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Materials Technical Memorandum 378

PROPOSED ACOUSTIC EMISSION LOCATION SYSTEM FOR
A FULL-SCALE FATIGUE TEST

I.G. SCOTT

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I.G. SCOTT

SUMMARY

Various aspects of a proposed AE location system are reviewed. Basic sensor arrays are considered, solutions to the describing equations are found, and various problems are identified. Location using AE appears to be based on simple premises and, as a consequence, practical application involves the use of a variety of experience-based techniques.

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16. ABSTRACT:

Various aspects of proposed AE location system are reviewed. Basic sensor arrays are considered, solutions to the describing equations are found, and various problems are identified. Location using AE appears to be based on simple premises and, as a consequence, practical application involves the use of a variety of experience-based techniques.

CONTENTS

1. INTRODUCTION

A full-scale fatigue test on a CT-4 trainer aircraft is presently being planned at ARL. At selected time intervals, NDI (principally radiography) will be conducted on fatigue-critical parts of the structure. As the spar joint is not inspectable without disassembly, it is proposed that acoustic emission (AE) testing be used as the NDI for this region.

There is little Australian experience in defect location with AE. Brown et al[1] of AAEC have used a commercial 3-transducer unit to locate flaws in a steam vessel pressurised to failure. Martin[2] used a commercial 2-transducer unit to locate AE signals emanating from growing defects in a MACCHI spar undergoing laboratory fatigue testing. A modification, proposed by Landy[3], was made to this equipment so that it could be used with minimal sensor separation. In this modified form, the equipment was used for fatigue-monitoring of laboratory test specimens representative of MIRAGE refurbishment (Sparrow)[4]. AE equipment, designed and made by Battelle Northwest Laboratories (BNW), is installed in a MACCHI aircraft; a zone-isolation technique (Hutton and Skorpik)[5] is being used to make in-flight measurements of AE from a single cracked hole.

Overseas, BNW are under contract to DSTO to develop equipment to monitor critical regions of the MIRAGE spar[6] presently undergoing fatigue testing at F+W in Switzerland. As part of the contract, BNW are to assist in transferring the technology developed for this test to ARL. In preparation for the transfer, some sensor array design will be undertaken at ARL for the CT-4 test and specialised data acquisition and handling equipment will be developed. Thereby, much-needed experience in coping with these aspects of the AE technique will be obtained.

It is presently proposed that ARL purchase transducers, pre-amplifiers and time-of-flight measuring equipment. This memorandum discusses certain aspects of AE technique peculiar to defect location, including the disposition of transducers to form the array, and proposes methods for calculation, storage and possible display of source location results.

2. PREVIOUS WORK

Very little work on defect location using AE has been published, although commercial equipment for the purpose is readily available from overseas suppliers, several U.S. firms can be contracted to do location work and a draft ASTM specification[7] (E 569-76) exists. Parry[8] describes the EXXON approach to location while Kelly et al[9] show how DUNEGAN-ENDEVCO equipment can be used. Examination of commercial literature suggests that most recent advances have been made in the areas of data acquisition, handling and display.

The hexagonal array is described by Vetrano et al[10], and Kelly et al[9], while Cross et al[11] deal mainly with triangular arrays. Analytical solutions for the spherical surface are found by Asty[12], for a 4-transducer arrangement by Ying et al[13], and, using an approach similar to an Apollonian construction, for three transducers by Tobias[14]. Much of this work is discussed in detail below.

Commercial location systems are capable of handling fifty or more transducers spread over the surface of a large structure (pressure vessel, fuel tank, etc.), but the building block for this assemblage is a 3- or 4-transducer array. The basic arrays are shown in Figure 1.

Consider the simple 2-sensor array (Figure 1a). A signal from the AE source will generally arrive at one transducer before the other. The difference in arrival times ΔT is measured and, knowing the velocity c of surface waves in the specimen, possible source locations are defined by two hyperbolae. The curve furthest from the first-hit sensor is declared invalid but location is unique only for a long, narrow specimen, where it can be assumed that the source lies on the line joining the sensors.

A similar explanation is applicable to crossed pairs of sensors (Figure 1b). Time difference measurements define two sets of hyperbolae which intersect at 4 positions within the array. The valid intersection is that which is closest to the first-hit sensors, which are necessarily contiguous.

The most commonly used array comprises three transducers arranged in the form of a triangle (Figure 1c). Equilateral triangle arrays can be combined to form hexagonal arrays (Figure 1d) to cover a large area or to obtain detailed information about a part of a structure. The arrangement is economical of sensors which, although common to adjacent triangles, can be multiplexed in the ΔT measuring unit. Time differences are measured relative to the first-hit sensor, thus enabling two hyperbolae to be defined, the source being located at the intersection of the two curves. Commonly a fourth sensor is used to confirm the location, particularly when the intersection point is not well-defined or the source is located outside the array. DUNEGAN-ENDEVCO introduced the 'inside-out' array, comprising an equilateral triangle array with the extra sensor at the centroid; this array is used to locate sources outside the array at distances up to 4 times the array spacing.

Other arrays are (i) the true 4-sensor array with the sensors located at the corners of either a square or a rectangle, and (ii) a variant on the crossed pairs array where unequal transducer separation results in a diamond or rhombus shape.

A regular transducer pattern is not essential and 3 or 4-sensor configurations are often used to suit particular situations. Analytical solutions become quite tedious and a direct system calibration (see 4.2) becomes mandatory. Display of located sources is likely to be greatly simplified if regular arrays are used.

3. TIME DIFFERENCES AND SOURCE LOCATION

Given the location of the array sensors on the test structure and the sequence of signals from the sensors, the location of the source can be accomplished in various ways.

3.1 Graphical Solutions

Graphical solutions are simple to develop and are easy to conduct but are limited to the demonstration of concepts.

Assume that the material is acoustically isotropic. Then, for an idealised situation (non-dispersive material), the wavefront of an AE event occurring at $T = 0$ will have propagated distance cT_1 in all directions at $T = T_1$. Now assume a value for ΔT (and implicitly $c\Delta T$) and draw pairs of circles, each with a sensor as centre, and having radii differing by $c\Delta T$. The points of intersection of these pairs of circles define a hyperbola for given $c\Delta T$.

For a 2-transducer arrangement and a given range of $c\Delta T$, a zone can be defined by two hyperbolae, but of greater interest is usually the length of line (joining the transducers) intercepted by the hyperbolae. For a 3- or 4-sensor arrangement, at least one point of intersection is generated for each sensor pair.

Cross et al[11] describe an Apollonian-circles construction for 3 sensors. With centres on the two transducers, circles are drawn having radii proportional to ΔT_{2-3} and ΔT_{1-3}. A circle drawn to encompass the third transducer and which is tangent to the other circles, locates the source at its centre. The correct solution is confirmed by consideration of the hit order of the sensors.

3.2 Analytical Solutions

Solutions to any array configuration are not particularly difficult but may become tedious for irregular arrays. Consequently, most of the work has been done with symmetrical arrangements.

Tobias[14] solves the 3-sensor case using an approach derived from the Apollonian construction, claiming that otherwise the presence of square roots makes the analytical solution extremely difficult. It is not clear how well this claim is justified. Asty considers the plane as a special case of the spherical surface; while there may well be justification for developing the spherical case, the plane results are just as easily found using simple coordinate geometry. In solving the original equations, both authors generate false solutions and as a consequence various discriminants are needed to sort valid from invalid sources. Ying et al[13] use a novel approach to solve the 4-sensor case; after the 2-transducer case is solved, the axes are transformed leading almost immediately to the desired solution for 4 sensors forming a rectangular or diamond shaped array. Hence, for sensors located at ($\pm$f, 0) and (0, $\pm$f') along the x and y axes respectively, the coordinates of the source are:

$$x = a\,b'\left[\frac{b^2 + a'^2}{b^2b'^2 - a^2a'^2}\right]^{\frac{1}{2}} \text{ and } y = a'b\left[\frac{a^2 + b'^2}{b^2b'^2 - a^2a'^2}\right]^{\frac{1}{2}}, \qquad (1)$$

where $2a = c\Delta T_{1-2}$, $2a' = c\Delta T_{3-4}$, $b^2 = f^2 - a^2$, $b'^2 = f'^2 - a'^2$ and sensors 1,2 and 3,4 are located at ($\pm$f, 0) and (0, $\pm$f') respectively.

3.3 Numerical Solutions

Tobias used FORTRAN IV routines to generate a 64 x 64 element tabulation in which ΔT was expressed in terms of transit time and he displayed his results by plotting hyperbolae. Deterioration in spatial resolution outside the area defined by the sensors was noticeable, particularly for the 'inside-out' array. Tobias also discussed the occurrence of ambiguous solutions; for the equilateral triangle array, most of these occur close to the sensors. While, in general, ambiguities can be resolved by using an extra sensor, each arrangement needs separate examination.

Validity problems can sometimes be avoided by calculation of numerical solutions - given the source coordinates, the various ΔT can be calculated. However, if coordinates are sought for given ΔT, the usual problems with ambiguity may occur. It sometimes helps to use both sets of calculations. Using the Ying et al equations, the coordinates are calculated for given f, f^1 with $0 < a' < f'$ and $0 < a' < f'$ being changed progressively in equal increments. The program for a HP 25 calculator is given in Table 1. The expressions for x and y are similar and only minor alterations are needed to change from one program to the other. The results of this calculation, for one quadrant of a surface with transducers at (f, 0) and (0, f'), are displayed in Figure 2, other quadrants being images of the quadrant displayed. Examination of this figure confirms the Tobias finding that areas or regions of maximum sensitivity or resolution are easily seen but his ambiguities are not readily identified.

3.4 Transducer Sequences

Some of the ambiguities discussed by various workers can be resolved in practice by observing the order in which each sensor is hit.

Consider the triangle ABC (Figure 3), divided as shown into six regions by means of the median. For three sensors located at the apexes of the triangle, there are six possible orders for signal arrival, each of which defines a triangular region from which the signal originated. It will be seen from Figure 2 that once array symmetry is lost the straight lines degenerate to curves.

Consider the square array (Figure 4). Eight regions are defined by the axes and two lines of unit slope passing through the origin. These regions extend outwards away from the transducer array, but restrictions placed on ΔT can ensure location only within the bounds of the array. Although there are 24 possible orders of signal arrival, all but eight of these are forbidden and each region is uniquely defined by the order of arrival of the signal at the first three sensors. A sample analysis is given in Figure 5.

Each quadrant of a four-transducer array can also be identified by measuring sign as well as magnitude of ΔT. Assume positive ΔT_{1-2} to mean that sensor 1 is first hit and that the source is located to the right of an axis defined in Figure 6. This approach often minimises the computer time needed to calculate source position.

4. DATA HANDLING

Data can be handled in several ways, some of which are discussed below.

4.1 Direct Calculation

For almost any array, equations similar to (1) can be derived and these, together with the hit-order of the sensors, enable coordinates to be assigned to an AE source. Depending on the available computer memory, this information can be stored, displayed on a CRO, or entered to an X-Y plotter; in the last case, no further storage is needed. The choice may depend on computing speed because, during some tests, an event could occur every 10 ms.

4.2 Calibration and Look-up Tables

Prior to any test, direct calibration of the entire system using a pulser is mandatory. The pulser is positioned at known locations on the specimen, the measured location is noted, and any necessary corrections are made.

Locations can be identified using a grid (Cross et al[11]) which can be laid out on a surface of almost any shape and the size of which can be varied to suit surface detail. A signal is applied at each intersection point of the grid and the ΔT values are printed out to form a map of locations corresponding to ΔT values. The measured ΔT are then compared with stored ΔT to read out source coordinates.

There are two difficulties with these look-up tables. Firstly, the computer must recognise locations close to, but not identical with, the grid intersection points associated with a particular ΔT pair; this may involve added computer time. The second difficulty relates to the size of memory needed to store information about the specimen surface, some of which will rarely be used.

4.3 Zone Identification and Sparse Array Storage

The specimen surface can be divided into zones defined by ΔT (Figure 2). Now the computer needs only to determine the limits within which the respective ΔT lie. Delta-T pairs are stored according to their location along with event information (generally one count per event). After a large number of events have been stored, the available memory may be filled. The computer can then be directed to search for the locations holding only a single count. This information is discarded and a spare memory address is created. This approach is called sparse array storage and is supposed to be economical of memory space. Only those zones to which a large number of entries have been made are retained and an estimate of defect severity can be made from events per zone. Provided zones are small, their locations should be sufficiently defined. This approach affords the advantage that only signals from those regions of the specimen which are supporting extensive AE activity will be recorded.

In the triangular array of Figure 3, regions defined by order of signal arrival can be subdivided into zones defined by ΔT. A linear approximation to the hyperbolic boundaries can usually be made. A separate look-up table for each region is not needed because each region is an image of the others.

4.4 Display

Undoubtedly, the most satisfying display is of verified AE sources on a scaled representation of the test article - particularly for specimens such as pressure vessels where failure may well initiate from a manufacturing defect in the middle of an otherwise featureless region. If the amplitude of an event is available, a three-dimensional display may be needed. However, this information is often discarded and the density of events is assumed to be sufficient indication of defect intensity. Also, during fatigue tests on aircraft structures, cracks are most likely to develop from one of the many fastener holes. Hence the fatigue-critical parts of the structure can be zoned to include (preferably) one fastener per zone, in which case a graphic display is no longer needed and a listing of events against identified fasteners should suffice. A new listing can be produced daily in a form which can be readily stored.

5. IDENTIFIED PROBLEMS

Even before testing commences, some problems are readily identified. The AE signals are in the form of surface waves traversing the specimen surface and hence changes in surface roughness, the presence of edges and protuberances, fastener holes, etc. will all cause dispersion, unwanted reflections or excessive transit times. Similarly, for most real materials, the sound wave velocity will vary with orientation. Compensation may be hard to arrange but most of the effects can be controlled using direct calibration.

Location is most easily applied to thin-walled structures where the specimen approximates to a two-dimensional sheet. In the present case, the CT-4 spar is three-dimensional and multi-layered, and signals from sources well below the surface to which the sensors are attached are likely to give false readings. Depending on how these signals develop, it may be necessary to relocate at least one of the transducers, using it as a guard transducer to identify and discard signals coming from the wrong layer. Alternatively, it may be possible to apply acoustic coupling between layers in order to simplify signal paths.

Electrical disturbances are expected to affect all transducers simultaneously and to give a false location at the origin of the axes. By ensuring that the origin does not cover an anticipated AE source, signals of this nature can be discarded. For each transducer pair, external electrical signals will result in additional false locations lying on a line normal to the line joining the transducers. These lines tend to coincide with the lines which divide the surveillance region (Figure 3).

An unusually large AE signal coming from a major defect may not be identified per se and could even be missed altogether if it occurred while another (smaller) AE signal was being processed. However, an unusually large signal will be accompanied by attendant signals and the probability of all of these being missed is extremely low. Otherwise, it will be necessary to record event amplitude information.

6. RECOMMENDATIONS

Final details of transducer arrangement have not yet been decided but examination of the CT-4 spar shows that it will be difficult to attach four transducers to the upper surfaces. Presently, it appears that four transducers will be used, up to two of these being used as guard transducers located on the spar web. Time-difference measuring equipment will provide ΔT's relative to a first-hit transducer.

The recommended procedure is as follows:

1. Fatigue-critical spar fasteners will be identified and the spar will be divided into a number of zones, each of which will contain a minimum of fatigue-critical fasteners.

2. The chosen sensor array will be attached to the spar and a pulser will be used to determine if adequate resolution of signals from fasteners can be obtained. Assuming $c = 5$ mm/μs and fasteners at 40 mm pitch, ΔT measured to 1 μs should provide adequate resolution. It is anticipated that the location of the transducers will be an iterative process.

3. Possible ambiguous signals will be sought and eliminated by varying the sensor array, by redefining the function of each sensor or by some presently undefined approach.

4. A table will be prepared listing possible hit-orders of transducers along with corresponding sectors of the specimen; a separate table will list the limits of ΔT for the various zones. These tables will be stored in the computer.

5. Delta-T's from individual transducers will be input to the computer in digital form; a signal proportional to the total AE, if available, will also be input.

6. The ΔT will be sorted in ascending order of magnitude, each maintaining identity with its corresponding transducer. Hit-orders will be compared with the appropriate look-up table and sectors will be assigned. results which cannot be assigned will be discarded.

7. The ΔT will be used with the appropriate look-up table to locate sources within zones.

8. Signals will be input to the structure from a pulser in various locations to prove the system and necessary amendments will be made, this will be an iterative process.

9. Threshold-value levels for the ΔT unit will be monitored and adjusted as needs arise. This will be particularly desirable as considerable fretting occurs during test.

10. The computer will be programmed to accept data in the sparse array or similar format, and, in the absence of amplitude information, a single count will result from each AE event.

11. Read-out from the computer will be in column format with appropriate tabular headings. The time of each event will be recorded so that correlation with rig loads or some observed parameter will be possible.

12. A separate read-out will be produced daily or at suitable times in the testing program (e.g. maintenance stops, etc). A running total of all signals will be maintained in the computer.

7. CONCLUSIONS

The possible use of AE to monitor a complicated part of an aircraft undergoing fatigue testing has been explored, in the course of which AE location techniques have been examined. No major problems are presently apparent which would prevent the application of AE to this structure but clearly final detail must await the identification of suitable equipment along with the availability of the test vehicle for experimental purposes.

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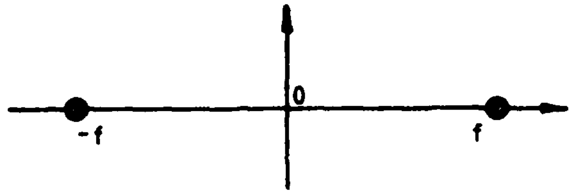
TABLE 1:- PROGRAM TO SOLVE FOR COORDINATES GIVEN ΔT

Program below solves for x; to solve for y change step 13 to RCL 3, step 15 to RCL 6, step 29 to RCL 4 and step 31 to RCL 5.

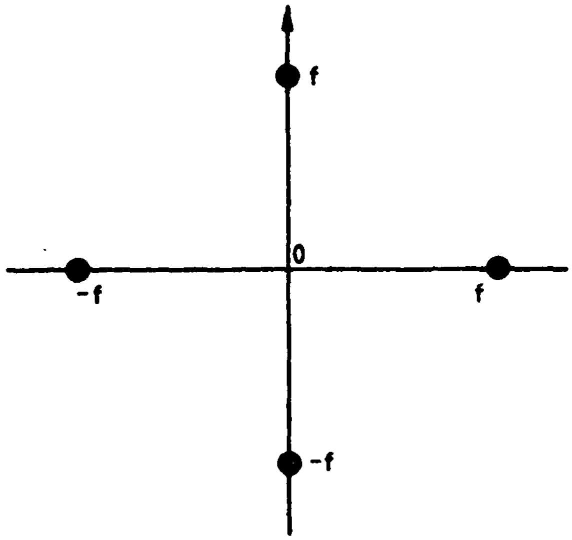
01	24	01	RCL 1	
02	24	03	RCL 3	
03	15	02	gx^2	
04		41	−	
05	14	02	f$\sqrt{x}$	
06	23	05	STO 5	
07	24	02	RCL 2	
08	24	04	RCL 4	
09	15	02	gx^2	
10		41	−	
11	14	02	f$\sqrt{x}$	
12	23	06	STO 6	
13	24	05	RCL 5	
14	15	02	gx^2	
15	24	04	RCL 4	
16	15	02	gx^2	
17		51	+	
18	24	05	RCL 5	
19	24	06	RCL 6	
20		61	X	
21	15	02	gx^2	
22	24	03	RCL 3	
23	24	04	RCL 4	
24		61	x	
25	15	02	gx^2	
26		41	−	
27		71	÷	
28	14	02	f$\sqrt{x}$	
29	24	03	RCL 3	
30		61	x	
31	24	06	RCL 6	
32		61	x	
33	14	74	f PAUSE	
34	24	03	RCL 3	
35	24	07	RCL 7	
36	14	71	f (x=y)	
37	13	00	GTO 00	
38	14	74	f PAUSE	
39		01	1	
40		00	0	
41	23	51	03	STO + 3
42	13	01	GTO 01	

STO 1	f^2	STO 3	a	STO 5	b
STO 2	f'^2	STO 4	a'	STO 6	b'
				STO 7	limit for a

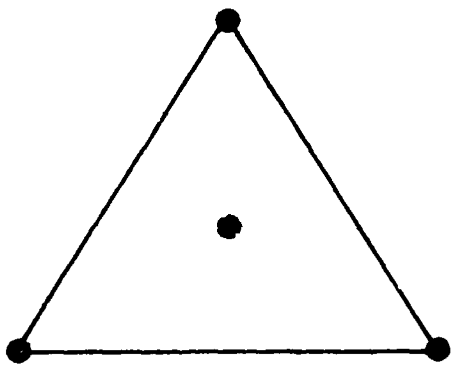
f = 200; f' = 100; limit for a = 200; a is incremented by 10 at conclusion of each run; a is advanced by hand.



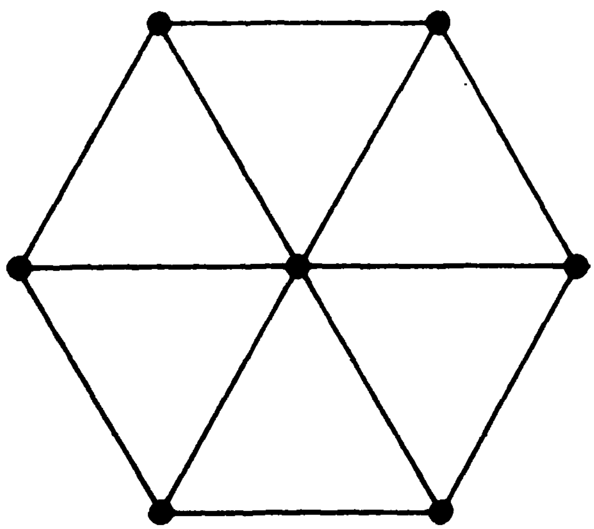
(a) 2-sensor array; sensors located at (±f, 0)



(b) 4-sensor array; crossed pairs of sensors located at (±f, 0), (0, ±f)

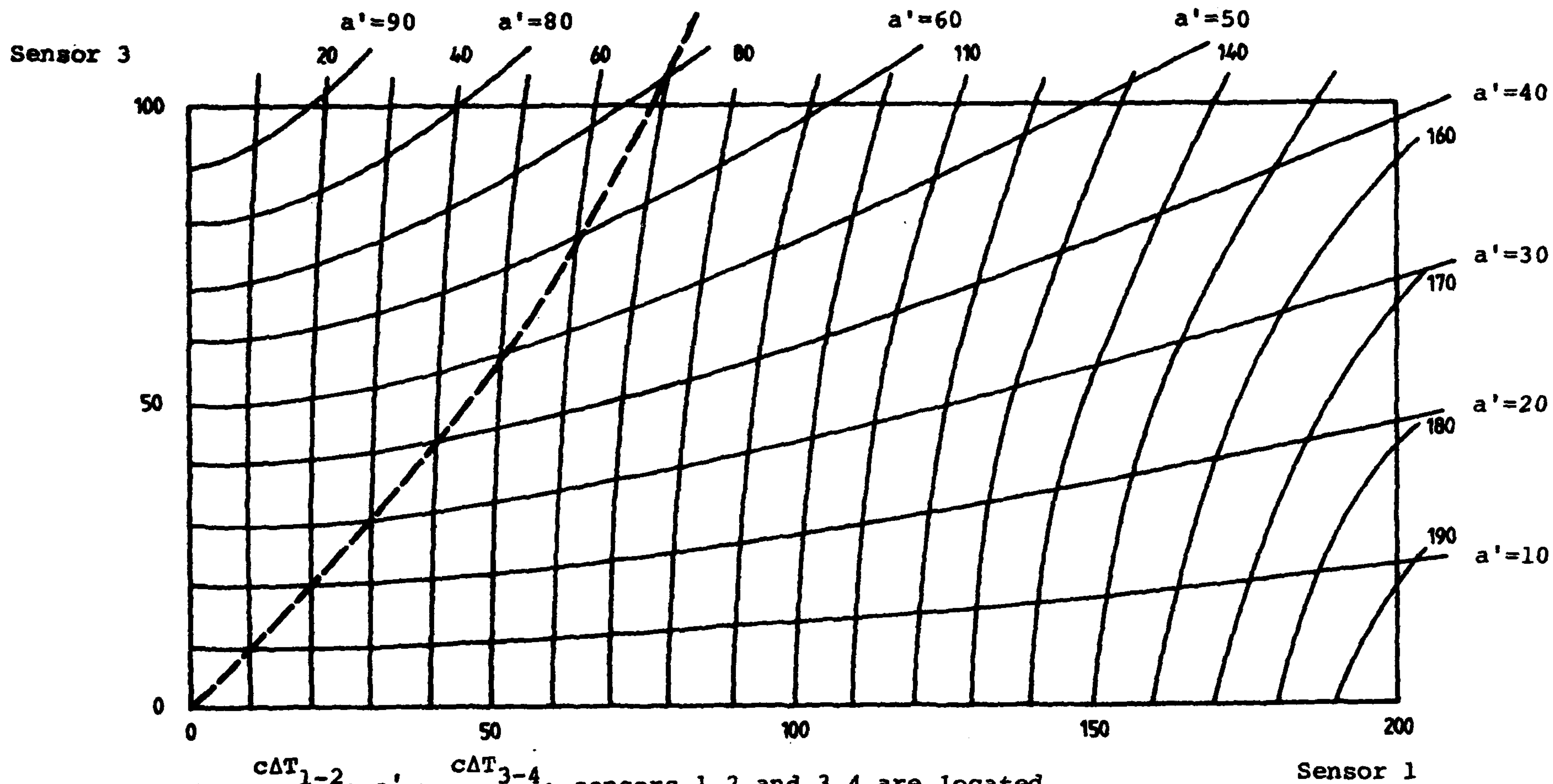


(c) Triangular array; 3-sensors at apexes of equilateral triangle. Addition of a fourth sensor at the centroid results in "inside-out" array.



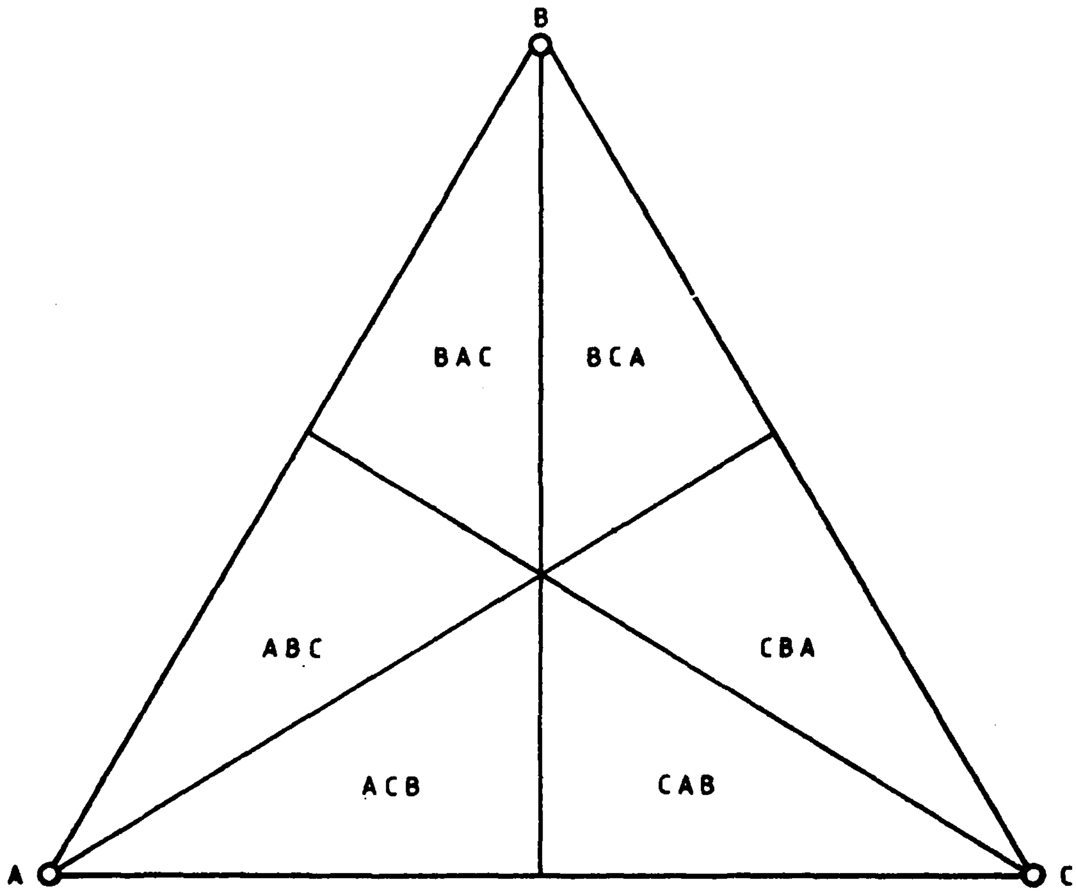
(d) Hexagonal array; sensors located at apexes of equilateral triangles which are interlocked to form hexagon.

FIG. 1: BASIC ARRAYS FOR LOCATION



$a = \frac{c\Delta T_{1-2}}{2}$; $a' = \frac{c\Delta T_{3-4}}{2}$; sensors 1,2 and 3,4 are located at $(\pm f,0)$ and $(0,\pm f')$ respectively; dotted line is for $a=a'$; other quadrants are images of this quadrant above axes.

FIG. 2 CONTOUR MAP FOR EQUAL ΔT (calculated)



The equilateral triangle ABC is divided into six triangular regions by the medians; the order of signal arrival is shown for sources originating within each region.

FIG. 3: ORDER OF SIGNAL ARRIVAL-TRIANGULAR ARRAY

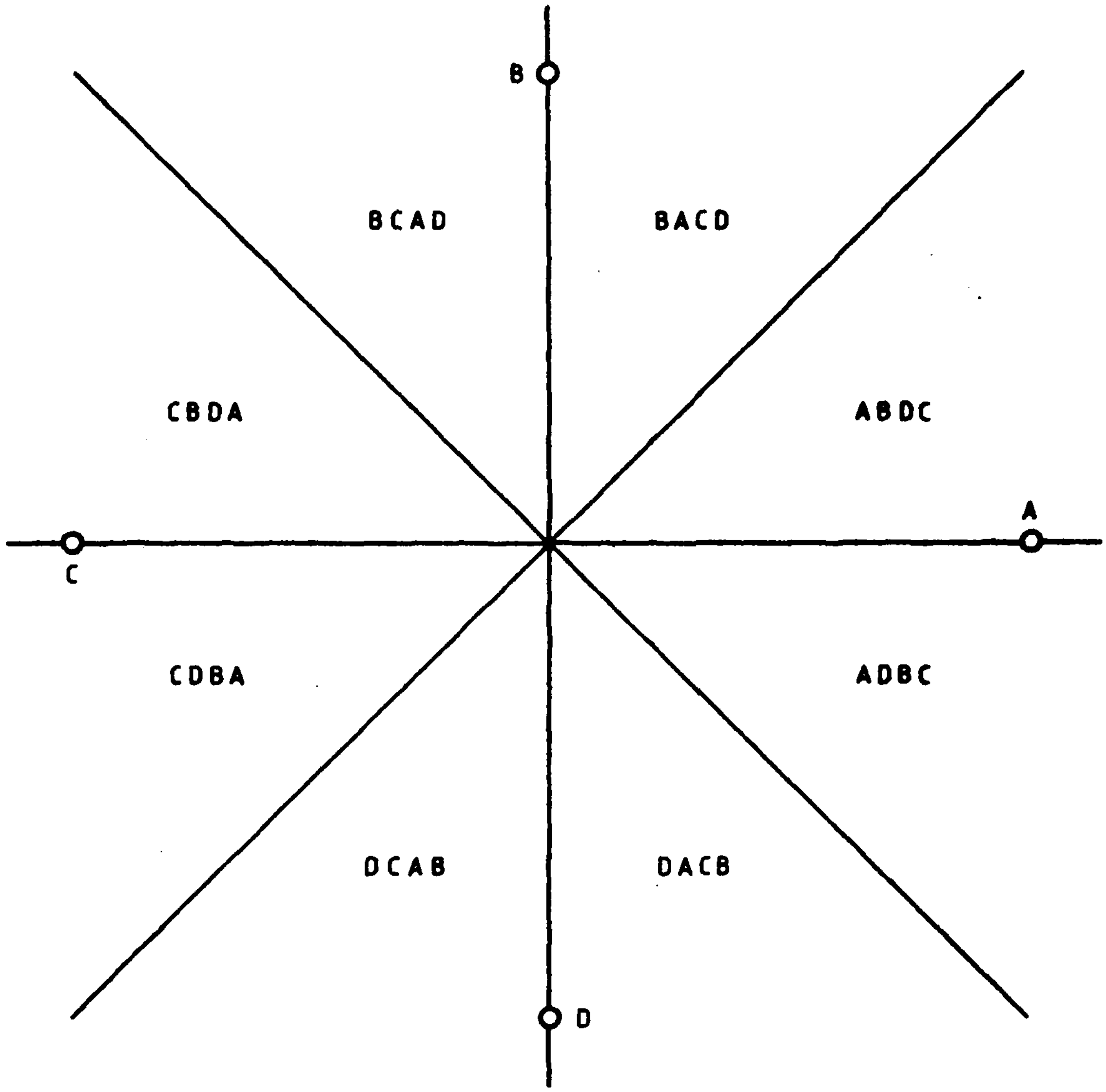
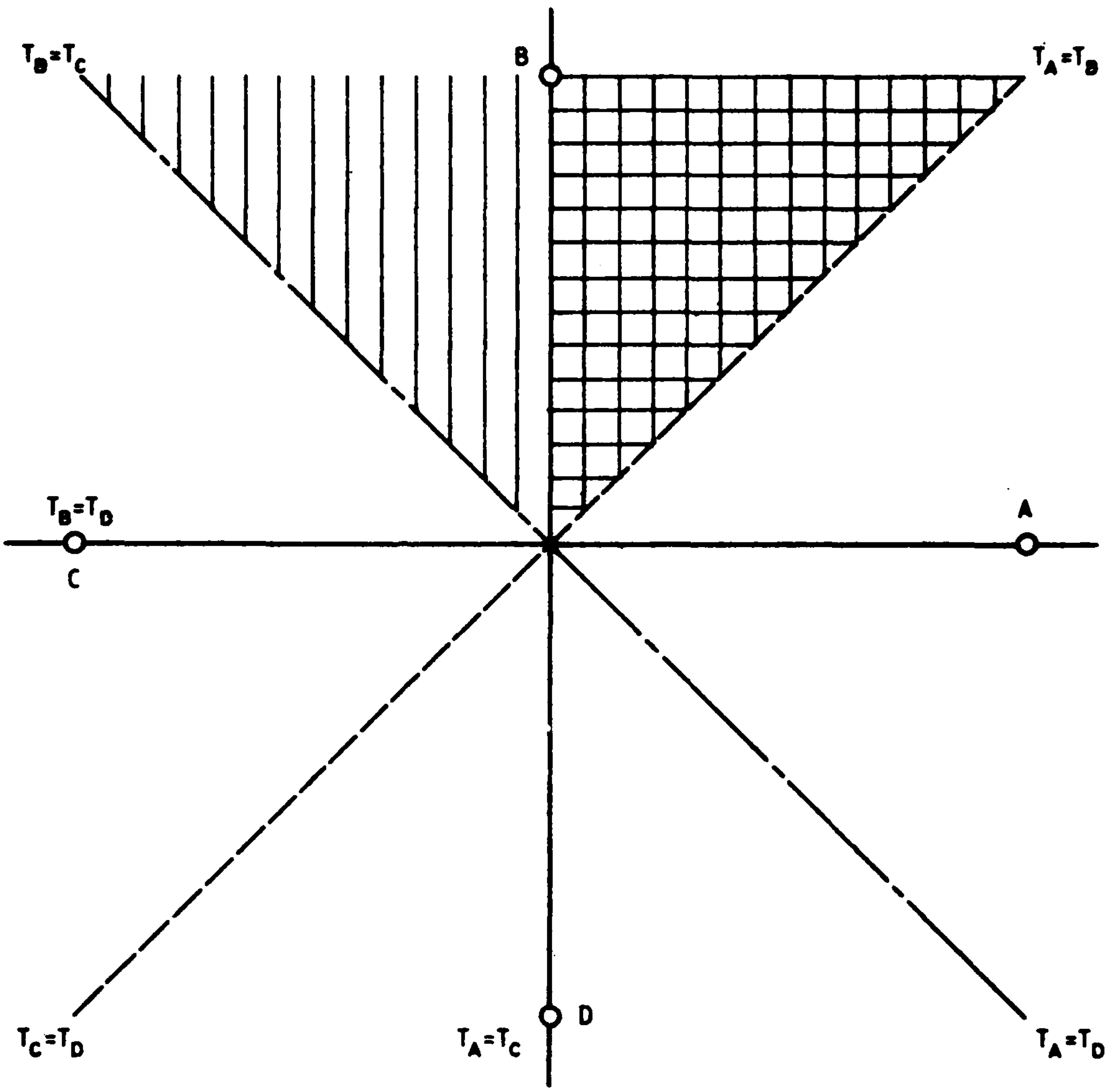


FIG. 4: ORDER OF SIGNAL ARRIVAL-SQUARE ARRAY



Sources located on the dotted line are equidistant from sensors A and B (also C and D).
Sources located on the chained line are equidistant from sensors B and C (also A and D).
Sources located on the horizontal (vertical) axis are equidistant from sensors B and D (A and C).
Sources located within the region defined by vertical hatching are closest to sensor B, which will be first hit; sources located within the doubly-hatched region are closer to A than to C and D is further away than any. Hence order of arrival is BACD.

FIG. 5: ANALYSIS OF SQUARE ARRAY

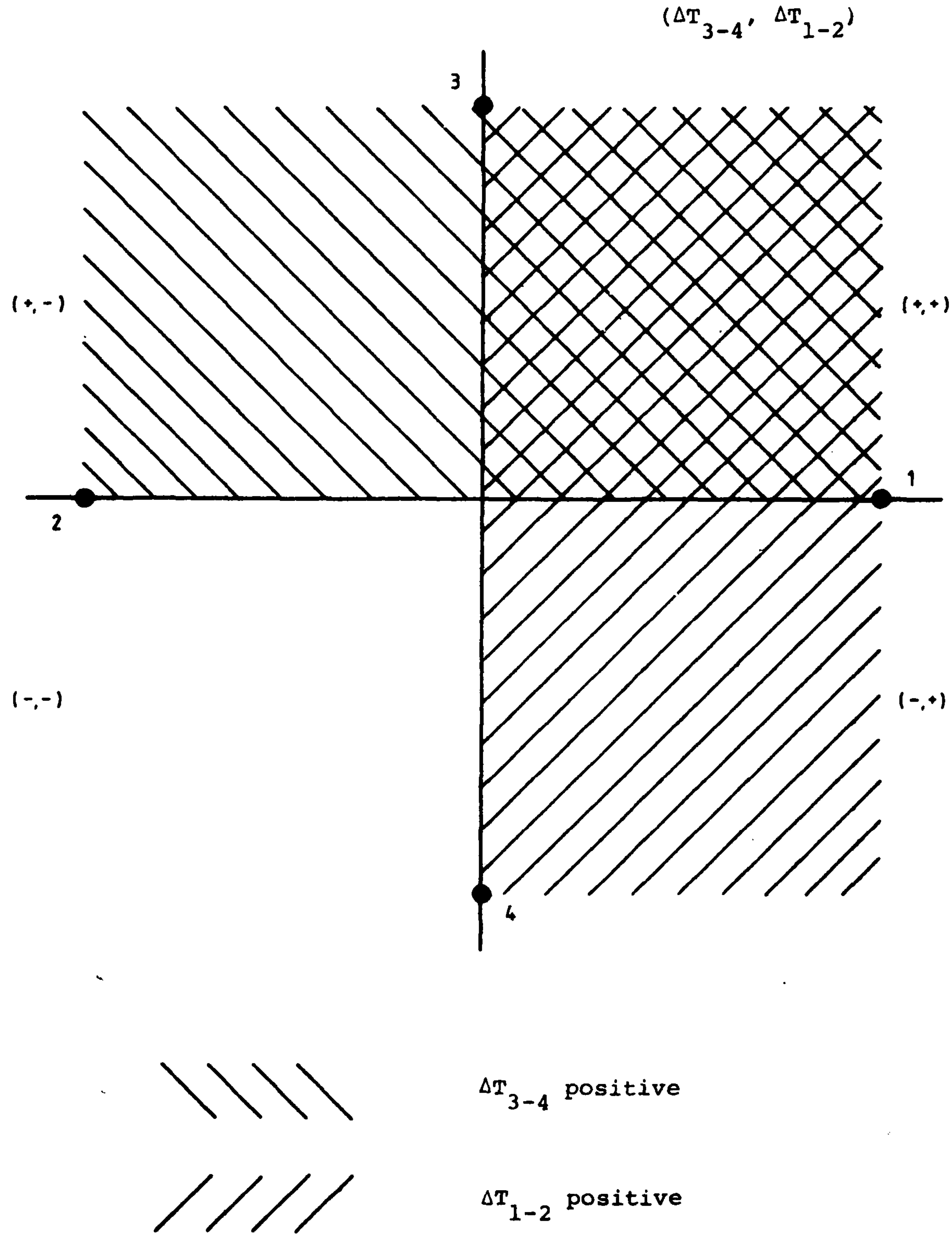


FIG. 6: SUBDIVISION OF ARRAY REGION BY SIGN OF ΔT

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