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DIRECT INVERSION IN COMPLEX GEOMETRIES

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ABSTRACT

Progress on the POFIFS high frequency flaw imaging method is described. Both theoretical and experimental advances have occurred during the current year. Some success was achieved at imaging an off-axis trailer hitch flaw. However, the issue of variable speed was not completely resolved and research on this issue will continue.

INTRODUCTION

The objective of our research is to develop a production line technique for imaging flaws in solids. During our first year of support we adapted an appropriate portion of our high frequency inversion theory, originally developed for applications in geophysics, to the situation encountered in nondestructive evaluation. The computer algorithm developed for this purpose produced both an image of the flaw structure and an estimate of its reflection coefficient. The theory for this algorithm was based on reproducing a band-limited version of the characteristic function(s) of the flaw(s) in an otherwise homogeneous body with known external geometry. Below, we refer to this theory by the acronym POFIFS (Physical Optics Far Field Inverse Scattering). We have ascertained that the particular family of observation directions used had a profound influence on the quality of the inversion obtained. Thus, during this first year, we established a suitable (and probably near optimal) family of observation angles given the total number of observations to be made in a given viewing aperture.

Early researches in inversion problems made it clear that while direct estimation of the characteristic function from band-limited high frequency data produces a rather fuzzy image of inhomogeneities, [1-6] a derivative of the characteristic function (being more singular) is much more amenable to reproduction by such data. A series of papers by us, our associates and others [3, 7-11] had established the theoretical base for extracting such derivative information from aperture limited, i.e., band-limited and aspect-angle-limited data, in a stable manner. In the final computer implementation, the boundary of a flaw is displayed as the peak of a sinc-like function and the amplitude of this peak is in known proportion to the reflection coefficient.

At the end of the first support year, [12] a series of tests were performed by Richard Elsley at Rockwell. These tests established, to the satisfaction of our sponsors, that our inversion method (as implemented in a FORTRAN code delivered to Rockwell) was extremely stable even in the face of a paucity of viewing angles of observation and lower than desirable frequency range. These tests also indicated, in a preliminary manner, stability and robustness of the method when applied to laboratory data.

The nondestructive testing environment has many features which distinguish it from the geophysical environment and, after our initial success of designing a stable inversion algorithm in the first year, the second and third years have been devoted to improving our inversion method to take account of these features.

In the geophysical case, the layers are more or less horizontal. Consequently, the vertical derivative of the characteristic function provides adequate surface definition for this environment. In the NDE case, however, the orientation of the flaw boundaries is totally unknown. Since a directional derivative involves the cosine of the angle between a surface tangent of the flaw and the observation direction, the indicating peak of the sinc-like function is masked in observation directions which are nearly tangent to the flaw. Although the wide aperture of angles sometimes available to the experimenter would compensate to some extent for this defect of the inversion scheme, it was clearly desirable to extend the theory and implementation to remove this defect, if possible.

A major accomplishment of our second year in the program was to do just this. In essence, the idea behind this improvement was to find an algorithm that directly produces the surface of a flaw, rather than its characteristic function. This direct imaging of the surface function (the "singular function" of the surface) obviates the necessity for choosing a fixed derivative direction. [13] This is particularly desirable in the NDE environment, where such a fixed direction has no intrinsic relation to the problem.

An extra benefit of this theoretical advance was that it eliminated the need to compensate for the direction cosine factor in deriving reflection coefficient estimates.

At the end of the second support year, we received laboratory data to test the new algorithm. At this time, we discovered several additional features of nondestructive testing data. The most salient of these are the gradual velocity changes from one direction of observation to another and the gradual variations in the geometry of the observation surface.

At the end of the second year, we dealt with these matters by employing measurements made on a
second test object of similar manufacture with a known flaw geometry. This procedure was clearly inaccurate and not generalizable to production line testing. Nonetheless, it sufficed to remove the principal variations in surface geometry and velocity and thus provide a preliminary test of the new "singular function" algorithm. The reproduction of the unknown flaw geometry (dimensions on the order of 600 microns) was quite adequate and thus encouraged us to pursue more suitable means of dealing with these variations. [14]

THEORETICAL RESULTS

Clearly, if the surface geometry is unknown to an extent comparable to the flaw sizes we seek to detect, a complete and accurate reproduction of the flaw is impossible. One way to overcome this shortcoming is to use low frequency back face reflections to establish a coordinate system. Another idea is to develop direct methods for measuring the surface geometry of the test object to the necessary accuracy. The program has the issue of surface geometry before it for future research.

During the first quarter of the present support year, we examined the question of estimating the velocity variations. In the experiment of the second year, these variations with direction were observed to be as much as 2%. Since the probing signal travels great distances relative to the diameter of flaws we must resolve, this seemingly small variation can have an effect which is the order of the entire flaw size. It is not clear whether real world objects would have as great a velocity variation as the test objects (which are subjected to great pressure during their manufacture), but nonetheless it seems likely that significant velocity variations will occur. Thus, both we and our sponsors agreed that compensation for velocity variations should be the prime focus of our research.

While the problem of detecting sharp velocity changes such as occur at a flaw boundary of sufficient contrast has been adequately resolved, the general question of detecting gradual large scale changes is more difficult. We have derived an integral equation whose unknown is the desired velocity variation, but its accurate numerical inversion in a three dimensional setting presents both mathematical and technological difficulties not yet resolved. However, the flaw imaging algorithm, as now constituted, requires only the average velocity between the source entry point and the flaw reflection. Thus, detailed, pointwise, velocity determination is not essential to the problem of flaw description.

At present, we have not investigated the possibility of determining the requisite average velocities from the full integral equation. Our first approach has been to attempt to determine a radial velocity in each observation direction. That is, we seek a one-dimensional scheme which will produce corrected average velocities for our three dimensional flaw inversion algorithm. Although not a perfect solution, these corrections should reduce the inaccuracies considerably. Depending on the performance of these one-dimensional corrections, we will later decide whether the question of three-dimensional corrections should be pursued in this problem.

All methods for determining the large scale velocity variations require wide-band data; in particular, low frequency data. During the first half of this year, we considered five possible methods of approximately determining these variations. The first three methods use only a narrow band in the low frequency regime. It is a well-developed portion of the Rockwell program, due to Elsley, et al., to measure centroid location and higher moments of the flaw geometry by using low frequency methods. We had hoped that these measurements could be made on the same test object for which we received data and at the same angles as the high frequency data supplied to us. It became apparent, however, that due to the other demands made on the low frequency group at Rockwell, the centroid determinations could not be accomplished in a timely manner. We hope that the Elsley method will be used to determine the centroid location in the near future.

So as not to delay our portion of the program, we developed three methods of a similar type to Elsley's. The first of these is to use the peak obtained by inverse Fourier transforming the observations after applying a low cut digital filter and source signature deconvolution. The idea behind this is that at low frequency the flaw acts like a point located at its centroid. From this measurement and a determination of the elapsed time between signal entry into the medium and signal reflection, an average velocity in each direction is determined.

Our second low frequency approach is to use the same centroid measurement to determine an artificial time origin for each observation which, in effect, places the flaw center (centroid) at the center of an artificial sphere. Thus, this method involves translation of each observation, while the first involves a stretching of each observation.

The third method we developed involves using wide-band measurements to determine a one-dimensional velocity variation profile in each observation direction. An analogous algorithm for the geophysical case had already been developed by us, so it only remained to compute the average variation and construct a computer code.

The fourth method we are considering is the use of the back face reflection. This information is simple to use only for simple geometries such as the "trailer hitch" titanium spheres which are the initial object of our investigations. Nonetheless, at this stage of the research this information is important as a check on the other methods and possibly for providing calibrations.

A final theoretical achievement of the current support year was the development of an algorithm for obtaining flaw descriptions of a body immersed in a fluid bath. This algorithm requires as data the responses from the test object to a family of plane wave probes. It thus has the disadvantage of requiring a large amount of data and subsequent computer manipulation of that data. We hope to find other algorithms for this configuration which make less demand on the experiments and on the computer.
THE EXPERIMENT

Recently, Dr. James Martin collected an extensive set of data on a trailer-hitch sample containing an oblate ellipsoidal flaw of revolution whose axes are 600 microns and 400 microns (30 mils and 15 mils). To provide a more realistic test of the POFFIS algorithm, we had requested and Dr. Martin carried out an equipment modification which allowed tilting of the titanium sphere. Since the flow was originally machined with axes respectively normal and parallel to the mounting, this new flexibility allowed for the more realistic case of a flaw orientation whose axes did not coincide with the axes of the observation system.

The inversion scheme is based on a partition of the unit sphere into \( M \) latitudes and \( 2 \cdot M \) longitudes, which are optimally spaced for stability of the scheme. In practice only a subset of the \( 2 \cdot M^2 \) observation will be available and indeed the POFFIS algorithm was successfully tested last year [14] using observations taken only an octant of the surface. In the current set of experiments, we have selected \( M = 7 \) and thus a full set of observations would total 98. The mounting of the trailer hitch prevents data collection on the southern most latitude so the total feasible number of observations is 84. Since the "limited aperture" aspect of the algorithm is no longer in question, it was decided to collect data at all 84 feasible locations. Dr. Martin took two sets of data at these locations. One was made with a 5MHz, \( \frac{a}{2} \) transducer ("high" frequency data) while the other was made with a 2MHz, \( \frac{a}{4} \) transducer ("low" frequency data). In order to obtain reflection coefficient estimates, the high frequency data must be deconvolved with respect to the source signature. To obtain this signature, an additional observation was made for each transducer on a hemisphere. Finally, a small number of lines were taken with other transducers.

ANALYSIS

The analysis began with the signature deconvolution of the high frequency data. This provides the primary input data for the inversion algorithm. Since it is known that the internal structure of the test object contains only a single flaw, the deconvolved signals should be constant in magnitude and linear in phase within the frequency band of adequate signal-to-noise ratio. We did, indeed, obtain such a result in the band 1.9 - 11.0 MHz. The lower value corresponds to a "ka" range of .8 to 1.6 as we move around the ellipsoid. Since the inversion algorithm assumes high frequency data, we applied an additional low cut digital filter and used only the band 4.3 - 11.0 MHz (ka from 1.8 to 3.6 for the lower value). It was further observed that the amplitude of this deconvolved signal was relatively constant and the phase was nearly linear. See Figure 1.

The Fourier inversion of this deconvolved signal produced a band limited pulse, or sinc function. After examining the data, we hypothesized that the observed source line had passed through a caustic on its propagation path. This has the effect of producing a phase shift in the Fourier domain: \(+ n/2\) for positive frequencies and \(- n/2\) for negative frequencies. We adjusted for this in the deconvolution and then found that the Fourier transform exhibited the appropriate sinc-like behavior. The question of optimal deconvolution remains before us (especially since the source experiment is not yet completely standardized), but we feel that our current technique provides an adequate result. See Figure 2.

![Figure 1](image1)

![Figure 2](image2)
The next step in the analysis was to deconvolve the low frequency data. This provides the data necessary for the various velocity determination schemes. Here the phase shift problem encountered above did not occur, but a near null in the source frequency spectrum at 0.4 MHz (ka from 0.2 to 0.4), prevented successful deconvolution in the region necessary for the low band and wide band velocity determination methods. An order of magnitude calculation indicated that a small air gap between the base of the hemisphere and its mounting would cause a frequency null in this range. Dr. Martin was able to separate the hemisphere from its mounting and indeed found such a gap. Furthermore, he has recently informed us that by appropriately altering the mount, he was able to remove the low frequency source null. We look forward to using this new source record in the near future for velocity determinations.

While Dr. Martin investigated the source mounting issue, we fell back on the use of back-face reflections to determine a working set of velocities. Since the observation points used are symmetric with respect to the origin, on 12 of the 84 lines we had the opportunity to determine the velocity two times. On several lines, we discovered that there were serious discrepancies in the two velocities determined from opposite directions on the diameter.

Since our inversion method is a three-dimensional synthesis, an incorrect speed determination on a line not only causes a mis-estimate of the flaw size but can also cause a defocussing effect which obscures the indicating sinc-function peaks in the output on that line and nearby lines. Indeed, upon employing the average speed (on the 70 lines where two determinations were possible), we were completely unable to locate peaks at 9 of the 84 output points and peak location was uncertain at several other points. The maximum flaw diameter found was about 600 microns, at approximately the correct orientation, but other geometrical data (axes orientation, volume, etc.) were not computed because of the generally poor results. In cooperation with Richard Elsley, Dr. Martin has recently discovered a likely cause of the back-face velocity discrepancies we observed. At the lower sampling rate used for the low frequency data, the recording device was found to drop about two data points per record in regions where the recorded signal was of low amplitude.

Given this explanation, it is clear that using the minimum velocity of each pair, rather than the average, probably would have given a more consistent set of velocities. However, since Dr. Martin will soon be able to record a data set which does not have missing points, we do not plan to make further use of the present low frequency data set. However, it is worth noting in passing that each missing data point corresponds to an underestimate of 60 microns in flaw size. Thus, if there were two missing data points on the lines near our reconstructed maximum diameter our flaw size estimate would increase to 880 microns which is in good agreement with the original specification of 800 microns.

Realistically, the effort to reduce the POFVIS inversion method to practice must be regarded as an iterative loop between experiment and theory. Both of these must evolve hand-in-hand for the effort to succeed. It is not surprising that in this first large scale data collection and analysis effort difficulties should emerge both with the experiment and the analysis. These difficulties largely frustrated our efforts to test the velocity estimation technique described above. However, this data analysis represented only about two months of effort. Furthermore, the rapidity with which these difficulties are being resolved bodes well for future success, both short term and long range.

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REFERENCES


J.D. Achenbach, Chairman (Northwestern University): There is five minutes before the next session is supposed to start. Let's have one question.

Gordon Kino (Stanford University): I think I would like to make a comment rather than a question. It seems to me one thing that has got to be done with these numerical techniques - they're very powerful and so on - but somehow you have to get some rough-cut numerical techniques because it is no use doing a measurement where you have to go back six months later and say, "Oh, we didn't have it lined up." You have got to get some technique where you get a quick result on line and then you can massage the hell out of it.

Norm Bleistein (Denver Applied Analytics): We do that by hand and eyeball. I take the input lines that Jim gives me and I have a rough idea what the size and orientation is by doing that. We really can do that kind of thing, so it's really potentially there. And one of the things we are hoping for, for these considerations where we try the data and see what the data is and decide it this way, is that we would formalize those things just because we are repeating the same kind of seat-of-the-pants operations over and over again. But I quite agree with you we want to do that as a first step.