All-False cone pair, then  $\tau \geq \frac{180^\circ}{4} - \frac{\arccos(\theta)}{2}$ .

**Proof:** Assume that a cone pair satisfies the All-False Lemma, i.e., the conditions  $\gamma_{\min} > \arccos(\theta)$  and  $\gamma_{\max} < 180^\circ - \arccos(\theta)$  hold. Based on the two inequations above,  $\gamma_{\max} - \gamma_{\min} < 180^\circ - 2\arccos(\theta)$  and  $\gamma_{\max} - \gamma_{\min} = 4\tau <$

$180^\circ - 2 \arccos(\theta)$  are true. Thus when the All-False lemma is satisfied,  $\tau < \frac{180^\circ}{4} - \frac{\arccos(\theta)}{2}$ .  $\square$

The range of  $\tau$  is related to the minimal correlation thresholds. In this application domain, the pairs with absolute correlations over 0.3 are interesting to the domain experts. As shown in Fig. 6, All-False filtering provides stronger filtering than All-True filtering for almost all values of cone sizes and correlation thresholds. Thus we choose the cone span  $\tau$  for maximizing All-False filtering conditions. The value of  $\arccos(\theta)$  is less than  $72.5^\circ$  for  $\theta \in (0.3, 1]$ , so the cone span  $\tau$  should not be greater than  $\frac{180^\circ}{4} - \frac{\arccos(\theta)}{2} = 8.75^\circ$ .

## 4.2 Experimental Results

*Experiment 1: Effect of Coning* The purpose of the first experiment was to evaluate under what coning sizes the savings from filtering outweighs the overhead. When the cone is small, the time series in the cone are relatively homogeneous, resulting in a small cone span  $\tau$ . Although it may result in more All-False and All-True pairs of cones, such cone formation incurs more filtering overhead because the number of cones is substantially increased and the number of filtered instances in each All-False or All-True pair is small. When the cone is large, the value of the cone span  $\tau$  is large, resulting in a decrease in the number of All-False and All-True pairs. The effects of the All-False and All-True filtering in the given data are investigated.

*Experiment 2: Effect of Minimal Correlation Thresholds* In this experiment, we evaluated the performance of the filtering algorithm when the minimal correlation threshold is changed. Various minimal correlation thresholds were tested and the trends of filtering efficiency were identified with the change of minimal correlation thresholds.

**Effect of Coning** This section describes a group of experiments carried out to show the net savings of the algorithm for different cone sizes. For simplicity, we only changed the cone size for one dataset. According to the analysis of the previous section, the land cone size is fixed at  $1 \times 1$ . We carried out a series of experiments using the fixed minimal correlation threshold, the fixed land cone size, and various ocean cone sizes. The minimal correlation threshold  $\theta$  was fixed at 0.5. Fig. 7 (a) shows the net savings as a percentage of the computational cost of the nested loop join algorithm for different ocean cone sizes. The x-axis represents the different cone sizes ranging from  $1 \times 1$  to  $6 \times 6$ , and the y-axis represents the net savings in computational cost as a percentage of the costs using the simple nested loop join algorithm. The net savings range from 40 percent to 62 percent.

**Effect of Minimal Correlation Thresholds** In this experiment, we investigated the effects of minimal correlation threshold  $\theta$  on the savings in computation cost for correlation analysis. The land and ocean cone sizes were fixed at  $1 \times 1$  and  $3 \times 3$  respectively, and a series of experiments was carried out for different  $\theta$ s.

Fig. 7 (b) shows the total savings as a percentage of the computational cost of the nested loop join algorithm for different  $\theta$ s. The x-axis represents the different cone sizes ranging from  $1 \times 1$  to  $6 \times 6$ , and the y-axis represents the total savings as a percentage of the computational cost of the nested loop join algorithm. The net savings percentages range from 44 percent to 88 percent with the higher savings at higher values of correlation thresholds. Thus when other parameters are fixed, the filtering algorithm generally achieves better performance as the minimal correlation threshold is increased.

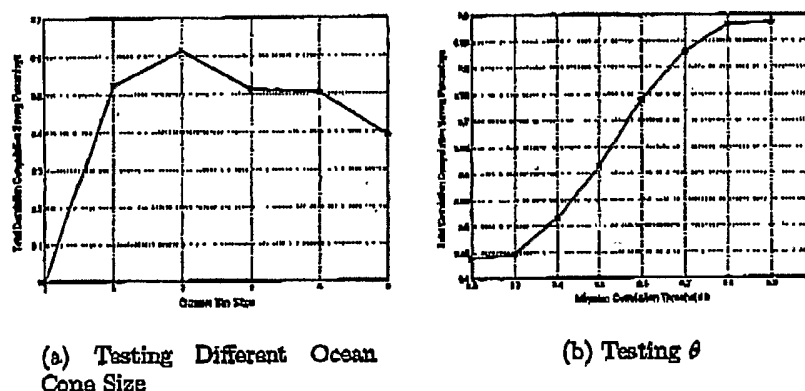


Fig. 7. Testing Different Cone Sizes and Minimal Correlation Threshold  $\theta$

## 5 Conclusion and Future Work

In this paper, a filter-and-refine correlation analysis algorithm for a pair of spatial time series datasets is proposed. Experimental evaluations using a NASA Earth science dataset are presented. The total savings of correlation analysis computation range from 40 percent to 88 percent. In future work, we would like to explore other coning methods, such as clustering and time series dimensionality reduction and indexing methods [1, 4, 6]. Clustering and spatial methods using other schemes may provide higher filtering capabilities but possibly with higher overheads. Time series dimensionality reduction and indexing methods will also be explored to determine the tradeoff between filtering efficiency and overhead.

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## Complex Wavelet Analysis of Ultrasonic Signals

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**Abstract** Ultrasonic signal is always composed of a series of transient impulsive waveforms, which are created during the propagation of ultrasonic wave when it meets the discontinuities presenting in the material, such as inclusions, voids, micro cracks, the surface of the object being inspected, and so on. Complex wavelet based envelop detection method was designed to extract the impulsive features contained in the signal. And the complex wavelet based correlation analysis was further proposed for distinguishing the 'real impulsive waveform' that indicates the object being searched from a number of unrecognized waveforms also presenting in the signal. The effectiveness of both methods was proved by practical experiments on a common tube sample. The experiments proved that, by using the proposed methods, the impulsive waveform that really indicates the end surface of the tube could be distinguished successfully. With the aid of the analysed results and the calibration equation, the relative distance between the position where the transducer was placed and the end surface of the tube could be identified correctly. It is believed that the proposed methods will be widely applied to the analysis of ultrasonic signals.

**Keywords** ultrasonic signal; complex wavelet; envelop detection; correlation analysis.

### 1. Introduction

Nowadays, ultrasonic detection, as an important non-destructive testing means, has been increasingly used in many modern industry fields [1,2]. In practical applications, two types of ultrasonic transducers are usually used for different purposes. They are the delay line transducer and the surface wave transducer. The former is often used for measuring the thickness of the object, and the later is for measuring the relative distance of the object from the position where the transducer is placed. The ultrasonic waves sent from them propagate inside the material in different ways. The schematic diagrams of their working mechanisms are shown in Figures 1(a) and (b), respectively. For facilitating understanding, the ultrasonic signals collected by using such two types of transducers are also plotted in the figures.

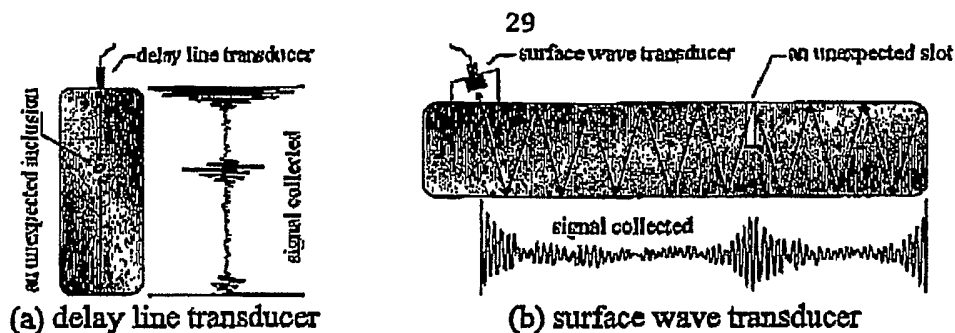


Fig. 1 Working mechanisms of ultrasonic transducers

From Figure 1, it is found that the ultrasonic signals collected by using both types of transducers are composed of a series of transient impulsive waveforms, which are created when ultrasonic wave meets the discontinuities presenting in the material. The discontinuities may be micro-inclusions, voids, cracks, deformations, and the end surface of the material or other unknown sources. The comparison of Figures 1(a) and 1(b) discloses that the signal collected by using surface wave transducer shows more complexity in composition than that collected by using delay line transducer. In other words, in the signal shown in Figure 1(b), besides the impulsive waveforms that really indicate the unexpected slot and the end surface of the material, a number of unrecognised waveforms are also present in the signal. Undoubtedly, these unrecognised waveforms would confuse people and make it hard to interpret the signal.

In addition, it is found in long term practice that the ultrasonic signal collected by using surface wave transducer always shows poor repeatability in time series. As an example, Figure 2 shows the signals collected from a ferrule tube at the same distance away from the end surface of the tube but at different circumferential locations  $0^\circ$ ,  $60^\circ$ ,  $120^\circ$ ,  $180^\circ$ ,  $240^\circ$  and  $300^\circ$ , respectively.

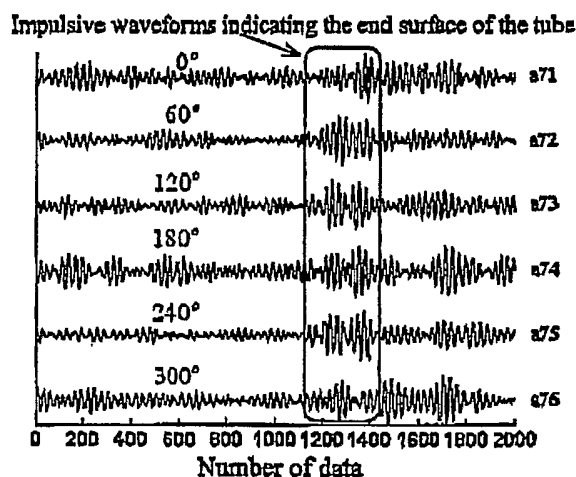


Fig.2 Signals collected at the same distance but at different circumferential locations

From Figure 2, it is seen that, in different measurements, more or less difference always exists on the positions of the impulsive waveforms that indicate the end surface of the tube, though the signals are collected at the same distance but at different circumferential locations. The existence of such minutia difference will

prevent people from evaluating the distance between the transducer and the end surface of the tube accurately.

In view of aforementioned reasons, the complex wavelet based envelop and correlation analysis methods are studied in this paper for interpreting the ultrasonic signals collected by using surface wave transducer. The rest of the paper is organized as follows. In Section 2, the complex wavelet based envelop detection method is designed for extracting the impulsive features contained in the signal. Section 3 further studies the complex wavelet based correlation analysis for distinguishing the 'real impulsive waveform' that indicates the object being searched from a large number of unrecognised waveforms also presenting in the signal. Section 4 verifies the effectiveness of both proposed methods by a series of practical experiments on a common tube sample. The summary of the work is finally done in Section 5.

## 2. Complex wavelet based envelop analysis

Ultrasonic signals are characterized by a number of impulsive waveforms. Envelop analysis is an effective method for extracting such kind of features in the signals. The conventional envelop detection method is based on Hilbert transform [3]. For an arbitrary real time series  $x(t)$ , its Hilbert transform  $y(t)$  can be defined as [4]

$$y(t) = \frac{P}{\pi} \int_{-\infty}^{\infty} \frac{x(\tau)}{t - \tau} d\tau \quad (1)$$

when the integral exists (i.e.  $\tau \neq t$ ). Where  $\tau$  is the time lag,  $P$  indicates the Cauchy principal value.

In essence, the Hilbert transform can be considered to be a filter that simply shifts phases of all frequency components of its input by  $-\pi/2$  radians.  $x(t)$  and  $y(t)$  form the complex conjugate pair of an analytic signal  $z(t)$ , as

$$z(t) = x(t) + iy(t) = A(t)e^{i\theta(t)} \quad (2)$$

with

$$A(t) = [x(t)^2 + y(t)^2]^{1/2} \quad (3)$$

$$\theta(t) = \tan^{-1}[y(t)/x(t)] \quad (4)$$

Where  $i = \sqrt{-1}$ . The time-varying function  $A(t)$  is the so-called instantaneous envelop of the signal  $x(t)$ , which extracts the slow time variation of the signal.

$$\omega = d\theta(t)/dt \quad (5)$$

is the so-called instantaneous frequency.

Because the Hilbert spectrum uses a transform rather than convolution as in the Fourier analysis, the practice demonstrates that, for a transient signal, the Hilbert spectrum does offer clearer frequency-energy decomposition than the traditional Fourier spectrum does. However during the implementation of the Hilbert transform, it deals with different frequency components without any distinguishing. Moreover, from equation (1), it is found that the computation of  $y(t)$  still requires the knowledge of  $x(t)$  for all values of  $t$ . Thus, the 'local' property of the Hilbert transform is in fact a 'global' property of the signal [5]. In view of these reasons, the complex wavelet based envelop detection method is designed in this paper for extracting the impulsive features contained in the signals.

The complex wavelet transform is a recently developed tool that uses a dual tree of wavelet filters to find the real and imaginary parts of complex wavelet coefficients [6]. Its approximate shift invariance, good direction selectivity and computational efficiency properties make it a good candidate for representing the transient features

contained in non-stationary signals [7]. It is adopted here for achieving an alternative envelop analysis, using which the desired transient impulsive features of the signal could be extracted more satisfactorily. Herein, the complex Morlet wavelet [8] is used because Morlet wavelet looks more like 'impulse' in geometric shape especially when its shape control parameter is adjusted to be a small value. According to the 'Matching Mechanism' of wavelet transform, the better the wavelet function matches the signal in geometric shape, the more accurate the feature of the signal can be represented by wavelet coefficients [9]. The complex Morlet wavelet is given by the formula

$$\psi(t) = \sqrt{2}e^{-t^2/\alpha^2} \left( e^{j\pi} - e^{-\pi^2\alpha^2/4} \right) \quad (6)$$

Where,  $j = \sqrt{-1}$ , the shape control parameter  $\alpha$  can be set to obtain desired time-frequency shaping in the wavelet transforms. When  $\alpha$  decreases, the wavelet waveform tends to be an impulse, while when  $\alpha$  increases, the wavelet waveform tends to be a cosine or sine waveform.

Its real and imaginary parts as well as the modulus of  $\psi(t)$  are

$$\text{Re}[\psi(t)] = \sqrt{2}e^{-t^2/\alpha^2} \left[ \cos(\pi) - e^{-\pi^2\alpha^2/4} \right] \quad (7)$$

$$\text{Im}[\psi(t)] = j \cdot \sqrt{2}e^{-t^2/\alpha^2} \sin(\pi) \quad (8)$$

$$|\psi(t)| = \sqrt{\{\text{Re}[\psi(t)]\}^2 + \{\text{Im}[\psi(t)]\}^2} \quad (9)$$

In practice, the constant term in formula (7) is often ignored for simplicity. Their geometric shapes when  $\alpha = 1$  are shown in Figure 3.

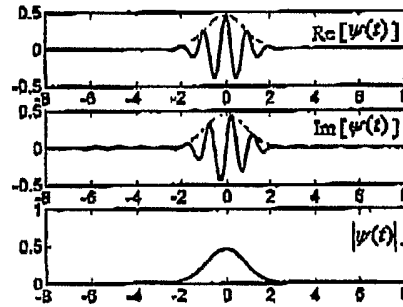


Fig.3 Complex Morlet Wavelet

Figure 3 discloses that the modulus  $|\psi(t)|$  can envelop both the real and imaginary parts of the wavelet function  $\psi(t)$  completely and smoothly. Thus, if the impulsive feature is represented by using  $|\psi(t)|$ , the refined signal should be more explicit and easier to be interpreted than those represented by  $\text{Re}[\psi(t)]$  and  $\text{Im}[\psi(t)]$ . Inspired by this idea, the complex wavelet based envelop is attained by using  $|\psi(t)|$ . The continuous wavelet transform (CWT) is defined as [10]

$$\text{CWT}_x(b, a) = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{\infty} x(t) \psi^* \left( \frac{t-b}{a} \right) dt \quad (10)$$

where  $x(t)$  stands for the time series signal to be analyzed,  $b$  and  $a$  ( $b, a \in \mathbb{R}$  and  $a \neq 0$ ) are the translation and dilation parameters, respectively. The duration of the mother wavelet  $\psi(t)$  is either compressed or expanded depending upon the choice of  $a$ . Hence, the CWT can extract both the local and the global variations of the signal  $x(t)$ . In fact, the CWT can be considered as the output of a bank of bandpass

filters whose center frequencies and bandwidths vary depending on the dilation parameter  $a$  in addition to the spectral properties of the mother wavelet function  $\psi(t)$ . The variable bandpass introduces different resolutions at different scales and thus, the CWT posses a multiresolution capability. Let the dilation parameter  $a$  be a variable changes from 10 to 700, the CWTs of the signals a71, a72, a73 and a74 shown in Figure 2 are calculated and the results are shown in Figure 4. In the figures, the impulsive features that really indicate the end surface of the tube are circled by four ellipses.

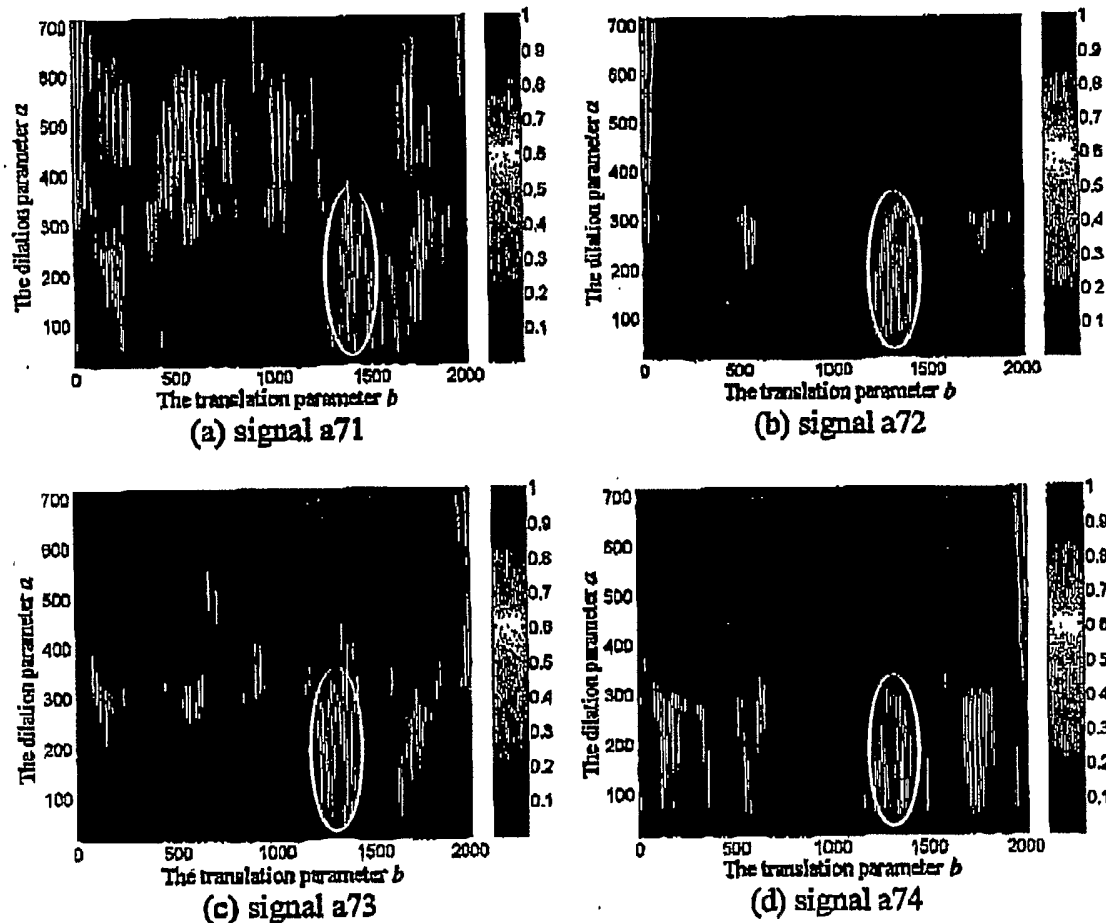


Fig.4 CWTs of the ultrasonic signals

Figure 4 shows that a number of impulsive features occur in the whole scale region from 10 to 700, but the 'real impulsive feature' clearly appears only in the limited region [50, 300]. Thus, when we analyze the signal, we do not need to investigate the wavelet coefficients at all scales. We can only use the coefficients generated at one scale, at which the 'real feature' is well represented, as the signal to be further analyzed. Benefited from the implementation of CWTs, the selected 'signal' will contain less disturbing frequency components and provide more explicit 'real characteristic waveform' easy to be identified.

Select the wavelet coefficients generated when the dilation parameter  $a=215$  as the signal for further analysis. The complex wavelet based envelop detection was carried out on the signals a71, a72 a73 and a74, respectively. The calculation results are plotted in Figure 5. The corresponding results obtained by using conventional envelop analysis [9] are also plotted in the figures for making comparisons.

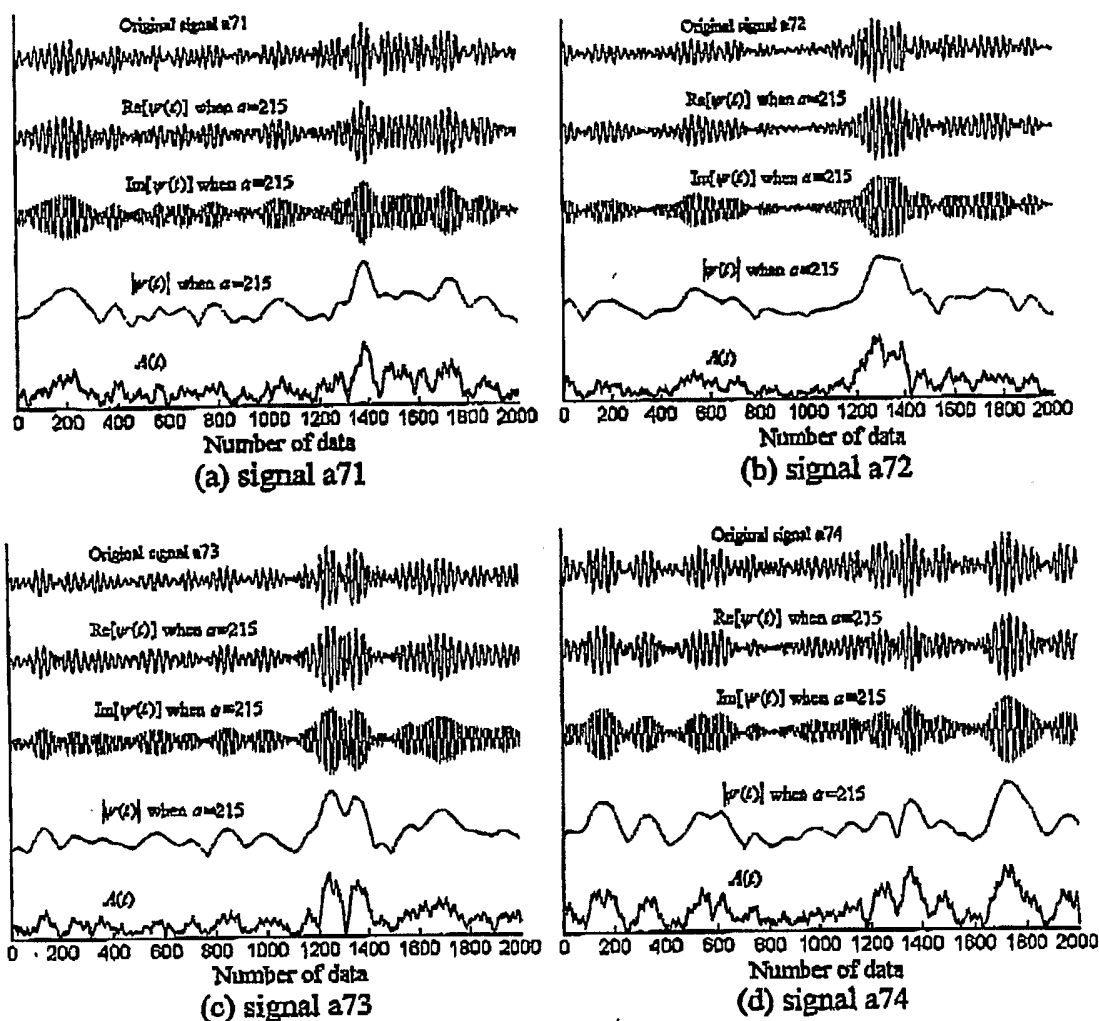


Fig.5 Signals and their envelop detection results

It is clearly seen from Figure 5(a) that, benefited from having been bandpass-filtered by wavelet function and the selection of the wavelet coefficients at an appropriate scale, the envelop detection result represented by  $|\psi(t)|$  is more explicit and smoother than that represented by  $A(t)$ . The purified result expressed by  $|\psi(t)|$  will undoubtedly ease the interpretation of the signal and hence, bring many benefits to further analysis. This advantage of the complex wavelet based envelop analysis is further confirmed by the results shown in Figures 5(b), (c) and (d). All these calculation results fully prove that, compared with the Hilbert transform based envelop detection method, the designed complex wavelet based envelop analysis is actually a more effective tool for extracting the impulsive features contained in the signals.

### 3. Complex wavelet based correlation analysis

From the envelop detection results shown in Figures 5, it is seen that, although the signal is fully refined, a number of unrecognized 'impulses' still exist in the signals. It is still difficult to distinguish the 'real impulse' from so many numbers of 'impulses'.

In order to tackle this knotty problem, the complex wavelet based correlation analysis is studied in the following.

It is well known that the impulsive waveforms are created when the ultrasonic wave meets the discontinuities presenting in the material during its propagation, and these discontinuities always distribute inside the material randomly, as Figure 6 shows.



Fig.6 Micro defects contained in material

Just due to the random distribution of these micro-defects, the signals collected at different circumferential locations, as shown in Figure 2, always have more or less difference in time waveforms, even though the signals are collected at the same distance away from the tube end. But anyway, it has no doubt that the ultrasonic wave will meet the end surface of the material at last and an impulsive waveform will be certainly created. This implies that whatever how many impulsive waveforms appear in the signal, there is always one and only one unique impulsive waveform indicates the end surface of the material. Suggested by this physical fact, the correlation analysis was adopted in this paper for distinguishing the 'real impulsive waveform' from the ultrasonic signals with a large number of unrecognised waveforms.

Correlation analysis is a useful method for identifying potentially interacting pairs of time series across two time series signals [11]. It was recently used to analyse the inherent temporal variability of ocean surface winds [12]. Herein, it is adopted to analyse the ultrasonic signals collected at different circumferential locations but at the same distance away from the end surface of the material.

Assume  $X = (x_1, x_2, \dots, x_n)$  and  $Y = (y_1, y_2, \dots, y_n)$  are two time series signals with the same length  $n$ . The correlation coefficient  $corr(X, Y)$  of these two time series is defined as

$$corr(X, Y) = \frac{1}{n} \sum_{i=1}^n \left( \frac{x_i - \bar{x}}{\sigma_X} \right) \cdot \left( \frac{y_i - \bar{y}}{\sigma_Y} \right) \quad (11)$$

where  $\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i,$

$$\bar{y} = \frac{1}{n} \sum_{i=1}^n y_i,$$

$$\sigma_X = \left( \frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2 \right)^{1/2} \quad \text{and}$$

$$\sigma_Y = \left( \frac{1}{n-1} \sum_{i=1}^n (y_i - \bar{y})^2 \right)^{1/2}.$$

For facilitating analysis, further assume  $\hat{x}_i = \frac{x_i - \bar{x}}{\sigma_X} (n-1)^{\frac{1}{2}},$   $\hat{y}_i = \frac{y_i - \bar{y}}{\sigma_Y} (n-1)^{\frac{1}{2}},$  and

introduce vectors  $\hat{X} = (\hat{x}_1, \hat{x}_2, \dots, \hat{x}_n),$   $\hat{Y} = (\hat{y}_1, \hat{y}_2, \dots, \hat{y}_n).$  Then, the formula (11) can be reorganized as

$$\text{corr}(X, Y) = \hat{X} \cdot \hat{Y} = \cos[\angle(\hat{X}, \hat{Y})] \quad (12)$$

$$\text{where } \cos[\angle(\hat{X}, \hat{Y})] = \frac{\sum_{i=1}^n x_i \cdot y_i}{\sqrt{\sum_{i=1}^n x_i^2 \sum_{i=1}^n y_i^2}}$$

By using the formula (12), the value of  $\text{corr}(X, Y)$  is normalized into the range  $[-1, 1]$ .

In stead of using the original signals, the results obtained by using the complex wavelet based envelop detection method are used for further correlation analysis. This is called the complex wavelet based correlation analysis. The correlation analysis between the signals a71 and a72 is conducted and the final result is plotted in Figure 7. The result generated by the conventional method, which performs the analysis by directly using the original signals, is also plotted in the figure for making a comparison.

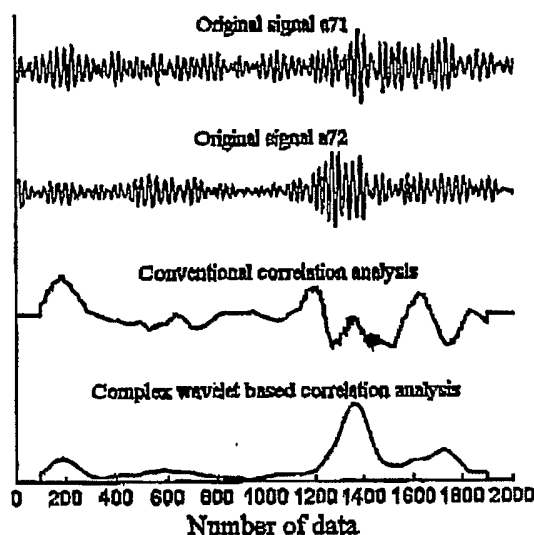


Fig.7 Correlation analysis between the signals a71 and a72

From Figure 7, it is obviously found that the 'real impulse' indicating the end surface of the material can be identified more easily and correctly from the result generated by the complex wavelet based correlation analysis rather than from that obtained by using the conventional method. Undoubtedly, the complex wavelet based correlation analysis provides an effective tool for distinguishing the 'real impulsive waveform' from ultrasonic signals.

#### 4. Experiments

In order to further verify the effectiveness of the proposed methods in practical application, a series of measurements were done on a common tube sample. The installation of the transducer is as shown in Figure 8.

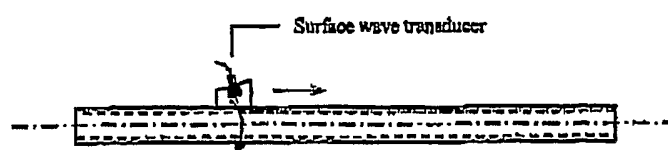


Fig.8 Scheme of experiments

Necessary to note that a contour was deliberately designed on the transducer's contacting surface, so that the transducer could contact the surface curvature of the tube completely and tightly. Move forward the transducer and collect the signals at the same distance away from the end surface of the tube but at different circumferential locations. The collected signals are as shown in Figure 2. The complex wavelet based correlation analysis results of the signals a71, a72 and a73 are shown in Figure 9.

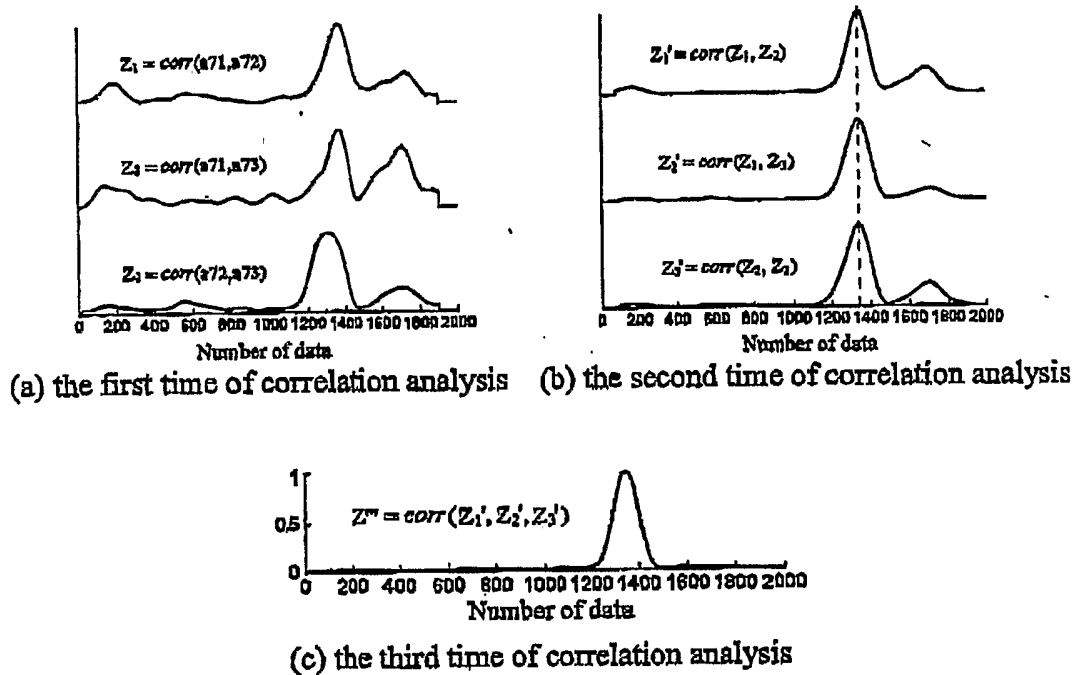


Fig.9 Complex wavelet based correlation analysis of the signals a71, a72 and a73

From Figure 9, it is found that a satisfactory result is obtained by using the complex wavelet based correlation analysis. In particular, after performing the second and the third times of correlation analysis, the further results become more explicit and easier to be identified. The exact position of the 'real impulsive waveform' can be easily determined from the result shown in Figure 9(c).

In order to further put the proposed methods into practice, the calibration work was done as follows. Firstly, the transducer was moved forward to the end surface of the tube in 5mm and 8 groups of signals were collected. Each group includes 3 signals, which are collected at the same distance away from the tube end but at different circumferential locations 0°, 120° and 240°, respectively. By performing the complex Morlet wavelet based correlation analysis of them, a coordinate position in Figure 10 can be determined, which are indicated by small circles. By the means of this method, 8 coordinate positions are determined from 8 groups of signals, as shown in Figure 10(a). Then, using the polynomial curve fitting technique (see Appendix), a calibration equation is derived from these coordinate positions. Secondly, a more detailed calibration was further done in the similar way, but the transducer was moved forward in 2mm rather than in 5mm, and 19 groups of signals were collected accordingly. The calculation results are shown in Figure 10(b), from which another calibration equation was derived too. Thirdly, based on the two calibration equations derived above, a compromise calibration equation is finally obtained as follows

$$y = 1.5885 \times 10^{-7} x^2 + 0.0124x - 20.5905 \quad (13)$$

Where the variable  $x$  denotes the number of data at which the real impulsive waveform occurs,  $y$  refers to the calibrated distance away from the end surface of the tube. The numerical results of the equation (13) are shown in Figure 10(c).

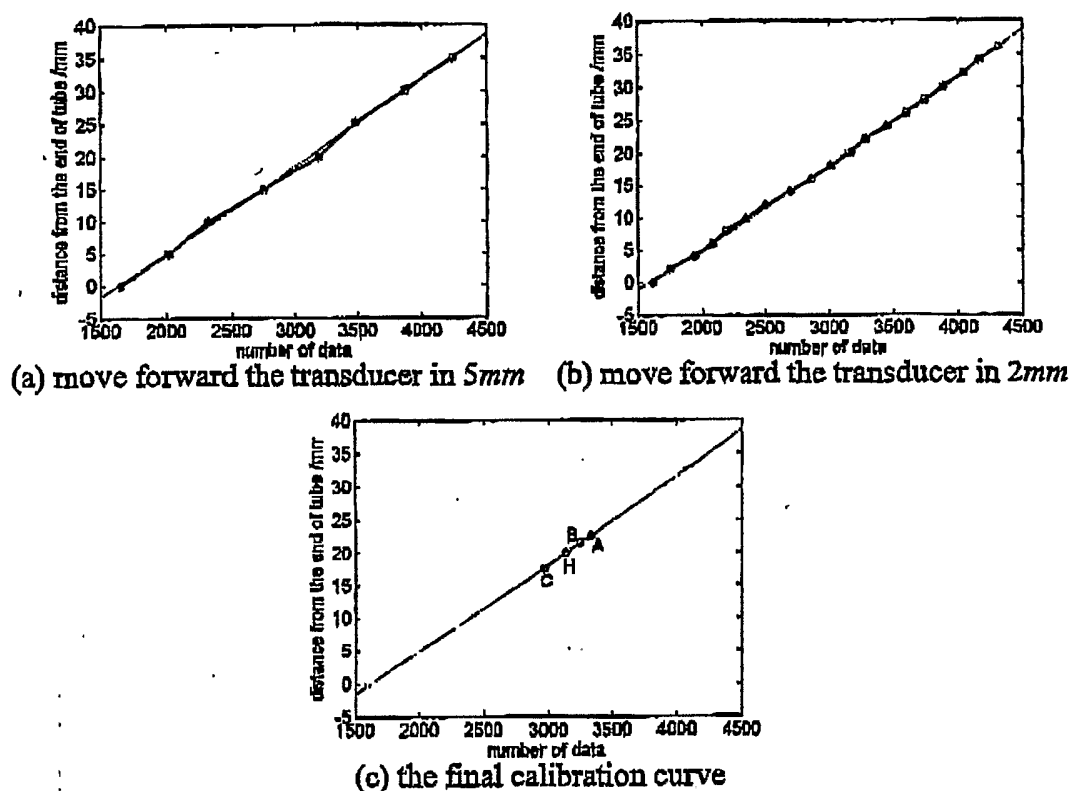


Fig.10 Data calibration

In order to investigate the accuracy of the compromised calibration equation (13), the transducer was moved to four arbitrary positions A, B, C and H. The measured results respectively at these four positions are listed in Table 1 and also plotted in Figure 10(c).

Table 1. Measured results

| Position | Actual distance<br>$d$ / mm | No. of data<br>$x$ in eqn.(13) | Measured distance<br>$d'$ / mm | Measurement error<br>$E =  d - d'  \times 100\% / d$ |
|----------|-----------------------------|--------------------------------|--------------------------------|------------------------------------------------------|
| A        | 22.3                        | 3337                           | 22.5572                        | 1.15                                                 |
| B        | 20.8                        | 3255                           | 21.4545                        | 3.15                                                 |
| C        | 17.5                        | 2967                           | 17.5987                        | 0.56                                                 |
| H        | 20.6                        | 3138                           | 19.8849                        | 3.47                                                 |

From Table 1, it is found that, at four arbitrary positions, all measurement errors are less than 3.5%. Obviously, such a small value of error could be completely acceptable by engineering. This conclusion can be also confirmed by Figure 10(c), where all calculated coordinate positions derived from the signals collected at positions A, B, C and H locate on the calibration curve. These results fully prove that the proposed methods are actually effective on the analysis of ultrasonic signals.

## 5. Summary

The complex wavelet based envelop analysis is designed for extracting the impulsive features of the signal, and the complex wavelet based correlation analysis is proposed for distinguishing the 'real impulsive waveform' from a number unrecognized impulsive waveforms also presenting in ultrasonic signals. The effectiveness of both methods on the analysis of ultrasonic signal is proved by the comparisons with the corresponding traditional methods and further confirmed by a series of experiments on a common tube sample. The experimental results show that all measurement errors are less than 3.5%, which can be completely accepted by practical engineering. Therefore, it is reasonable to believe that both the proposed methods will be widely adopted and extensively applied to the analysis of ultrasonic signals.

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## Appendix

The polynomial curve fitting technique can be described by the following figure

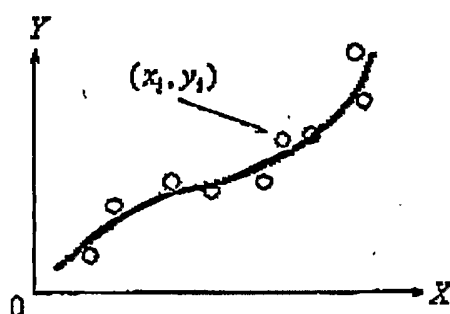


Fig.A1 The schematic diagram of polynomial curve fitting technique

Where a set of data  $X$  and  $Y$  with the same length  $N$  are required. Assume the resulted curve fitting equation is an  $m$ -order of polynomial, i.e.

$$y = c_0 + c_1x + c_2x^2 + \dots + c_{m-1}x^{m-1} + c_mx^m \quad (A1)$$

where  $c_i$  ( $i = 1, 2, \dots, m$ ) are the polynomial coefficients.

The equation (A1) can be expressed in matrix form

$$Y_{m+1,1} = X_{m+1,m+1} C_{m+1,1} \quad (A2)$$

where

$$Y = \begin{bmatrix} \sum_{i=1}^N y_i \\ \sum_{i=1}^N y_i x_i \\ \sum_{i=1}^N y_i x_i^2 \\ \vdots \\ \sum_{i=1}^N y_i x_i^m \end{bmatrix} \quad \text{and} \quad X = \begin{bmatrix} \sum_{i=1}^N 1 & \sum_{i=1}^N x_i & \sum_{i=1}^N x_i^2 & \dots & \sum_{i=1}^N x_i^m \\ \sum_{i=1}^N x_i & \sum_{i=1}^N x_i^2 & \dots & \dots & \sum_{i=1}^N x_i^{m+1} \\ \sum_{i=1}^N x_i^2 & \dots & \dots & \dots & \sum_{i=1}^N x_i^{m+2} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \sum_{i=1}^N x_i^m & \sum_{i=1}^N x_i^{m+1} & \dots & \dots & \sum_{i=1}^N x_i^{m+m} \end{bmatrix}$$

By solving the equation (A2), the polynomial coefficients can be easily yielded.

**Figure captions**

**Fig. 1 Working mechanisms of ultrasonic transducers.**

**Fig.1(a) delay line transducer.**

**Fig.1(b) surface wave transducer.**

**Fig.2 Signals collected at the same distance but at different circumferential locations.**

**Fig.3 Complex Morlet Wavelet.**

**Fig.4 CWTs of the ultrasonic signals.**

**Fig.4(a) signal a71.**

**Fig.4(b) signal a72.**

**Fig.4(c) signal a73.**

**Fig.4(d) signal a74.**

**Fig.5 Signals and their envelop detection results.**

**Fig.5(a) signal a71.**

**Fig.5(b) signal a72.**

**Fig.5(c) signal a73.**

**Fig.5(d) signal a74.**

**Fig.6 Micro defects contained in material.**

**Fig.7 Correlation analysis of the signals a71 and a72.**

**Fig.8 Scheme of experiments.**

**Fig.9 complex wavelet based correlation analysis of the signals a71, a72 and a73.**

**Fig.9(a) the first time of correlation analysis.**

**Fig.9(b) the second time of correlation analysis.**

**Fig.9(c) the third time of correlation analysis.**

**Fig.10 Data calibration.**

**Fig.10(a) move forward the transducer in 5mm.**

**Fig.10(b) move forward the transducer in 2mm.**

**Fig.10(c) the final calibration curve.**

**Fig.A1 The schematic diagram of polynomial curve fitting technique.**

**CLAIMS**

Having thus described the invention, we claim:

1. Apparatus for evaluating position of a conduit in a fluid coupling, comprising:

5 an ultrasonic transducer adapted to be installed relative to the coupling to transmit ultrasonic energy into the conduit; said transducer receiving ultrasonic energy and producing an electrical signal related thereto; and

an analyzer for receiving said electrical signal and producing an output that corresponds to axial position of an end of the conduit.

10 2. The apparatus of claim 1 wherein said output corresponds to axial position of the conduit end relative to said transducer.

3. The apparatus of claim 1 wherein said transducer produces transient ultrasonic energy.

15 4. The apparatus of claim 3 wherein said transducer comprises a shear wave transducer.

5. The apparatus of claim 3 wherein said transducer comprises a surface wave transducer or a delay line transducer.

6. The apparatus of claim 1 comprising a noise filtering function to filter noise from said electrical signal.

20 7. The apparatus of claim 6 wherein said electrical signal is stored digitally and said filtering is performed digitally.

25 8. The apparatus of claim 1 wherein ultrasonic energy is input at two or more different locations about the conduit, said transducer producing a plurality of electrical signals, each electrical signal being related to received ultrasonic energy and corresponding to a respective one of said locations.

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9. The apparatus of claim 8 comprising a correlation function of said plurality of electrical signals and wherein said analyzer produces an output that corresponds to axial position of an end of the conduit based on said correlation.

10. The apparatus of claim 1 wherein said analyzer comprises an analog to digital converter that digitizes said electrical signal, and a programmable digital circuit that receives said digitized electrical signal for noise reduction and correlation analysis.

11. The apparatus of claim 1 wherein said transducer comprises a face plate that is positioned against the conduit and is shaped to conform to an outer surface contour of the conduit.

12. The apparatus of claim 11 wherein said face plate comprises low attenuation plastic.

13. The apparatus of claim 12 wherein said face plate comprises acrylic resin.

14. The apparatus of claim 1 comprising a correlation function for two or more of said electrical signals.

15. The apparatus of claim 14 wherein said correlation function is based on a Morlet wavelet analysis.

16. The apparatus of claim 1 wherein said ultrasonic energy is correlated and filtered with a Morlet wavelet function.

17. The apparatus of claim 1 wherein the coupling comprises a body having a surface against which said end of the conduit contacts after a normal pull-up, said analyzer output providing an indication of quality of contact between said end of the conduit and said surface.

18. The apparatus of claim 17 wherein said quality of contact includes one or more of: contact surface area, load between said conduit end and said surface, gap between said conduit end and said surface, and squareness of said contact.

19. Apparatus for evaluating a fitting assembly of the type having a conduit and a fluid coupling installed thereon, comprising:

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a source adapted to apply mechanical energy waves into the conduit; said source receiving reflected energy waves and producing a signal related thereto; and

an analyzer for receiving said signal and producing an output that corresponds to axial position of an end of the conduit.

5           20.     The apparatus of claim 19 wherein said source produces ultrasonic waves.

          21.     The apparatus of claim 20 wherein said source comprises a separate transmitter and receiver.

          22.     The apparatus of claim 20 wherein said ultrasonic energy is in the form of at least one transient waveform applied into the conduit through the fluid coupling.

10          23.     The apparatus of claim 20 wherein said ultrasonic energy is correlated and filtered with a Morlet wavelet function.

          24.     The apparatus of claim 19 wherein said energy waves are applied at two or more different locations about the conduit, said source producing a plurality of said signals, each signal being related to reflected energy waves and corresponding to a respective one of said locations.

15          25.     The apparatus of claim 19 wherein said source produces shear wave energy.

          26.     The apparatus of claim 19 wherein said source applies energy waves into the conduit at an angle of about greater than 0° to about 90° from normal.

          27.     The apparatus of claim 19 in combination with a fluid coupling comprising a body and nut and at least one ferrule that secures the conduit within the coupling, said body comprising a shoulder against which said end of the conduit bottoms after the fitting is completely assembled onto the conduit.

          28.     The apparatus of claim 27 wherein said analyzer output provides an indication of quality of contact between said end of the conduit and said surface.

          29.     The apparatus of claim 19 wherein said analyzer applies noise reduction and correlation to two or more of said signals.

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30. A method for evaluating position of a conduit in a fluid coupling, comprising the steps of:

applying mechanical energy waves into the conduit at a first location that is axially spaced from an end of the conduit;

5 receiving reflected portions of said energy waves; and

determining axial position of said conduit end relative to said first location as a function of said reflected portions of said energy waves.

31. The method of claim 30 wherein the step of applying energy waves comprises the step of applying ultrasonic energy shear waves.

10 32. The method of claim 30 wherein said energy waves are transient.

33. The method of claim 30 wherein said determining step comprises converting said reflected portions of said energy waves into corresponding electrical signals and applying noise reduction to said electrical signals.

15 34. The method of claim 30 wherein said determining step comprises correlation analysis on said reflected portions.

35. The method of claim 34 comprising the step of applying said energy waves at two or more different radial positions about the conduit at said first location.

36. The method of claim 35 comprising the step of correlating and filtering said reflected portions using a Morlet wavelet correlation function.

20 37. The method of claim 30 comprising the step of determining the quality of a contact between said conduit end and a generally radial surface associated with a fluid coupling installed at said conduit end.

38. The method of claim 30 wherein said energy waves comprise shear energy waves.

25 39. The method of claim 30 wherein said energy waves are applied to the conduit at an angle within the range of about greater than 0° to about 90° from normal.

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40. A method for evaluating a fitting assembly of the type having a conduit and a fluid coupling installed thereon, comprising the steps of:

applying mechanical energy waves into the conduit at a first location that is axially spaced from an end of the conduit;

5 receiving reflected portions of said waves; and

determining a characteristic of the fitting assembly as a function of said reflected portions of said energy waves.

41. The method of claim 40 wherein said characteristic comprises either or both of the following: position of an end of the conduit within the coupling; and determining nature of  
10 abutment between an end of the conduit and a surface associated with the fluid coupling.

42. The method of claim 40 wherein said energy waves comprise transient mechanical waves.

43. The method of claim 42 wherein said waves comprise shear ultrasonic waves.

44. The method of claim 40 wherein said determining step comprises filtering and  
15 correlation analysis on said received portions.

45. The method of claim 44 wherein said correlation analysis is based on Morlet wavelet correlation.

46. The method of claim 40 wherein said waves are applied to the conduit at an angle within the range of about greater than 0° to about 90° from normal.

20 47. The method of claim 40 wherein said energy waves are input through the fluid coupling.

48. The method of claim 40 comprising the step of applying said energy waves to the conduit at different radial positions about said first location, and correlating said received portions.

25 49. A method for evaluating a fitting assembly of the type having a conduit and a fluid coupling installed on the conduit, comprising the steps of:

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applying mechanical energy waves into the fitting assembly;  
receiving reflected portions of said energy waves; and  
determining quality of contact between said conduit end and a generally radial surface  
associated with the fluid coupling.

5        50.     A method for evaluating bottoming of a conduit in a fluid coupling, comprising  
the steps of:

applying energy waves into the conduit;  
receiving reflected portions of said energy waves; and  
determining nature of contact between said conduit end and a generally radial surface  
10 associated with the fluid coupling installed at said conduit end.

51.     The method of claim 50 wherein nature of contact includes one or more of the  
following: amount of contact area, load between the conduit end and the radial surface, presence  
of a gap, presence of square abutment.

52.     The method of claim 50 wherein said energy waves are applied as transient shear  
15 ultrasonic energy waves.

53.     The method of claim 50 wherein said energy waves are applied as mechanical  
energy waves.

54.     The method of claim 53 wherein said mechanical energy waves are applied as  
transient shear ultrasonic energy waves.

20        55.     The method of claim 50 wherein said energy waves are applied to the fluid  
coupling.

56.     The method of claim 50 wherein said energy waves are applied from different  
radial positions at a selected axial location of the conduit.

57.     The method of claim 56 wherein said energy waves are applied using a plurality  
25 of ultrasonic transducers.

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58. The method of claim 50 comprising the step of filtering and correlating said received reflected portions.

59. The method of claim 50 wherein said waves are applied to the conduit at an angle within the range of about greater than 0° to about 90° from normal.

5 60. Apparatus for evaluating a fitting assembly of the type having a conduit and a fluid coupling installed thereon, comprising:

a source adapted to apply mechanical energy waves into the fitting assembly; said source receiving reflected energy waves and producing a signal related thereto; and

10 an analyzer that determines a characteristic of the fitting assembly as a function of said reflected portions of said energy waves.

61. The apparatus of claim 60 wherein said source comprises a separate transmitter and receiver.

62. The apparatus of claim 60 wherein said source produces transient shear ultrasonic energy waves.

15 63. The apparatus of claim 60 wherein said analyzer correlates said received energy waves.

64. The apparatus of claim 63 wherein said correlation is based on a Morlet wavelet correlation function.

20 65. The apparatus of claim 60 wherein said energy waves are applied to a fitting body that is associated with the fluid coupling.

66. The apparatus of claim 60 wherein said energy waves are applied to the conduit at an angle within the range of about greater than 0° to about 90° from normal relative to a longitudinal axis of the conduit.

25 67. The apparatus of claim 60 wherein said characteristic relates to bottoming of an end of the conduit in the fluid coupling.

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68. Apparatus for evaluating a fitting assembly of the type having a conduit and a fluid coupling installed on the conduit, comprising:

a source adapted to apply energy waves into the fitting assembly; said source receiving reflected energy waves and producing a signal related thereto; and

5 an analyzer for receiving said signal and producing an output that corresponds to nature of contact between the conduit end and a surface associated with the fluid coupling.

69. Apparatus for evaluating a fitting assembly of the type having a conduit and a fluid coupling installed on the conduit, comprising:

10 a source adapted to apply energy waves into the fitting assembly; said source receiving reflected energy waves and producing a signal related thereto; and

an analyzer for receiving said signal and producing an output that corresponds to axial position of an end of the conduit.

70. The apparatus of claim 69 wherein said axial position indicates bottoming of the conduit in the fluid coupling.

15 71. The apparatus of claim 69 wherein said source comprises a separate transmitter and receiver.

72. The apparatus of claim 69 wherein said source produces transient shear ultrasonic energy waves.

20 73. The apparatus of claim 69 wherein said analyzer correlates said received energy waves.

74. The apparatus of claim 73 wherein said correlation is based on a Morlet wavelet correlation function.

75. The apparatus of claim 69 wherein said energy waves are applied to a fitting body that is associated with the fluid coupling.

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76. The apparatus of claim 69 wherein said energy waves are applied to the conduit at an angle within the range of about greater than 0° to about 90° from normal relative to a longitudinal axis of the conduit.

77. The apparatus of claim 69 wherein said energy waves are input at two or more  
5 different locations about the conduit, said source producing a plurality of electrical signals in response to said received energy waves, each electrical signal corresponding to a respective one of said locations.

78. The apparatus of claim 77 comprising a correlation function of said plurality of electrical signals and wherein said analyzer produces an output that corresponds to axial position  
10 of an end of the conduit based on said correlation.

79. The apparatus of claim 69 wherein said analyzer comprises an analog to digital converter that digitizes said signal, and a programmable digital circuit that receives said digitized signal for noise reduction and correlation analysis

80. Apparatus for evaluating a fitting assembly of the type having a conduit and a  
15 fluid coupling installed on the conduit wherein the fluid coupling includes at least one ferrule, the apparatus comprising:

a source adapted to apply energy waves into the fitting assembly; said source receiving reflected energy waves and producing a signal related thereto; and

an analyzer for receiving said signal and producing an output that corresponds to a  
20 characteristic of the ferrule.

81. The apparatus of claim 80 wherein said characteristic is location of an indentation of the ferrule into the conduit.

82. The apparatus of claim 80 wherein said source comprises a separate transmitter and receiver.

83. The apparatus of claim 80 wherein said source produces transient shear ultrasonic  
25 energy waves.

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84. The apparatus of claim 80 wherein said analyzer correlates said received energy waves.

85. The apparatus of claim 84 wherein said correlation is based on a Morlet wavelet correlation function.

5 86. The apparatus of claim 80 wherein said energy waves are applied to a fitting body that is associated with the fluid coupling.

87. The apparatus of claim 80 wherein said energy waves are applied to the conduit at an angle within the range of about greater than  $0^\circ$  to about  $90^\circ$  from normal relative to a longitudinal axis of the conduit.

10 88. The apparatus of claim 80 wherein said energy waves are input at two or more different locations about the conduit, said source producing a plurality of electrical signals in response to said received energy waves, each electrical signal corresponding to a respective one of said locations.

15 89. The apparatus of claim 88 comprising a correlation function of said plurality of electrical signals and wherein said analyzer produces an output that corresponds to axial position of an end of the conduit based on said correlation.

90. The apparatus of claim 80 wherein said analyzer comprises an analog to digital converter that digitizes said signal, and a programmable digital circuit that receives said digitized signal for noise reduction and correlation analysis.

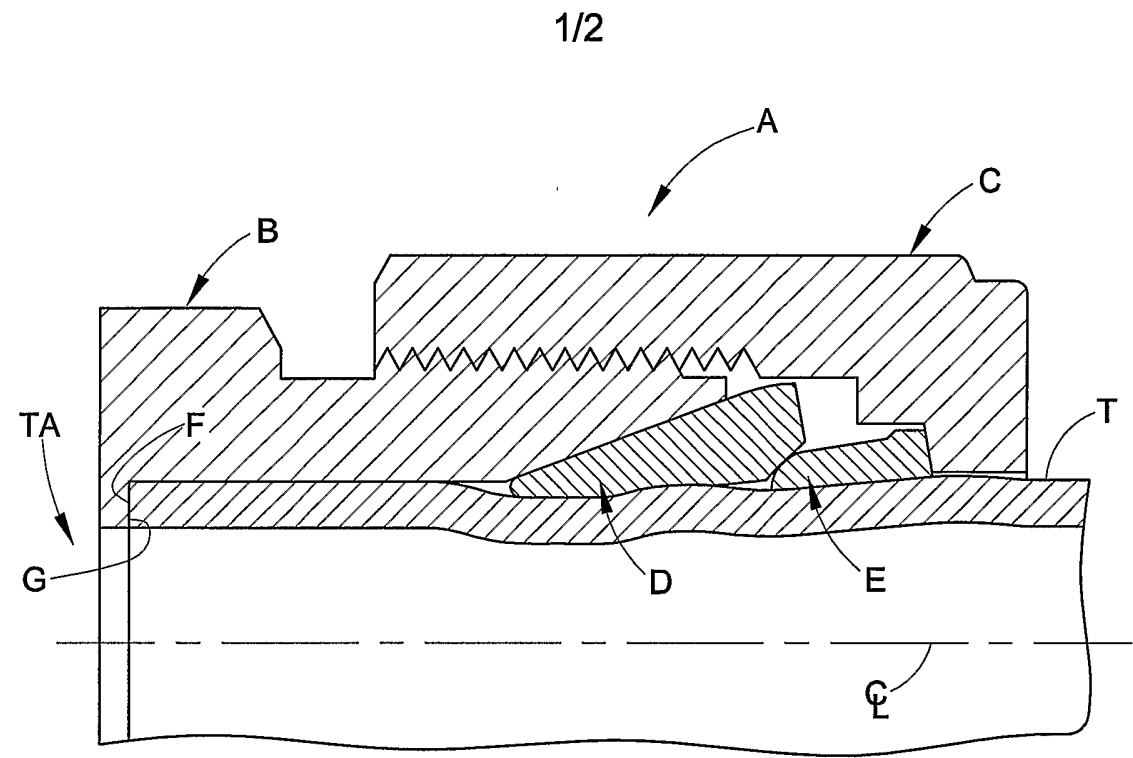


FIG. 1

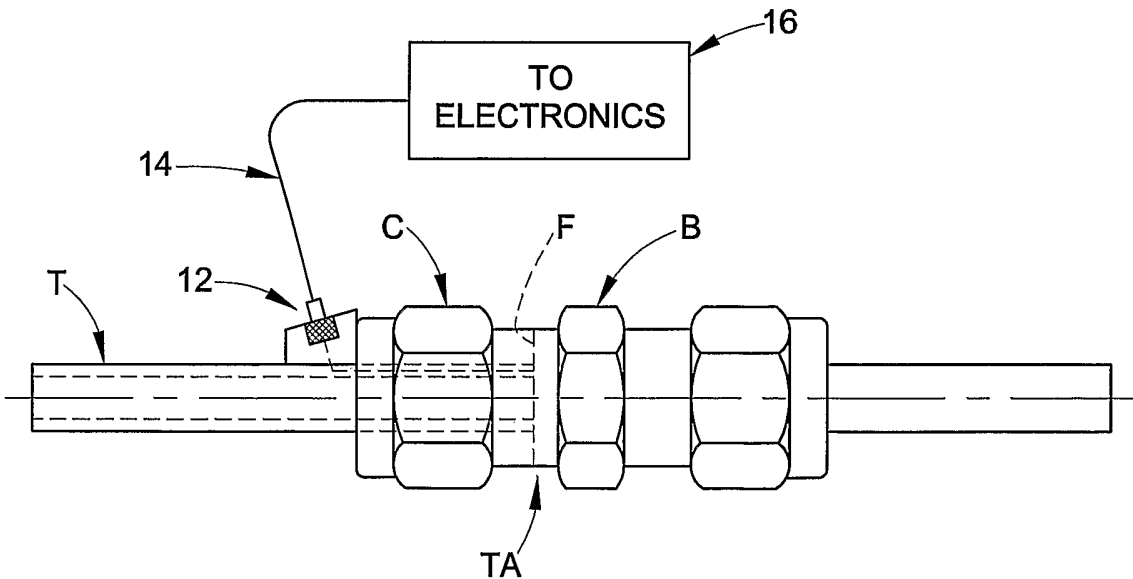


FIG. 2

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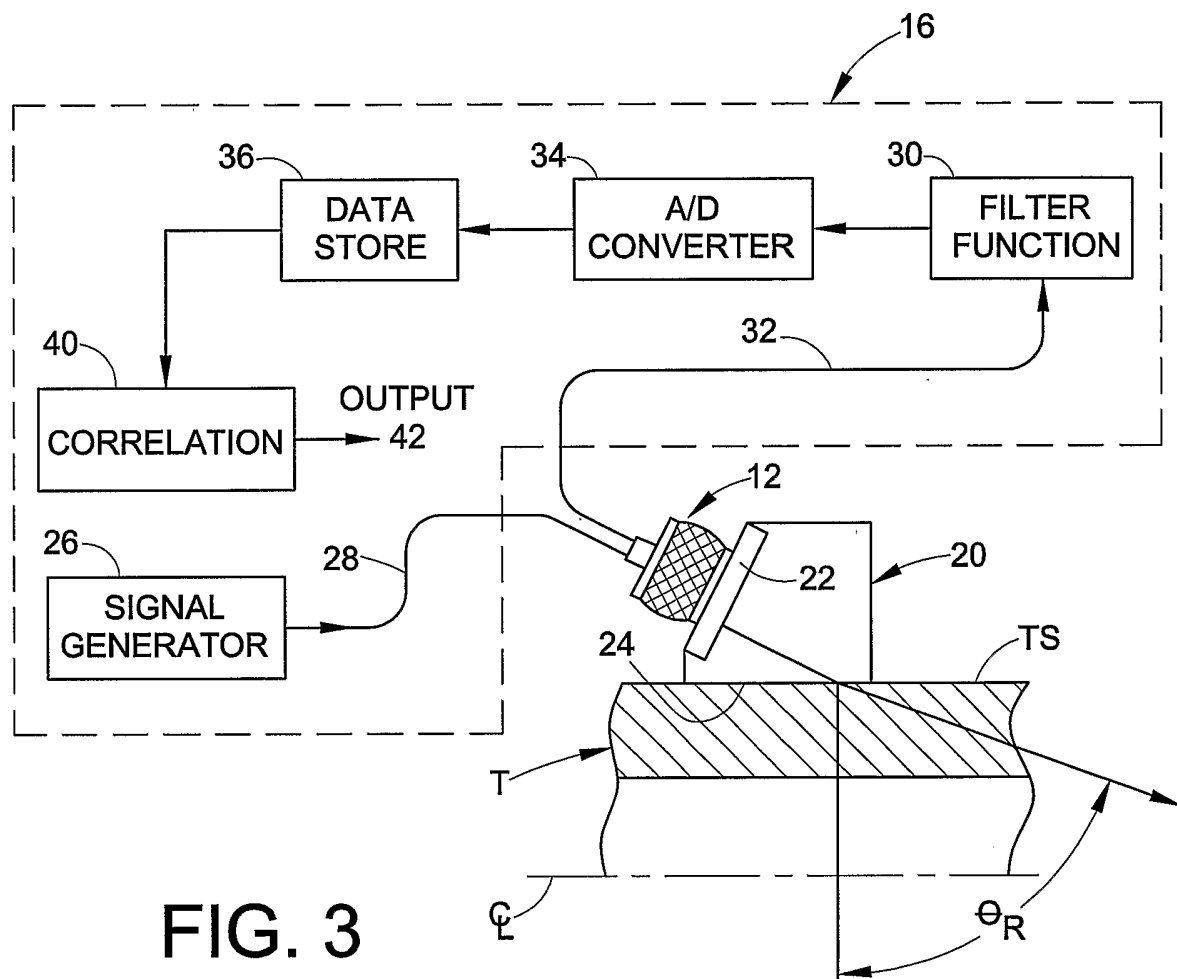


FIG. 3

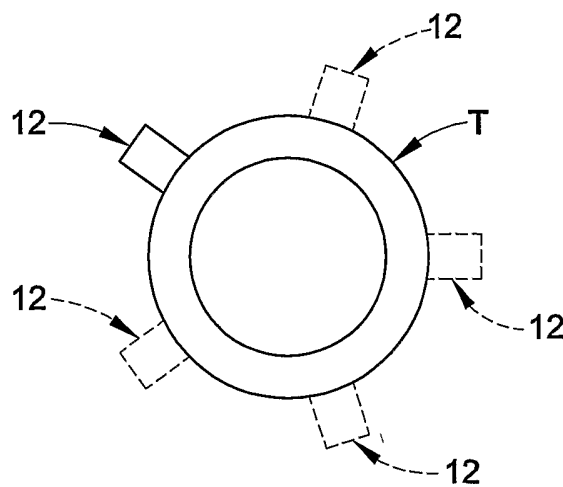


FIG. 4