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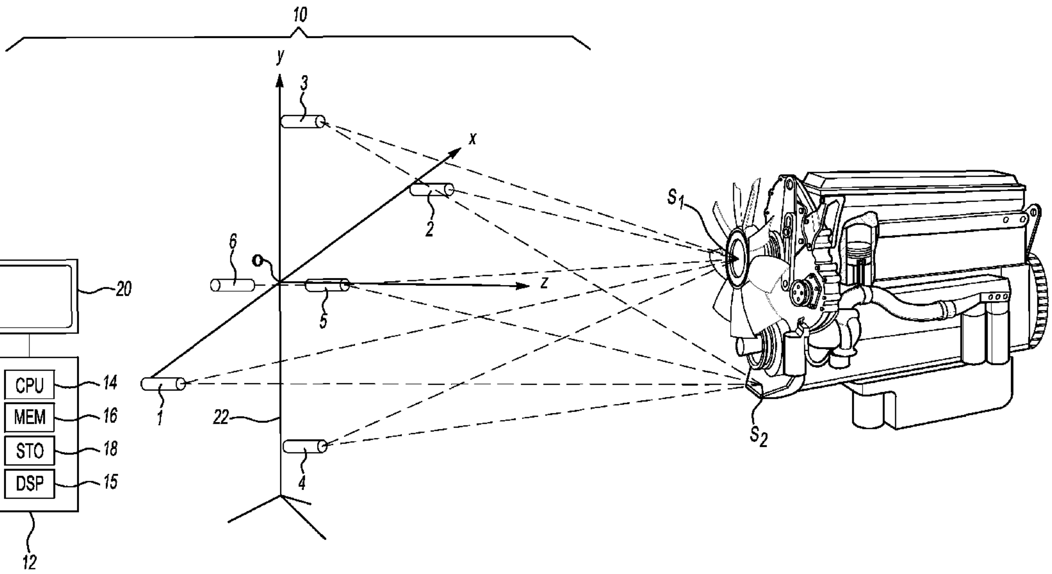

(57) Abstract: A system and method for locating arbitrary noise sources includes six microphones arranged in an array at any distance away from a target that may contain a number of noise sources. A first pair of microphones is arranged in a first plane and in a second plane perpendicular to the first plane. A second pair of microphones is arranged in the first plane and in a third plane perpendicular to the first plane and the second plane. A third pair of microphones is arranged in the first plane and the third plane. A processor receives signals from the first, second and third pairs of microphones based upon noise received from a noise source in an unknown location, and the processor determines the location of the noise source based upon signals from the first, second and third pairs of microphones.

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LOCATING ARBITRARY NOISE SOURCES

This application claims priority to United States Application No. 60/848,753, filed on October 2, 2006.

BACKGROUND

The present invention relates generally to a system and method for locating arbitrary noise sources.

Presently, beamforming is the main methodology utilized to locate noise source. The systems require taking measurements of the acoustic pressure through an array of 30 − 60 microphones and use beamforming to identify the directions in which sound waves are propagating in space.

Beamforming utilizes a phase delay technique to process the time-domain signals collected by each microphone. By adjusting the phases of measured acoustic pressure signals, one can form a sonic beam which points in the direction where sound is originated. Since beamforming employs a plane wave superposition, it can only identify the direction of wave propagation but not actual locations of sound sources. Beamforming is suitable for noise sources that are on a planar surface.

In reality, however, most structures are 3D with complex geometry. Thus, beamforming can only yield limited information of a noise source. In most cases, it only offers obvious results of noise source that one can do without it. For example, beamforming points out that noise of a vehicle running at its idle speed is from the engine without much further details. Moreover, beamforming cannot discern two sources that are separated by a distance less than one wavelength of sound. Thus, beamforming is suitable for high frequency sound sources but not for low frequency sound sources.

Near-field acoustical holography (NAH) can provide a very detailed and accurate analysis of the acoustic characteristics of a complex structure, including the source locations. However, NAH requires tedious setup of a conformal microphone array, which is time consuming. In many cases, engineers just want to get a quick "look" at the noise sources.

SUMMARY

Described herein is a new way of locating arbitrary noise sources. It pinpoints the noise source location by printing out its (x, y, z) coordinates in a few seconds. In particular, it requires six microphones, thus significantly reducing the hardware costs. Typically, these microphones can be arranged any distance away from a target that may contain a number of noise sources.

In contrast to beamforming and NAH, the present invention employs a different way of locating noise sources with significantly improved spatial resolution and accuracy. Instead of visualizing noise sources using color maps in which red dots indicate the locations of noise sources, this new technology is capable of outputting the (x, y, z) coordinates of these sources. Moreover, the results are 3D, not limited to a planar surface. In other words, it can not only display noise sources from one side to another, but also their depths. It works even when a target source is behind the microphone array. Most importantly, it only requires 6 microphones. Thus, hardware costs are substantially reduced.

This invention can pinpoint the locations of individual sources within an error margin of ±1 to 3%. In general, the errors in locating noise source decrease with the increase of dimensions of the array. Other configurations of measurement microphones may be equally effective as well. Moreover, it works even when a microphone array is facing in the opposite direction of the target. Signal processing techniques, such as band-pass filtering, kurtosis, and synchronized averaging, can be utilized to enhance signal to noise ratios, so that the measurement environment does not have to be quiescent. In other words, it functions even in a non-ideal environment in which the background noise level may be relatively high.

In a system according to one embodiment, a first pair of microphones is arranged in a first plane and in a second plane perpendicular to the first plane. A second pair of microphones is arranged in the first plane and in a third plane perpendicular to the first plane and the second plane. A third pair of microphones is arranged in the first plane and the third plane. A processor receives signals from the first, second and third pairs of microphones based upon noise received from a noise source in an unknown location, and the processor determines the location of the noise source based upon signals from the first, second and third pairs of microphones.

These and other features of the disclosure can be best understood from the following specification and drawings, the following of which is a brief description.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 illustrates a system for locating noise sources according to one embodiment of the present invention, positioned in front of noise sources.

Figure 2 is a plan view of the microphone arrangement of Figure 1.

Figure 3 is a side view of the microphone arrangement of Figure 1.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

A system 10 for locating noise sources is shown in Figure 1. The system includes a computer 12, including a processor 14, DSP 15 (optionally), memory 16 and (optionally) mass storage 18. Computer software for performing the functions described herein and any implied or necessary attendant functions are in memory 16 and executed by processor 14. Results may be displayed on a display 12, output to another system or process, or printed by a printer.

The computer 12 receives noise signals from a plurality of microphones 1-6 arranged on a stand 22 (connections are not shown, for clarity). Microphones 1-4 are arranged in a common x, y plane. Microphones 5 and 6 are positioned in front of and behind the x, y plane along a z-axis. The noise sources, S1, S2, in this example components of an internal combustion engine, may be positioned anywhere outside the x, y plane. Note that the description of the method below is for determining the location of a noise source S, which would be performed separately for each of the noise sources S1, S2, ..., SN.

Figure 2 is a plan view of the microphones 1-6. Consider the x-z plane on which the source S and microphones 1-6 are projected. The microphones 1 and 2 on the x-axis are separated by a distance D_1. Microphones 3 and 4 on the y-axis 3 are separated by a distance, D_2. Microphones 5 and 6 on the z-axis 5 and 6 are separated by a distance, H. The arbitrarily selected sources S are located at an unknown location whose coordinates (x, y, z) is to be determined with respect to the origin, O, of the coordinate system. Microphones 1 and 5 are separated by a distance, d. The length of the microphones is δ. The distances D_1, D_2, d, δ and H are known and stored in computer 12.

The unknown distance between source S and microphone 1 is denoted r. The distance between the source S and microphone 5 is denoted as $r + \Delta r_{15}$, and that between the source and microphone 2 as $r + \Delta r_{12}$. The angle between r and d is denoted θ and that between d and the x-axis is denoted β.

Note that r and θ are unknown a priori, whereas $\Delta r_{12} = c\Delta t_{12}$ and $\Delta r_{15} = c\Delta t_{15}$, where c stands for the speed of sound in the air, Δt_{12} indicates the time delay in the signals received by microphones 1 and 2, and Δt_{15} represents the time delay in the signals received by microphones 1 and 5. These time delays are obtained by taking cross correlations of the signals received by two microphones.

In this invention, the value of r is determined by using an iterative process given by

$$r = \frac{D_1^2 - (\Delta r_{12})^2}{2\left[\Delta r_{12} + D_1^2 \cos(\beta + \theta)\right]}, \tag{1}$$

where the angles β and θ are defined as

$$\beta = \tan^{-1}\left(\frac{H - 2\delta}{D_1}\right), \tag{2}$$

$$\theta = 2\tan^{-1}\left[\frac{R}{L-(r+\Delta r_{15})}\right], \tag{3}$$

$$R = \sqrt{\frac{(L-r)(L-r-\Delta r_{12})(L-d)}{L}}, \tag{4}$$

$$L = \frac{2r+\Delta r_{12}+d}{2}, \tag{5}$$

$$d = \frac{1}{2}\sqrt{D_1^2+H^2}. \tag{6}$$

Note that in Eqs. (1) to (6), δ is the length of a microphone, D_1 represents the distance between microphones 1 and 2, and H implies the distance between microphones 5 and 6. They are known quantities for a given microphone array. Δt_{12} and Δt_{15} are obtained by taking the cross correlation of signals between microphone 1 and 2, and that between microphones 1 and 5, respectively.

To solve Eq. (1) for r, we employ an iteration process. For example, we can make an initial guess of a value of r, say, $r = 1$ and substitute it into the right sides of Eqs. (3) to (5), which yield initial values of θ, R, and L. Substituting these values to the right side of Eq. (1) leads to the new value of r. Now repeat the steps described above using this new value of r in the subsequent iterations. This process continues until a convergence is reached. Typically, this iteration can be completed instantly because a convergence is reached very quickly.

Once r is determined, the x and z coordinates of the source are specified as

$$x = \frac{D_1}{2} - r\cos(\beta+\theta), \tag{7}$$

$$z = \delta + r\sin(\beta + \theta). \tag{8}$$

The y coordinate of the source can be determined in a similar manner. To this end, let us examine the y-z plane on which measurement microphones and unknown source S are projected (Figure 3).

Here we denote the unknown distance between the source S and microphone 3 as p, that between the source S and microphone 5 as $p + \Delta p_{35}$, that between the source and microphone 4 as $p + \Delta p_{34}$, that between microphones 3 and 5 as e, and that between microphones 3 and 4 as D_2. Further, we denote the angle between p and e as ϕ and that between e and the y-axis as α.

Note that p and ϕ are unknown, whereas $\Delta r_{35} = c\Delta t_{35}$ and $\Delta r_{34} = c\Delta t_{34}$, here Δt_{35} is the time delay in the signals received by microphones 3 and 5, and Δt_{34} represents the time delay in the signals received by microphones 3 and 4. They are obtained by taking a cross correlation of the signals received by microphones 3 and 5, and that between microphones 3 and 4, respectively.

Once again, p can be determined by an iterative process given by

$$p = \frac{D_2^2 - (\Delta p_{34})^2}{2\left[\Delta p_{34} + D_2^2\cos(\alpha + \phi)\right]}, \tag{9}$$

where the angles α and ϕ are defined as

$$\alpha = \tan^{-1}\left(\frac{H - 2\delta}{D_2}\right), \tag{10}$$

$$\phi = 2\tan^{-1}\left[\frac{Q}{M - (p + \Delta p_{35})}\right], \tag{11}$$

$$Q = \sqrt{\frac{(M-p)(M-p-\Delta p_{34})(M-e)}{M}}, \tag{12}$$

$$M = \frac{2p + \Delta p_{12} + e}{2}, \tag{13}$$

$$e = \frac{1}{2}\sqrt{D_2^2 + H^2}. \tag{14}$$

Note that in Eqs. (9) to (14), D_2 is the distance between microphones 3 and 4, which is known for a given microphone array. Using an iteration process, we can solve for p, which in turn leads to

$$y = \frac{D_2}{2} - p\cos(\alpha + \phi). \tag{15}$$

The above computations are carried out simultaneously. Therefore, once signals are received by the microphone array, the coordinates of an unknown source S can be determined immediately.

The formulations presented above are valid even when an unknown source S is behind the microphone array, i.e., in the $z < 0$ region. To discern whether the source S is in the $z > 0$ or $z < 0$ region, the sign of the cross correlation between the signals received by microphones 5 and 6 is checked. There is cross correlation between the signals received by microphones 5 and 6 as a ratio of the auto correlation of the signals received by the microphone 5 and that of the signals received by the microphone 6. Then, when the source S is in the $z > 0$ region, the signal will reach microphone 5 first. Consequently, the cross correlation will be positive. Conversely, when the source S is in the $z < 0$ region, the signal will reach microphone 6 first and the cross correlation will be negative. Again, the process would be performed separately for each of the simultaneous noise sources S_1, S_2 . . . S_N.

This system 10 is very effective and accurate in identifying the locations of unknown sound sources S simultaneously (as shown in Figure 1, the source S actually includes more than one simultaneous source of noise), especially for sources that produce transient or impulsive signals. Under this condition, it works even a non-ideal environment with relatively high background noise, so long as the signals in the time domain are recognizable. If it is an impulsive signal, which contains very high and broad frequency spectrum, then in the time domain the beginning and end of this signal can easily be identified to estimate the time delay. The accuracy and spatial resolution of this technology increases with the dimensions of the microphone array. The larger the values of D_1 and D_2 are, the higher the accuracy and spatial resolution of the result become. The computation speed may depend on the maximum sampling ratio of a digital signal processing board (DSP 15) in the computer. Typically, for a DSP 15 with 100kHz sampling ratio or higher, numerical computations can be completed in a fraction of one second only.

To enhance the signal to noise ratio in processing the data, a high-pass filter (not shown) may be added to minimize the low-frequency noise contamination in the input data. It should be noted that this invention cannot handle a pure tone; however, neither can beamforming. In other words, it cannot process input data that contains a pure sinusoidal signal. Therefore, to locate sources that produce harmonic sounds, a band of frequencies should be focused on, for example, a 100Hz bandwidth or wider, rather than a single frequency. This is because the processing time is inversely proportional to the bandwidth. The narrower the frequency bandwidth, the longer the computation time becomes. In the limit of a zero bandwidth, namely, a single frequency, the computation time is infinite. In other words, the result never converges.

In a method according to the present invention, the following procedures in locating unknown sound sources in a non-ideal environment are performed.

1. Set up a microphone array containing six microphones 1-6. If the dimension and configuration of this array are the same as those depicted in Figure 1, the formulations (1) to (15) may be used directly. If the dimensions and configurations must be changed, say, microphones 3 and 4 are not exactly in the middle of microphones 1 and 2, etc., then the formulations (1) to (15) must be changed to account for changes in dimensions and configuration of a microphone array. The microphones 1-6 should be phase-matched.
2. Select an orientation and measurement distance of a microphone array with respect to a target object. This present invention enables one to determine the coordinates of unknown sources at any locations, even behind the microphone array.
3. Calibrate the speed of sound in the air at the temperature and humidity under which tests are to be performed. This can be done by generating an impulse at the position of microphone 5, which will be picked by all six microphones 1-6. By taking cross correlation of the signals at any two microphones, we can

determine the time delay between these two microphones. Dividing the distance between these microphones by the time delay, we obtain the speed of sound.

4. Measure the signals emitted by unknown sources S using the microphone array 1-6.
5. Digitize the signals and calculate the coordinates of unknown sources S using formulations (1) to (15).
6. Display, print or transmit the coordinates of unknown sources S in tables and/or graphs.

This invention can be helpful to people who are concerned with locating unknown sound sources such as in quality control and troubleshooting the buzz, squeak, and rattle noise problems of a car seat, in identifying the location of a sniper, or in examining heart, lung, and other organs inside a human body. It enables one to get a quick "look" at sound sources accurately and cost-effectively because very few microphones are required.

In accordance with the provisions of the patent statutes and jurisprudence, exemplary configurations described above are considered to represent a preferred embodiment of the invention. However, it should be noted that the invention can be practiced otherwise than as specifically illustrated and described without departing from its spirit or scope. Alphanumeric identifiers on method steps in the claims are for convenient reference in dependent claims and do not signify a required sequence of performance unless otherwise indicated in the claims.

CLAIMS

1. A method for determining a three-dimensional location of at least one noise source including the steps of:

a) arranging a first pair of microphones in a first plane and in a second plane perpendicular to the first plane;

b) arranging a second pair of microphones in the first plane and in a third plane perpendicular to the first plane and the second plane;

c) arranging a third pair of microphones in the first plane and the third plane;

d) measuring sound from a noise source in an unknown location with the first, second and third pairs of microphones; and

e) determining the three-dimensional location of the noise source based upon said step d).

2. The method of claim 1 wherein said step e) further includes the step of determining a difference in time of travel of sound from the noise source to the first pair of microphones.

3. The method of claim 2 wherein said step e) further includes the step of determining a difference in time of travel of sound from the noise source to the second pair of microphones.

4. The method of claim 3 wherein said step e) further includes the step of determining a difference in time of travel of sound from the noise source to the third pair of microphones.

5. The method of claim 1 wherein said step e) further includes the step of determining a distance from the noise source to one of the microphones in the first pair of microphones based upon a difference in time of travel

of sound from the noise source to the one of the first pair of microphones and to the other of the first pair of microphones.

6. The method of claim 5 wherein the distance from the noise source to the one of the first pair of microphones is solved iteratively.

7. The method of claim 1 In this invention, wherein a distance from the source to one of the first pair of microphones is r, a distance from the source to the other of the first pair of microphones is $r + \Delta r_{12}$, a distance from the source to one of the third pair of microphones is $r + \Delta r_{15}$, δ is the length of a microphone, and D_1 represents the distance between the first pair of microphones, wherein r is determined by using an iterative process given by

$$r = \frac{D_1^2 - (\Delta r_{12})^2}{2\left[\Delta r_{12} + D_1^2 \cos(\beta + \theta)\right]}, \quad (1)$$

where the angles β and θ are defined as

$$\beta = \tan^{-1}\left(\frac{H - 2\delta}{D_1}\right), \quad (2)$$

$$\theta = 2\tan^{-1}\left[\frac{R}{L - (r + \Delta r_{15})}\right], \quad (3)$$

$$R = \sqrt{\frac{(L - r)(L - r - \Delta r_{12})(L - d)}{L}}, \quad (4)$$

$$L = \frac{2r + \Delta r_{12} + d}{2}, \quad (5)$$

$$d = \frac{1}{2}\sqrt{D_1^2 + H^2}. \quad (6)$$

.

8. A system for determining the location of at least one noise source comprising:

a first pair of microphones in a first plane and in a second plane perpendicular to the first plane;

a second pair of microphones in the first plane and in a third plane perpendicular to the first plane and the second plane;

a third pair of microphones in the first plane and the third plane;

a processor for receiving signals from the first, second and third pairs of microphones based upon noise received from a noise source in an unknown location, processor determining the location of the noise source based upon signals from the first, second and third pairs of microphones.

9. The system of claim 8 wherein the processor determines a difference in time of travel of sound from the noise source to the first pair of microphones.

10. The system of claim 9 wherein the processor determines a difference in time of travel of sound from the noise source to the second pair of microphones.

11. The system of claim 10 wherein the processor determines a difference in time of travel of sound from the noise source to the third pair of microphones.

12. The system of claim 8 wherein the processor determines a distance from the noise source to one of the microphones in the first pair of microphones based upon a difference in time of travel of sound from the noise source to the one of the first pair of microphones and to the other of the first pair of microphones.

13. The system of claim 12 wherein the processor solves for the distance from the noise source to the one of the first pair of microphones iteratively.

14. The system of claim 8 wherein the processor determines a three-dimensional location of the noise source.

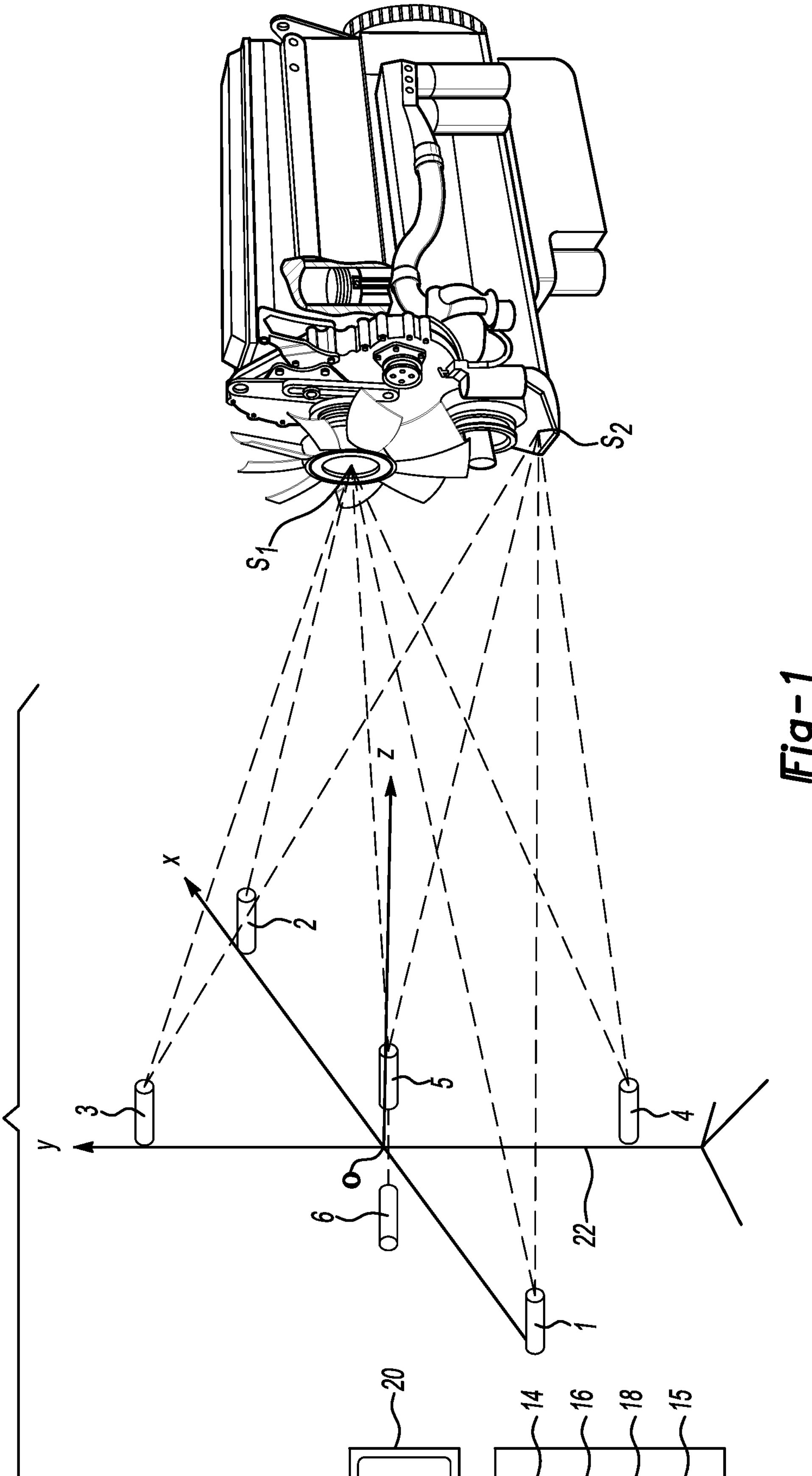

Fig-1

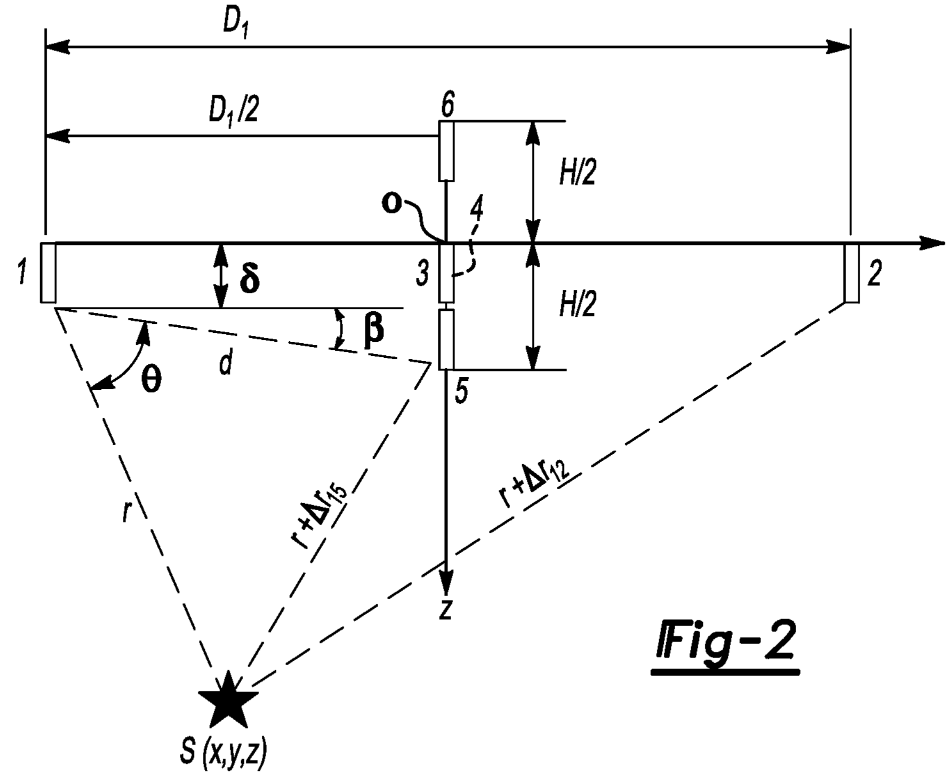
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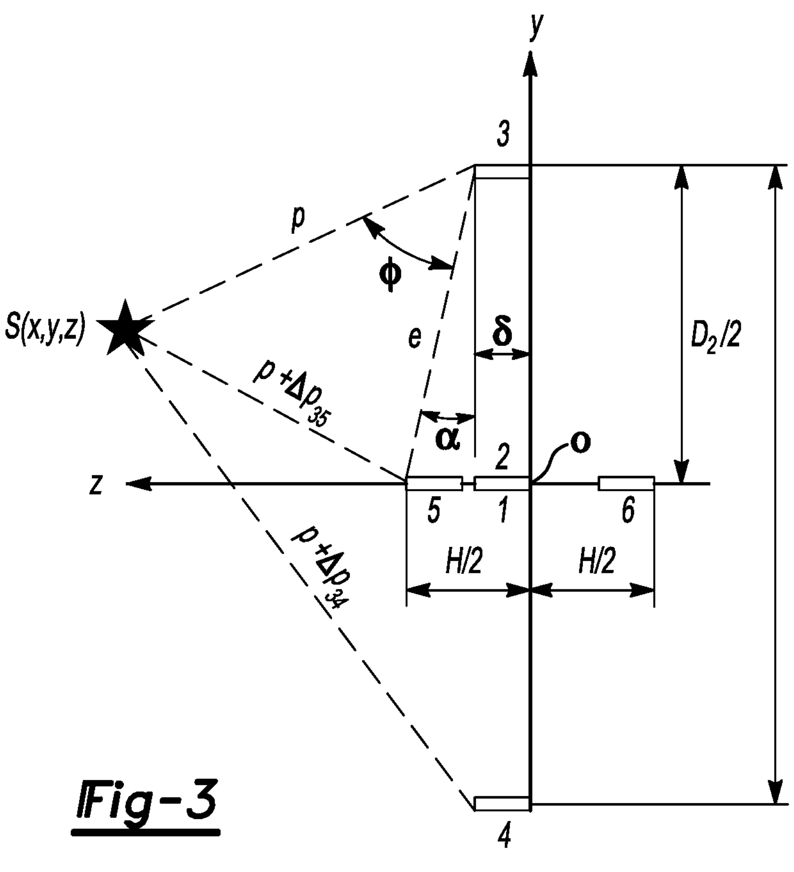
Fig-2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p
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S(x,y,z)
e
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D2/2
p+Δp35
α
2
o
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z
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6
H/2
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Fig-3

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2007/080148

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01S5/22 G01S11/14

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01V G10L G01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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X	US 2006/044942 A1 (BRINN MARSHALL S [US] ET AL BRINN MARSHALL SETH [US] ET AL) 2 March 2006 (2006-03-02) paragraphs [0021], [0023], [0031], [0036]; figure 2	1-6,8-13
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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
31 January 2008	27/02/2008

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Metz, Carsten

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2007/080148

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
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