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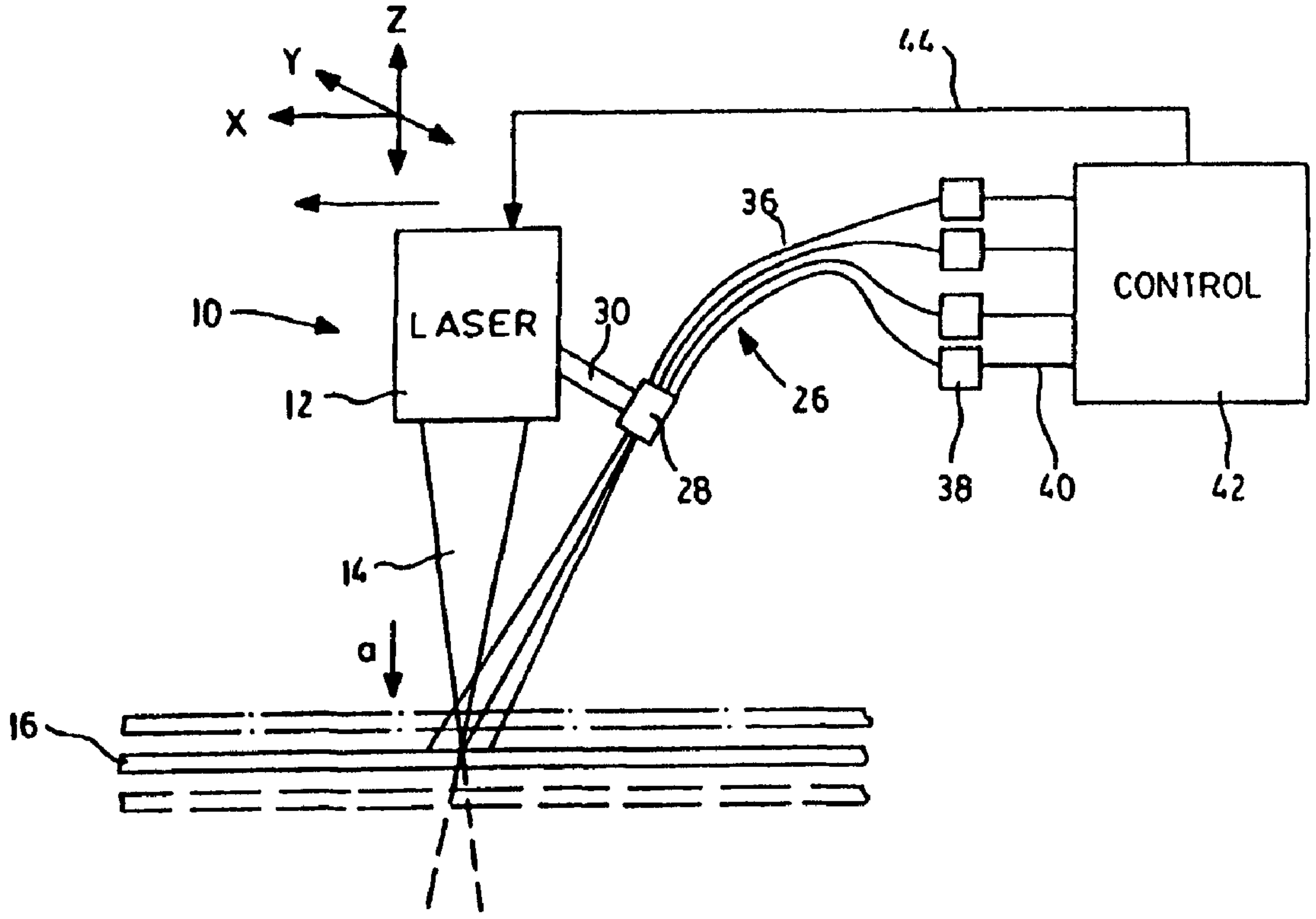
# (54) PROCEDE DE DETECTION D'ERREURS DANS LES TRAITEMENTS AU LASER

# (54) METHOD FOR LASER PROCESSING FAULT DETECTION



(57) Selon cette invention, les erreurs susceptibles d'être commises lors de traitements au laser, tels que la soudure, de composants, peuvent être identifiées par détermination d'une moyenne à partir d'un ensemble d'échantillons et par suivi de l'écart à la moyenne à l'intérieur de cet ensemble. Un coefficient représentatif des écarts d'un ensemble moyen de conditions est élaboré. Ce coefficient permet de contrôler plus d'un paramètre, en général les émissions IR et UV provenant du traitement au laser.

(57) Potential faults in laser processing of components, such as welding, are identified by determining an average from a set of samples and monitoring deviations from the average within the set. A coefficient indicative of deviations from an average set of conditions is developed that allows monitoring of more than one parameter, typically IR and UV emissions from the laser processing.

**PCT**

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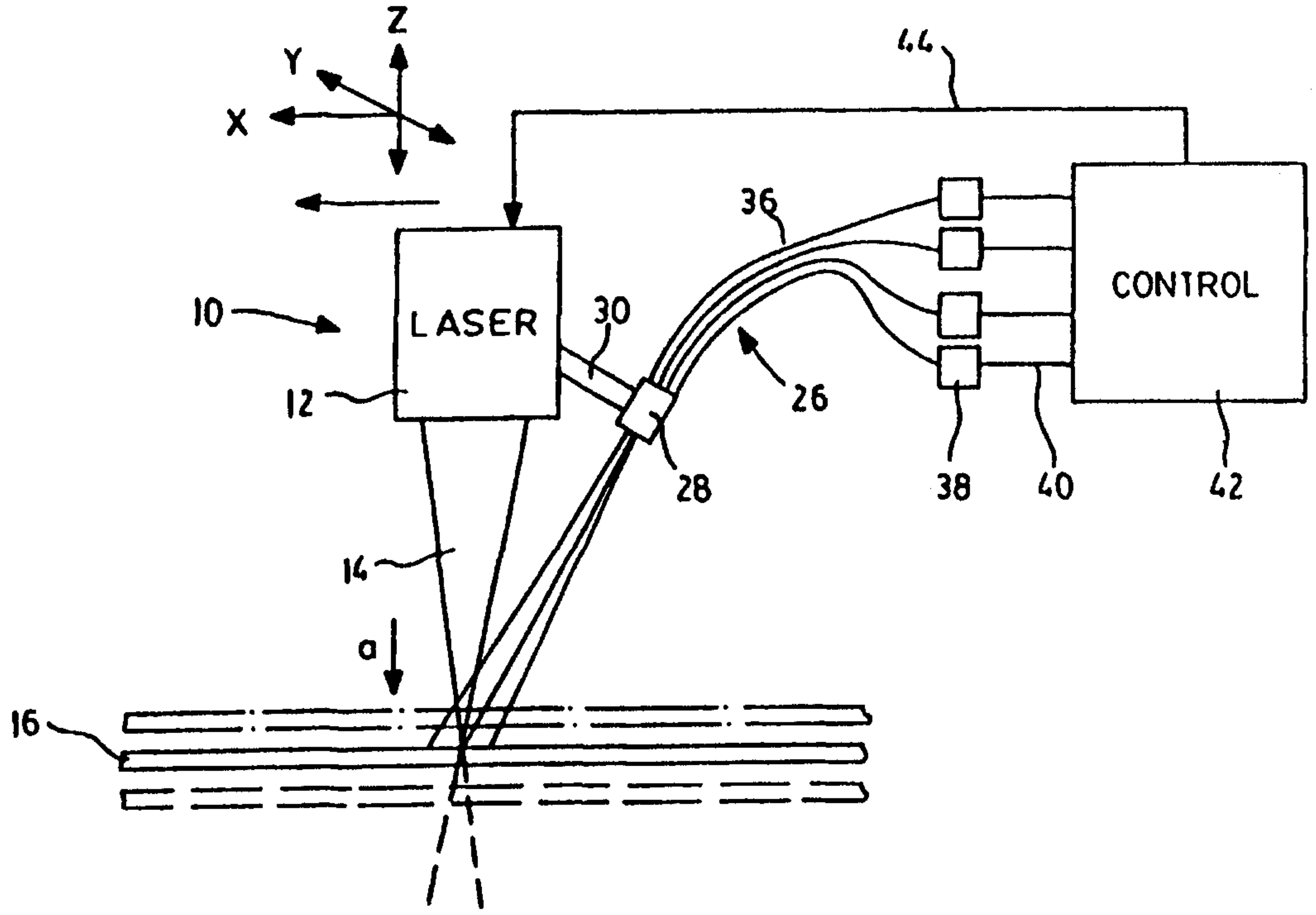
(54) **Title:** METHOD FOR LASER PROCESSING FAULT DETECTION



## (57) Abstract

Potential faults in laser processing of components, such as welding, are identified by determining an average from a set of samples and monitoring deviations from the average within the set. A coefficient indicative of deviations from an average set of conditions is developed that allows monitoring of more than one parameter, typically IR and UV emissions from the laser processing.

# METHOD FOR LASER PROCESSING FAULT DETECTION

## FIELD OF THE INVENTION

The present invention relates to laser processing.

## RELATED ART

It is well known to input energy to a component by causing a laser beam to impinge on the surface of the component. The energy is used to process the component, for example to weld two parts of the component, to cut the component or to surface treat the component. Close control of the interaction of the laser beam with the component is essential if consistent quality of processing is to be attained.

However, the quality of the laser processing depends on the consistency of the component being processed as well as the consistent application of the laser beam.

Welding with a continuous wave $CO_2$ laser is a well-established method for joining sheet metals in industry. Millions of tailored blanks are welded every year in the automotive industry. In production, the edges to be joined are usually prepared by a shear machine and the prepared sheets are transferred from the shear machine to the welding cell. It is inevitable that damage to the cutting edges will occur. Furthermore, cases of mismatch of the welding sheets will happen in a production environment. As a result, the laser-welded seams are not always perfect. Ripples, pinholes and large concavities in the welds can occur and detection of these defects in real time is desirable for quality control.

Optical emissions from the welding site contain significant information about the efficacy of the welding process. Conventionally the emissions from the weld site are monitored and characteristics of the emissions used to control the laser processing. As shown in U.S. patent 5,517,420 the characteristics of an image may be monitored and used to derive inputs to a fuzzy logic control. Such an arrangement provides good control over the laser processing and allows adjustments to be made as the processing progresses.

Whilst this control is effective to maintain optimum processing conditions, some difficulty may be experienced due to the nature of the laser processing itself. If a disturbance or transient condition occurs, the radiation from the weld site will likewise change. However, the detection of this kind of variation may be difficult because the emission from good welds itself is highly fluctuating. The amplitude of such fluctuations could be higher than the change that results from a disturbance so that detection of absolute changes in signal level may not produce satisfactory control.

It is therefore an object of the present invention to obviate or mitigate the above disadvantages.

## SUMMARY OF THE INVENTION

In general terms, the present invention monitors at least one signal obtained from the weld zone over a predetermined period. A set of samples is taken and an average obtained for each signal over this period. Fluctuations of samples from the average are monitored and compared to the average to obtain a coefficient indicative of the changes in the laser processing. Changes in the coefficient may then be used to monitor the laser processing either by controlling the parameters or by indicating potential flaws.

## DESCRIPTION OF THE DRAWINGS

An embodiment of the invention will now be described by way of example only with reference to the accompanying drawings in which: -

Figure 1 is a schematic representation of a laser welding process.

Figure 2 is a view on the line 2-2 of figure 1.

Figure 3 is a view on the line 3-3 of figure 2.

Figure 4 is a view in the direction of arrow a of figure 1.

Figure 5 is a representative signal obtained for UV emissions from the apparatus of figure 1.

Figure 6 is a representative signal obtained for IR emissions from the apparatus of figure 1.

Figures 7 – 12 are traces obtained from processing the traces represented in figures 5 and 6 for a series of tests performed with the apparatus of figure 1.

## DESCRIPTION OF PREFERRED EMBODIMENTS OF THE INVENTION

Referring therefore to figure 1, a laser processing apparatus 10 includes a laser 12 that propagates a beam 14 to impinge upon a work piece 16. The work piece 16 may be one of a variety of forms but in the examples illustrated comprises a pair of sheet metal components 18, 20 (Figure 4) abutting along respective edges 22, 24 to be welded to one another. It will however be appreciated that the work piece 16 may be a single sheet of material to be cut by laser beam 14 or may be a component to be surface treated by the laser beam 14.

An optical monitoring assembly 26 includes an optical head 28 secured to the laser 12 by means of an arm 30. The optical head 28 includes a housing 32 containing optical elements 34 that may be relatively adjustable to provide a variable focus for the monitoring assembly 26.

Optical fibers 36 are secured to the housing 32 and extend to respective photo diodes 38. In the embodiment of figure 1, four optical fibers 36 (indicated at 36a, 36b, 36c, 36d respectively) are provided and arranged in quadrature within the housing 32 and each will be associated with a respective photodiode 38a, 38b, 38c, 38d. It will be appreciated however that more or less optic fibers may be utilized depending upon the mode of control to be implemented as will be described in further detail below.

Each of the photodiodes 38 provides an output signal 40 connected to a control 42. Control 42 may operate in one or more of a plurality of modes to extract a control signal for laser 12. The control signal 44 may be used to control the movement to the laser 12 relative to the work piece 16 or the operation of the laser 12 as it moves over the work piece. The laser 12 is moveable along mutually perpendicular axes x, y, z relative to the work piece 16 to permit the beam 14 to follow the desired path.

As can best be seen from figure 4, the beam 14 impinges on the surfaces of components 18, 20 and produces a weld pool 50. As the beam 14 moves along in a direction parallel to the edges 22, 24 it progressively melts the edges which then solidify to weld the two components 18, 20 to one another. Control of the beam 14 is provided by the monitoring assembly 26 in conjunction with the control 42.

The optical head 28 focuses the fibers 36 to respective discreet locations (indicated as 37a,37b,37c,37d) adjacent to or within the weld pool 50. As illustrated in figure 4, one of the fibers 36a is focused in advance of the pool 50 at 37a and another, 36b, focused behind the pool 50 at 37b. The two other fibers 36c and 36d respectively are focused on opposite sides of the pool 50 at 37c and 37d respectively. The respective photodiodes 38 will therefore receive information from the plume, the pool itself and regions surrounding the weld pool and may use that information to provide control signals to the control 42. Typically the information received will relate to the intensity of the emissions at the pool 50 and this information may be refined by providing appropriate filters to select specific wave lengths of radiation for transmission to the photodiode 38 or by selecting a photodiode with specific response characteristics. As well as controlling the movement of the head, the control signals 40 are used to monitor the efficacy of the laser processing.

As can be seen in figures 5 and 6 two different signals are extracted from the detected emissions, namely a UV signal indicated (x) and an IR signal indicated (y).

Preferably, the signals received from a pair of fibers, e.g. 36a,36b, are used to provide respective signals. A signal received from the plume would typically have a stable UV content and a signal from the pool would have a stable IR content. By selecting signals from different locations, stable signals can be obtained for each selected parameter. A single fiber may be used for monitoring both parameters but in this case it is advantageous to time shift(s) the sampling intervals for each parameter so that separate events are monitored. Where two fibers are used a time shift is not necessary although may be incorporated if desired.

$$\{x_I\} = \{x_1, x_2, \ldots, x_n\} \quad \text{and}$$
$$\{y_I\} = \{y_1, y_2, \ldots, y_n\}$$

are the two sets of data representing UV and IR radiations respectively either from one of the fibers 36 or from a pair of fibers. These data are collected in a time interval t→t+Δt. $x_o$ and $y_o$ are the mean values of these two set of data such that

$$x_0 = \frac{1}{n}\sum_i^n x_i$$

$$y_0 = \frac{1}{n}\sum_i^n y_i$$

For any sample i $x_i = x_0 + \Delta x_i$

$$y_i = y_0 + \Delta y_i$$

Where the $\Delta x_i$ and $\Delta y_i$ are fluctuations around the mean value. A normalized coefficient is

$$\eta = \frac{\sum_{i=0}^{n-s} x_i y_{i+s}}{\left(\sum_{i=0}^{n-s} \cdot x_i^2 \sum_{i=s}^{n} y_i^2\right)^{1/2}}$$

defined as

in which $s$ is the correlation length i.e. the number of samples corresponding to the offset or time shift of the signals. The summation terms in the above expression can be written as

$$\sum_{i=0}^{n-s} x_i y_{i+s} = \sum_{i=0}^{n-s} (x_0 + \Delta x_i)(y_0 + \Delta y_{i+s}) = (n-s)x_0 y_0 + \sum_{i=0}^{n-s} \Delta x_i \Delta y_{i+s}$$

$$\sum_{i=0}^{n-s} x_i^{\;2} = \sum_{i=0}^{n-s} (x_0 + \Delta x_i)^2 = (n-s)x_0^{\;2} + \sum_{i=0}^{n-s} \Delta x_i^{\;2}$$

$$\sum_{i=s}^{n} y_i^{\;2} = \sum_{i=s}^{n} (y_0 + \Delta y_i)^2 = (n-s)y_0^{\;2} + \sum_{i=s}^{n} \Delta y_i^{\;2}$$

The coefficient η can therefore be expressed as

$$\eta = \frac{1+\alpha}{(1+\beta)^{1/2}(1+\gamma)^{1/2}}$$

Where

$$\alpha = \frac{\sum_{i=0}^{n-s} \Delta x_i \Delta y_{i+s}}{(n-s)x_0 y_0}$$

$$\beta = \frac{\sum_{i=0}^{n-s} \Delta x^2{}_i}{(n-s)x_0^{\;2}}$$

and

$$\gamma = \frac{\sum_{i=s}^{n} \Delta y_i^{\;2}}{(n-s)y_0^{\;2}}$$

For smooth deep penetration welding process, plasma radiation has a regular dynamic fluctuation and the signals have a mean value larger than the fluctuation amplitude. For this reason, the values of α, β and γ are very small. Thus the coefficient η can be simplified as

$$\eta = (1+\alpha)\left(1-\frac{\beta}{2}\right)\left(1-\frac{\gamma}{2}\right) = 1-\delta$$

Where

$$\delta = \frac{\beta+\gamma}{2} - \alpha$$

For plasma emission, $\alpha$ is very small (close to zero) due to the chaotic fluctuation. Thus $\delta > 0$.

It will be noted that $\alpha$, $\beta$ and $\gamma$ indicate the deviation of individual samples from the average of the whole set of samples to provide the coefficient $\eta$. The greater the deviation and more prolonged the deviation, the greater the value of $\delta$.

If the welding process goes smoothly, the correlation coefficient $\eta$ is close to 1. If the absolute values of the measured emissions vary progressively, as may be expected with a satisfactory weld process, the values of $\Delta x_i$ and $\Delta y_i$ would vary only slightly relative to the mean $x_0$, $y_0$. Accordingly, the coefficient $\eta$ would remain close to 1.

However, when disturbance occurs, large spikes or an extremely low signal would be detected. Some of the $\Delta x_i$ or $\Delta y_i$ become large, so that $\beta$ and $\gamma$ could be a large value compared to $x_0$ and $y_0$. In this event, the value, $\beta$ and $\gamma$ are significant and therefore the value of the coefficient drops considerably. Larger disturbances or significant transient conditions, therefore, cause a bigger drop in $\eta$ value. In this way, $\eta$ can be used to indicate various weld faults, from surface roughness or ripples to pinholes and a failed weld.

Several weld trials were performed to make a butt joint of dissimilar steel sheets in a simulation of tailored blank welding. In order to test the algorithm developed above, both good welds and bad welds were produced. For bad welds, various kinds of weld faults were introduced by means of filing the seam edge or making a mechanical gap in the butt fitting. In each example, two sheets of galvanized steel were arranged with edges butting. One sheet was 1 mm thick and one was 1.6 mm thick. In those experiments, the welding speed was kept at the value with which full penetration is achieved. Good welds were judged by a smooth, uniform weld bead. Unacceptable welds were defined as welds with rough bead, ripples and pinholes or with a large concave. In the extreme case, when the gap between sheets is too big, the weld completely failed.

The optical emission signal data were collected and the coefficient $\eta$ calculated as described above. The results are presented in Figures 7 – 12.

Referring therefore to figure 7, the edges of the sheets were maintained in abutment to obtain optimum welding conditions. The trace of coefficient $\eta$ is shown for a good weld having a smooth bead. It will be noted that coefficient $\eta$ remains reasonably constant, >0.9.

In a second test, the sheets were arranged with the adjacent edges progressively diverging as illustrated schematically in figure 8a. Initially the weld was satisfactory but as the gap increased the weld broke down. The trace in figure 8b indicates that the coefficient $\eta$

is initially maintained above 0.9 but as the gap widens the coefficient becomes more erratic with values in the order of 0.6 to 0.8.

A third sample was arranged with a gap at each end of the seam as shown schematically in figure 9a. Initially, as seen from the trace in figure 9b, the coefficient $\eta$ has a low value as the weld is unstable but attains values greater than 0.9 in the zone where the sheets abut. As the gap increases, a degradation of the weld zone occurs and the coefficient $\eta$ again reduces to values of 0.6 to 0.8.

In a fourth test, shown in figure 10, pinholes were replicated by filing nicks in the edge at specific locations. The location of the pinholes is clearly identifiable on the trace of figure 10(b) by the reduction of the value of the coefficient $\eta$ to as low as 0.4. Between the pinholes, a stable weld is attained.

The distinction between pinholes and an increased gap is readily seen in figure 11. The location of the pinhole is clearly identified with the spike reduction to 0.4 but the value of $\eta$ becomes less consistent with values below 0.8 as the weld zone becomes less stable.

In the arrangement of figure 12, a gap was enlarged at one end, as shown in figure 12a. The trace in figure 12b shows a stable value followed by a breakdown in welding as the beam encounters the gap. The beam established small bridges along the seam providing an increased value of the coefficient $\eta$ but still in the 0.4 to 0.8 range rather than a stable value above 0.9.

From the above samples, it will be appreciated that a consistent indication of potential faults or unsatisfactory weld conditions can be obtained from the value of the coefficient $\eta$.

It can be seen that for smooth, good weld, the correlation coefficient is in the range of 0.9 to 1. When a potential weld fault occurs, the value $\eta$ has a significant change. Pinholes correspond to sharp spikes in the coefficient; surface roughness and ripples provide an $\eta$ value in the range of 0.6 ~0.85 whereas a deep drop in the value of $\eta$ indicates welds with a large concave. When $\eta$ is close to zero, the weld is completely failed. Therefore, $\Delta\eta = 1 - \eta$ may be taken to be representative of the degree of weld fault.

The value of the coefficient $\eta$ may be used in a number of ways. Firstly, a value of $\eta$ below a certain value may be used as a flag to indicate that a welded component may need further inspection. Because the signal is correlated to time, the position of the potential flaw may be located on the component and a visual inspection made. If the flaw is acceptable or occurs in an area of the component that may subsequently be removed then the component could be used. Otherwise the component is rejected.

Alternatively, the value of coefficient η may be utilized as an error signal in a closed loop control for laser 12. It will be noted that the tests above were conducted under constant weld parameters. The value of the coefficient may be used to control the speed of the weld head along the seam so that as, for example, the gap widens, the speed reduces to maintain a satisfactory weld.

As a further alternative, the value of the coefficient η may be used as an input to a fuzzy logic control, as exemplified in the above US patent with an appropriate rule set developed on the basis of observed characteristics.

By using correlation coefficient η to describe the welds, a simple and effective indication of weld quality is obtained. Furthermore, the description of coefficient η is universal and is not affected by different systems parameters such as laser power on achievable welding speed. It is also not affected by the gain of the signal detection device. As a further advantage no precise optical alignment is required for the detecting system.

Although the invention has been described with reference to certain specific embodiments, various modifications thereof will be apparent to those skilled in the art without departing from the spirit and scope of the invention as outlined in the claims appended hereto.

# THE EMBODIMENTS OF THE INVENTION IN WHICH AN EXCLUSIVE PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:

1. A method for detecting a change in a processing characteristic of a melt zone provided on a work piece by a laser beam of a laser processing apparatus comprising the steps of:
monitoring an emission from said weld zone to obtain a set of samples of said emission over a predetermined time period; averaging said set of samples to produce an average value; monitoring fluctuations in said emission; and comparing said fluctuations to said average value for generating a quantity representative of variability in said processing characteristic.
2. A method according to claim 1 further comprising the step of comparing a pair of said emissions for producing said set of samples.
3. A method according to claim 1, wherein said emission comprises a UV emission.
4. A method according to claim 1, wherein said emission comprises a IR emission.
5. A method according to claim 1 further comprising the step of identifying a position of a change in said processing characteristic along a work piece due to a variation in said quantity greater than said predetermined range.
6. A method according to claim 5 further comprising the step of signaling a further inspection of a processed work piece due to variation in said quantity.
7. A method according to claim 1 further comprising the step of utilizing said quantity to provide a feed back control signal in said laser processing apparatus.
8. A method according to claim 7 wherein said apparatus is adjusted by said feedback control signal to maintain said quantity at a predetermined value.
9. A method according to claim 8 wherein said feed back control signal is used to control relative movement between said beam and said work piece.
10. The method according to claim 1, wherein said quantity represents a quality of said melt zone.
11. A method according to any one of claims 1 to 10 further comprising the step of controlling translation of said laser beam relative to said workpiece along a predetermined path in response to variations of said quantity.
12. A method according to claim 11 further comprising the step of comparing emissions received from a pair of locations disposed in a spaced relationship along said path and

adjusting said beam to maintain said emissions in a predetermined ratio and thereby maintain a focus of said beam on said workpiece.

13. A method according to claim 12 further comprising the step of monitoring said quantity and adjusting said beam to maintain said quantity at a predetermined value.

14. A method according to anyone of claims 1 to 11 comprising the step of obtaining a pair of emissions and generating a coefficient from said pair of emissions such that a deviation from said average for both of said emissions produces a corresponding deviation in said coefficient.

15. A method according to claim 14 wherein said coefficient is of the form

$$\eta = \frac{\sum_{i=0}^{n-s} x_i y_{i+s}}{\left( \sum_{i=0}^{n-s} x_i^2 \sum_{i=s}^{n} y_i^2 \right)^{1/2}}$$

where $x_i$ is an instantaneous measurement of said UV emission at one of said locations,

$y_{i+s}$ is an instantaneous measurement of said IR emission at a second of said locations separate from said one,

s is a correlation length, and

n is a total number of said samples in said set of samples.

16. A method according to claim 15 wherein said samples are obtained from two spatially separated locations.

17. A method according to claim 15 wherein said samples are temporally separated.

18. A method for monitoring a laser process in which a laser beam impinges upon a workpiece at a melt zone, said method comprising the steps of monitoring a pair of emissions of different characteristics, combining said characteristics to obtain a quantity indicative of the variability in said laser processing and controlling movement of said beam relative to said workpiece to maintain said quantity within a predetermined range.

19. A method according to claim 18 wherein a set of samples of said emissions is obtained and an average of each of said emissions is obtained therefrom, variations in said emissions being compared with said average to determine fluctuations thereof.

20. A method according to claim 19 wherein said emissions are combined to provide a coefficient from said pair of emissions such that a deviation from said average for both of emissions produces a corresponding deviation in said coefficient.

21. A method according to claim 20 wherein said coefficient is of the form

$$\eta = \frac{\sum_{i=0}^{n-s} x_i y_{i+s}}{\left( \sum_{i=0}^{n-s} x_i^2 \sum_{i=s}^{n} y_i^2 \right)^{1/2}}$$

where $x_i$ is an instantaneous measurement of said UV emission at one of said locations,

$y_{i+s}$ is an instantaneous measurement of said IR emission at a second of said locations separate from said one,

s is a correlation length, and

n is a total number of said samples in said set of samples.

22. A method according to anyone of claims 18 to 21 wherein said emissions are selected to provide an indication of the focus of said beam relative to said workpiece.

23. A method according to any one of claims 18 to 21 wherein said emissions are selected to provide an indication of the lateral position of said beam to a predetermined path of the beam along said workpiece.

24. A method according to any one of claims 18 to 21 wherein said emissions are selected to provide an indication of the extent of the melt zone.

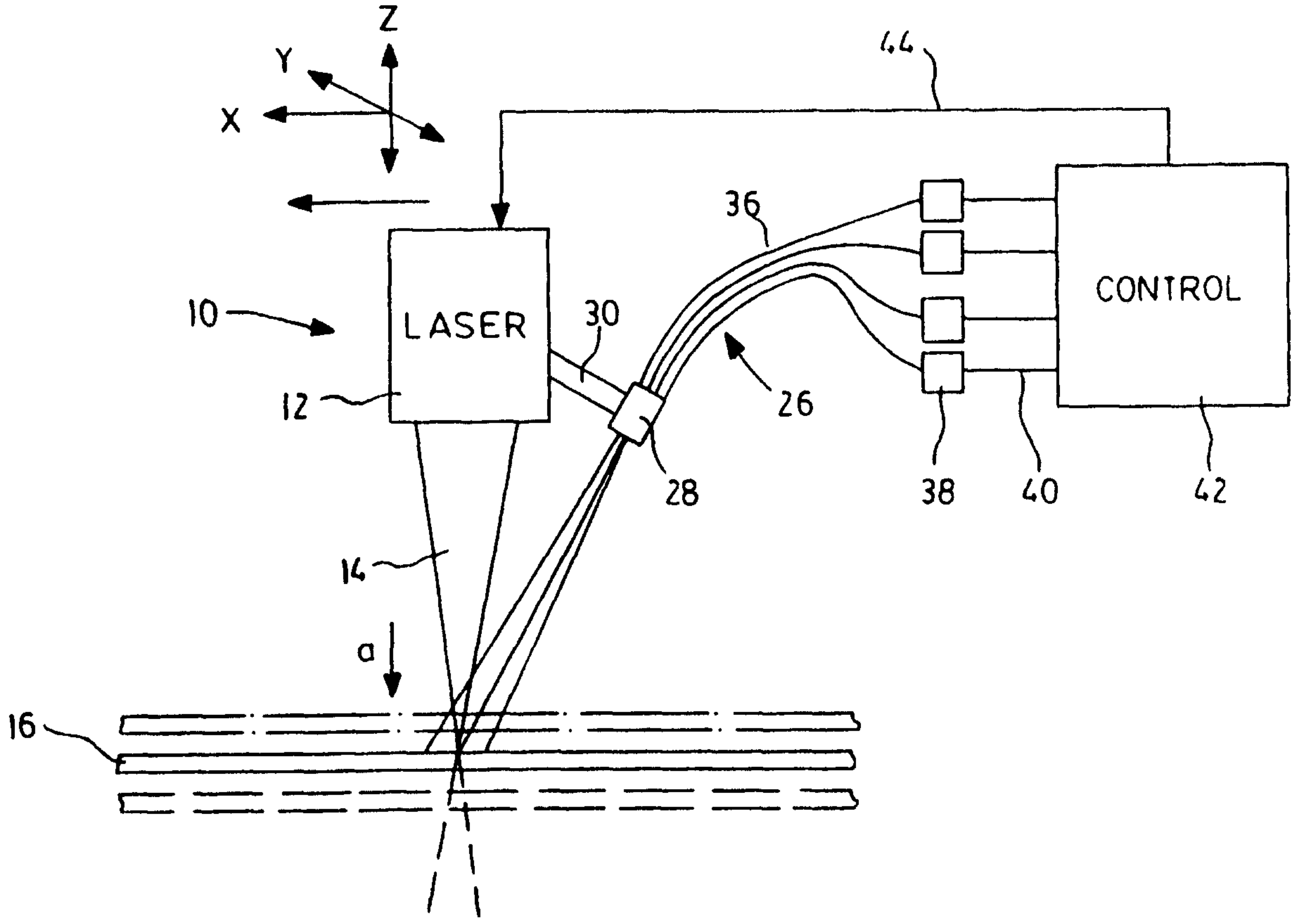


FIG. 1

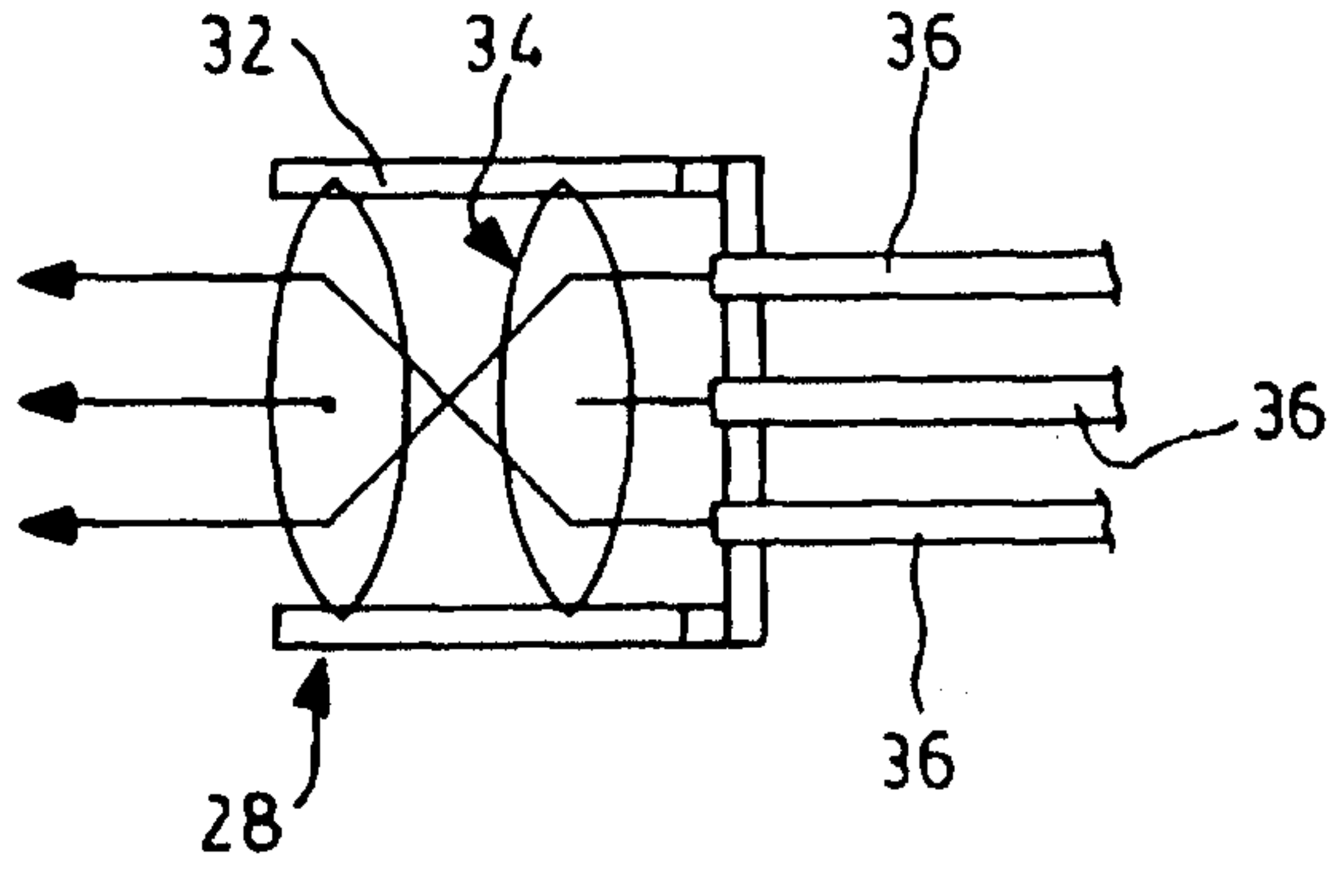


FIG. 3

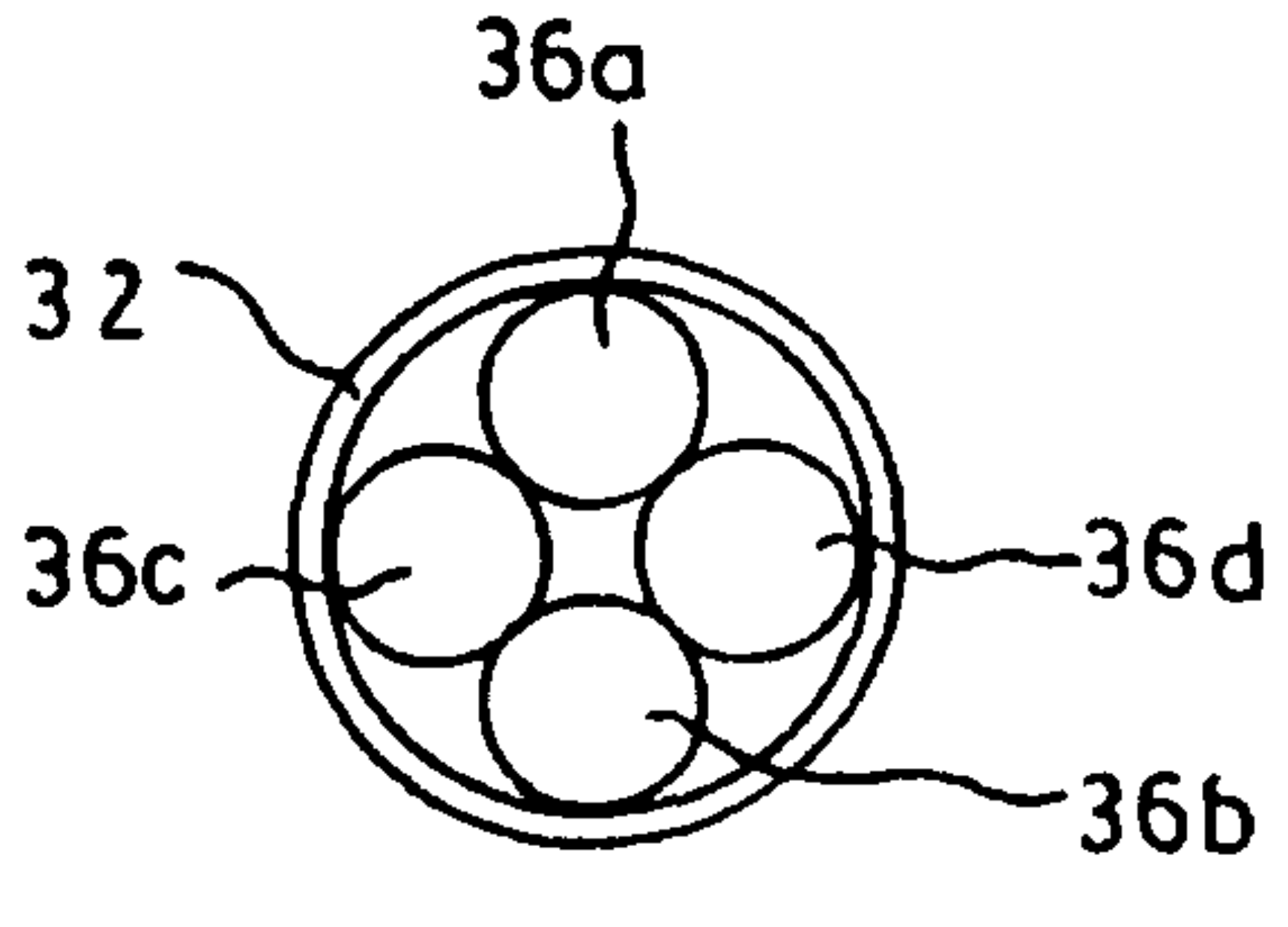


FIG. 2

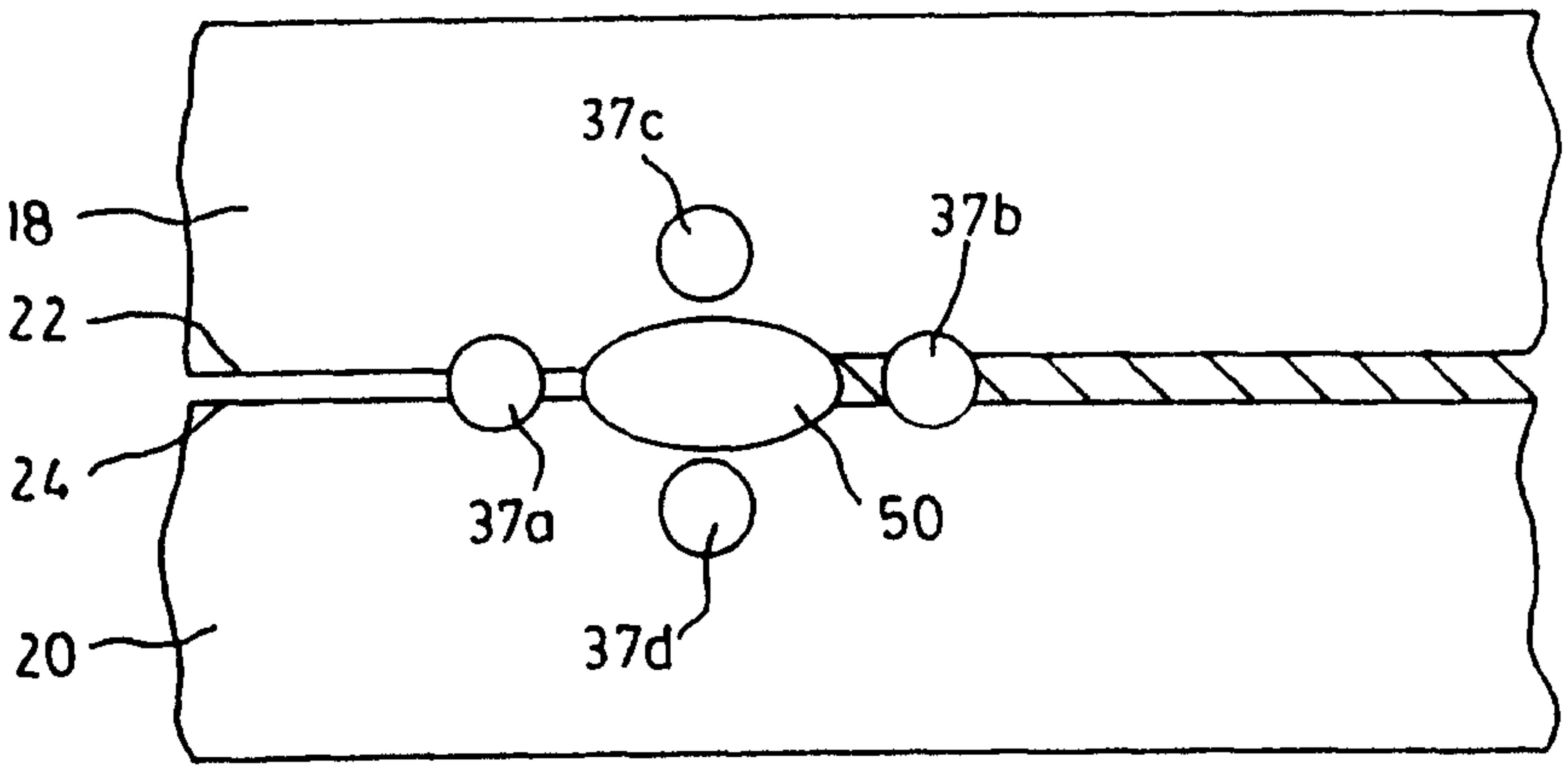


FIG. 4

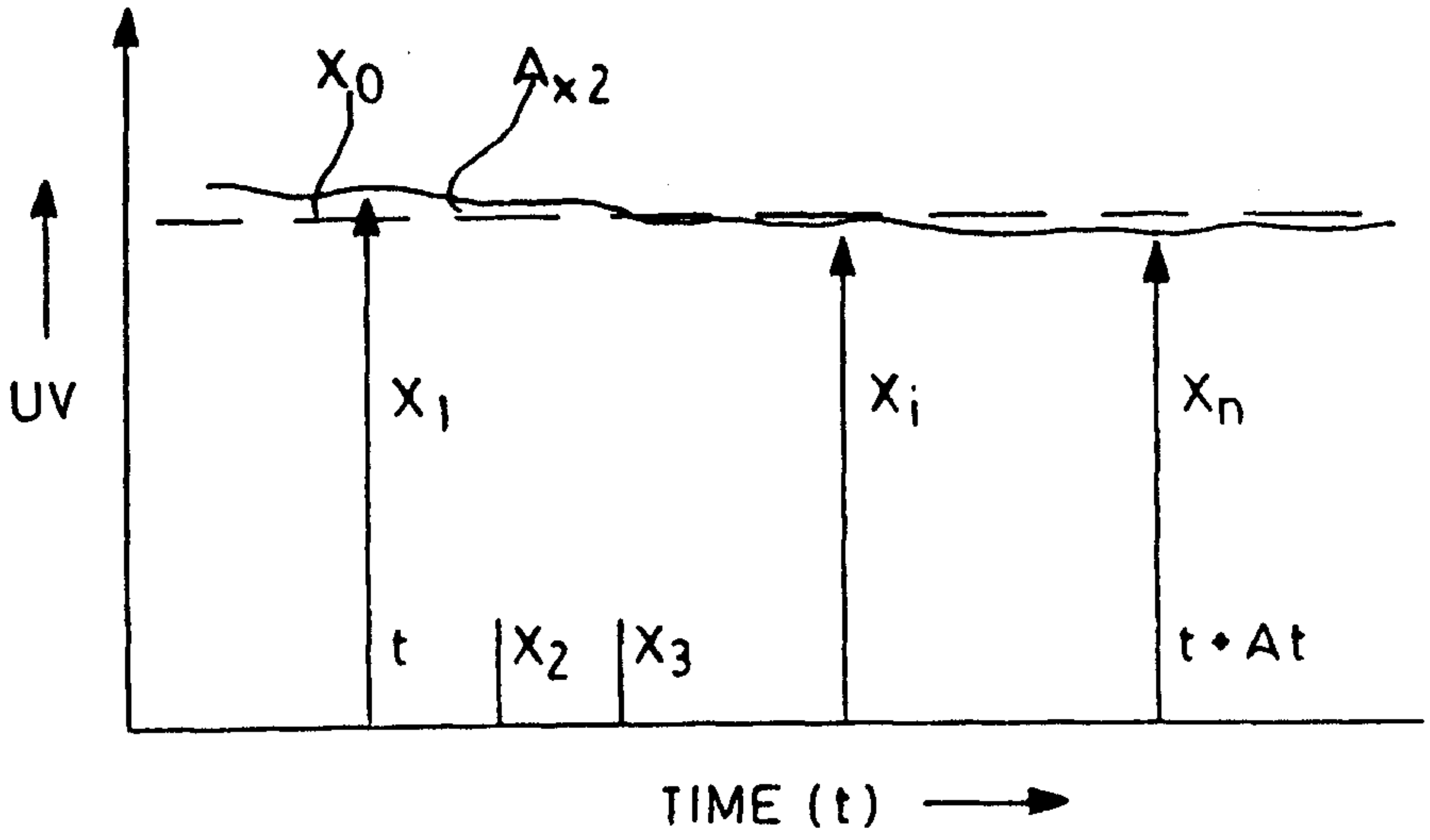


FIG. 5

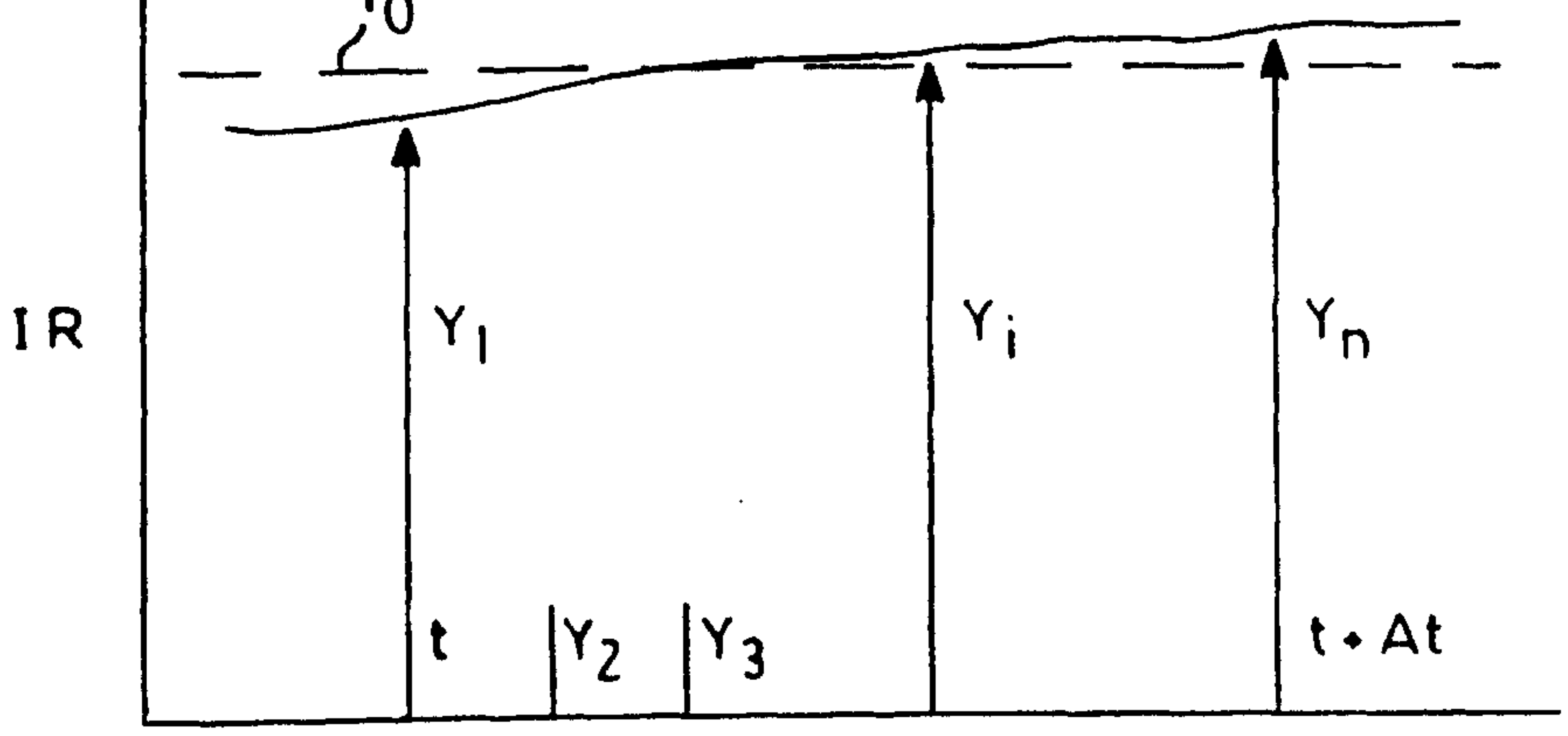


FIG. 6

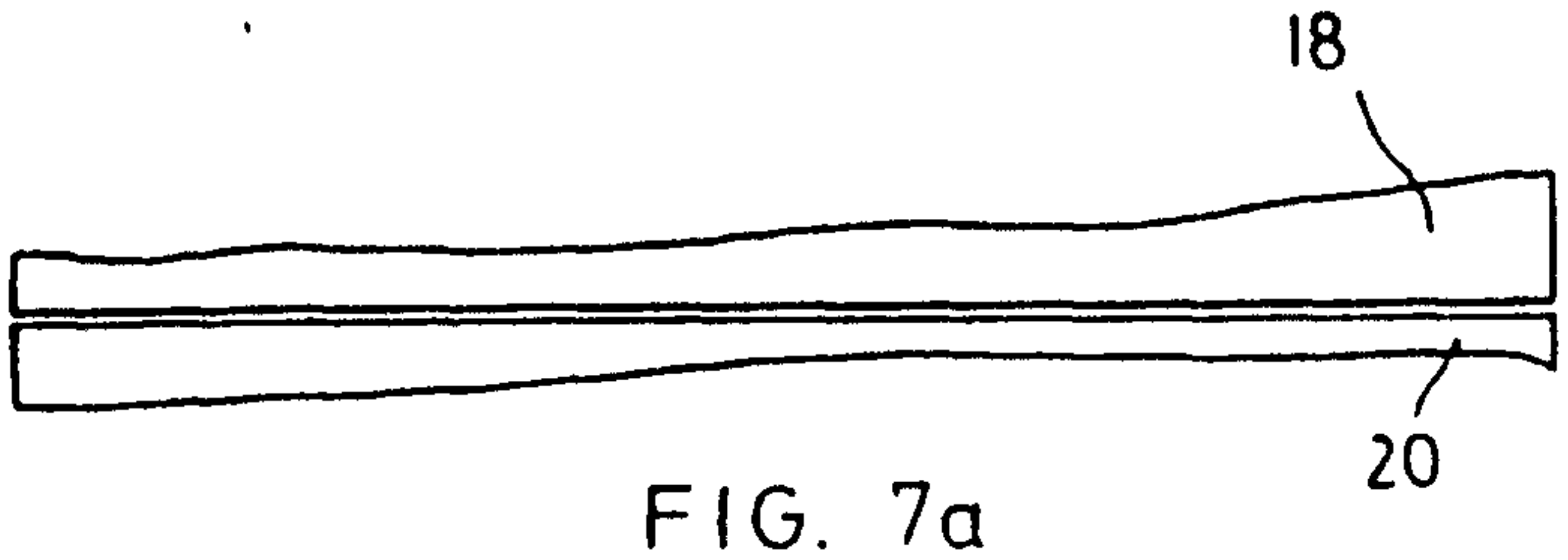


FIG. 7a

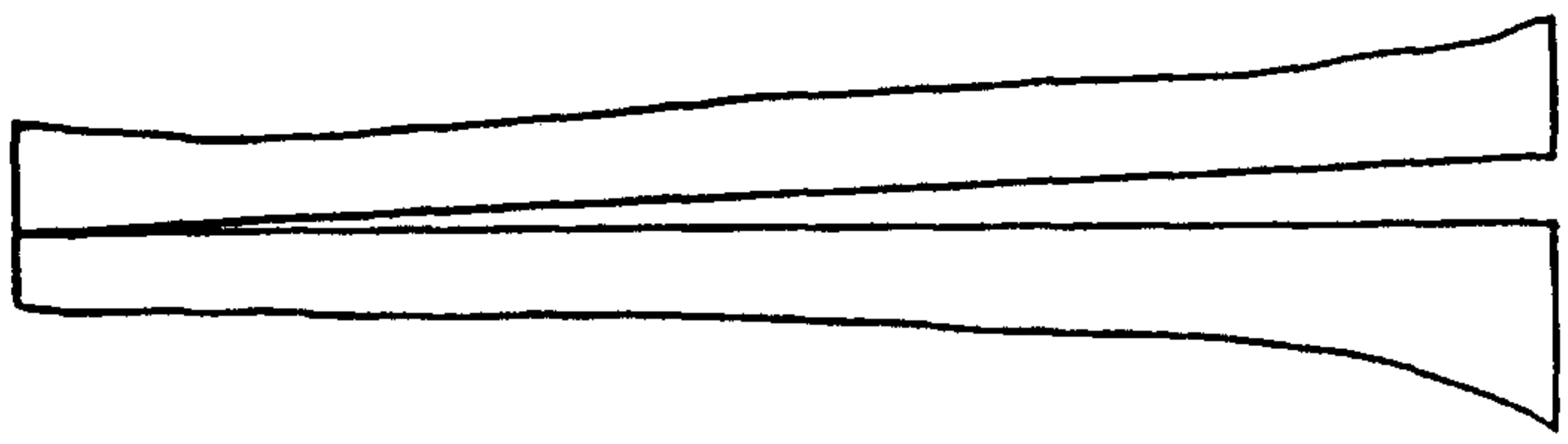


FIG. 8a

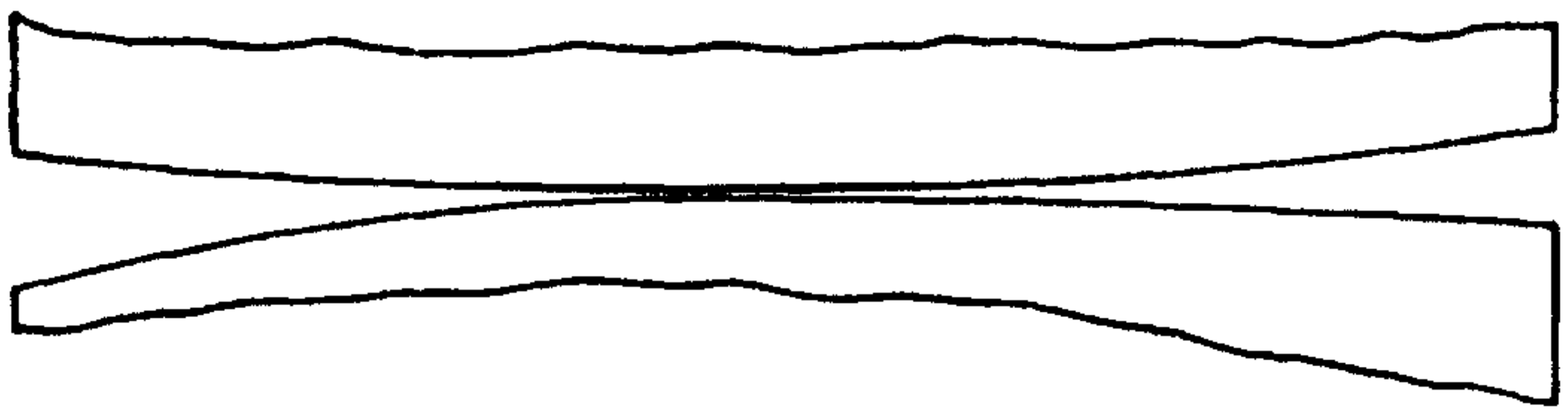


FIG. 9a

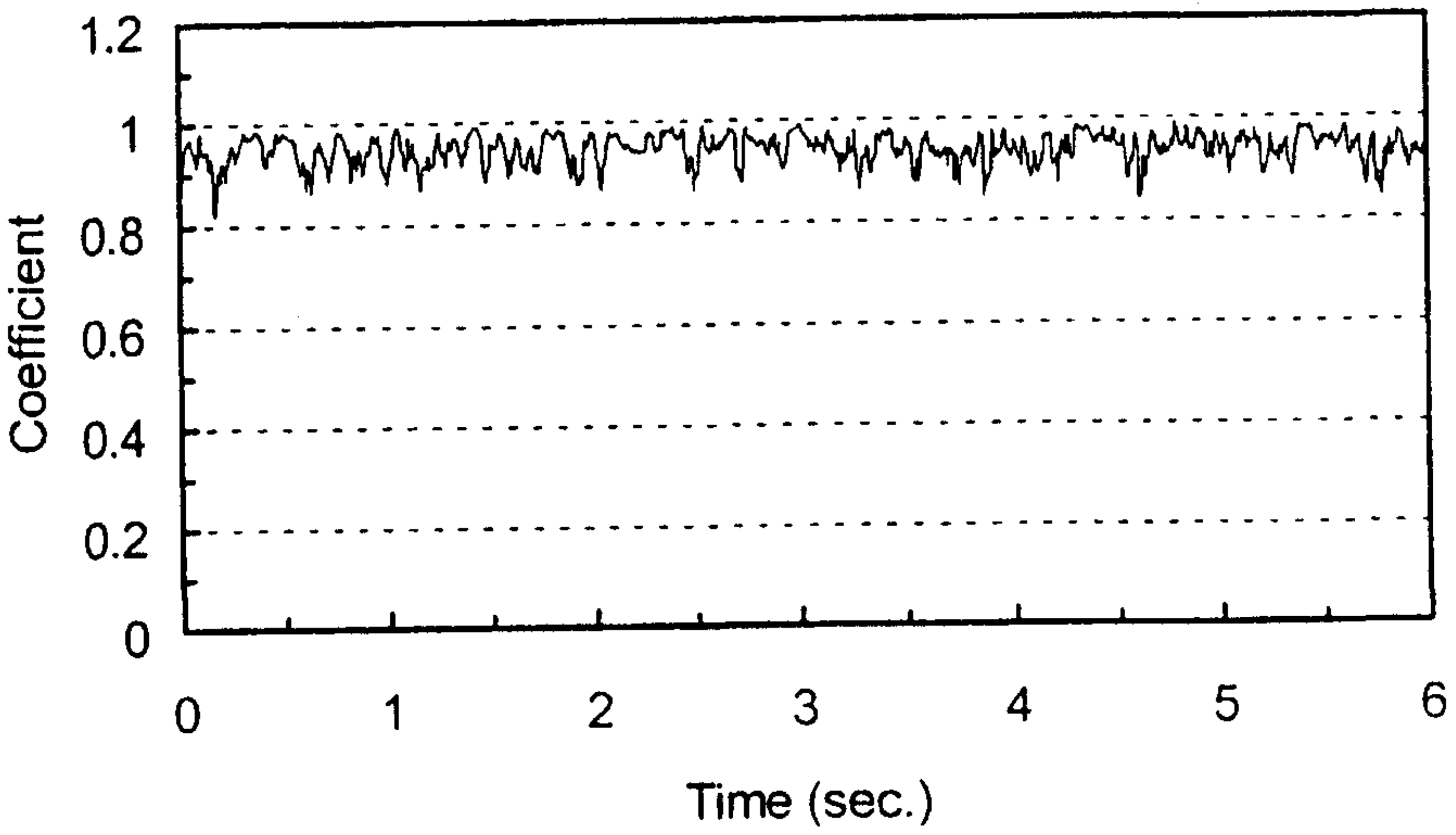


Fig.7(b)

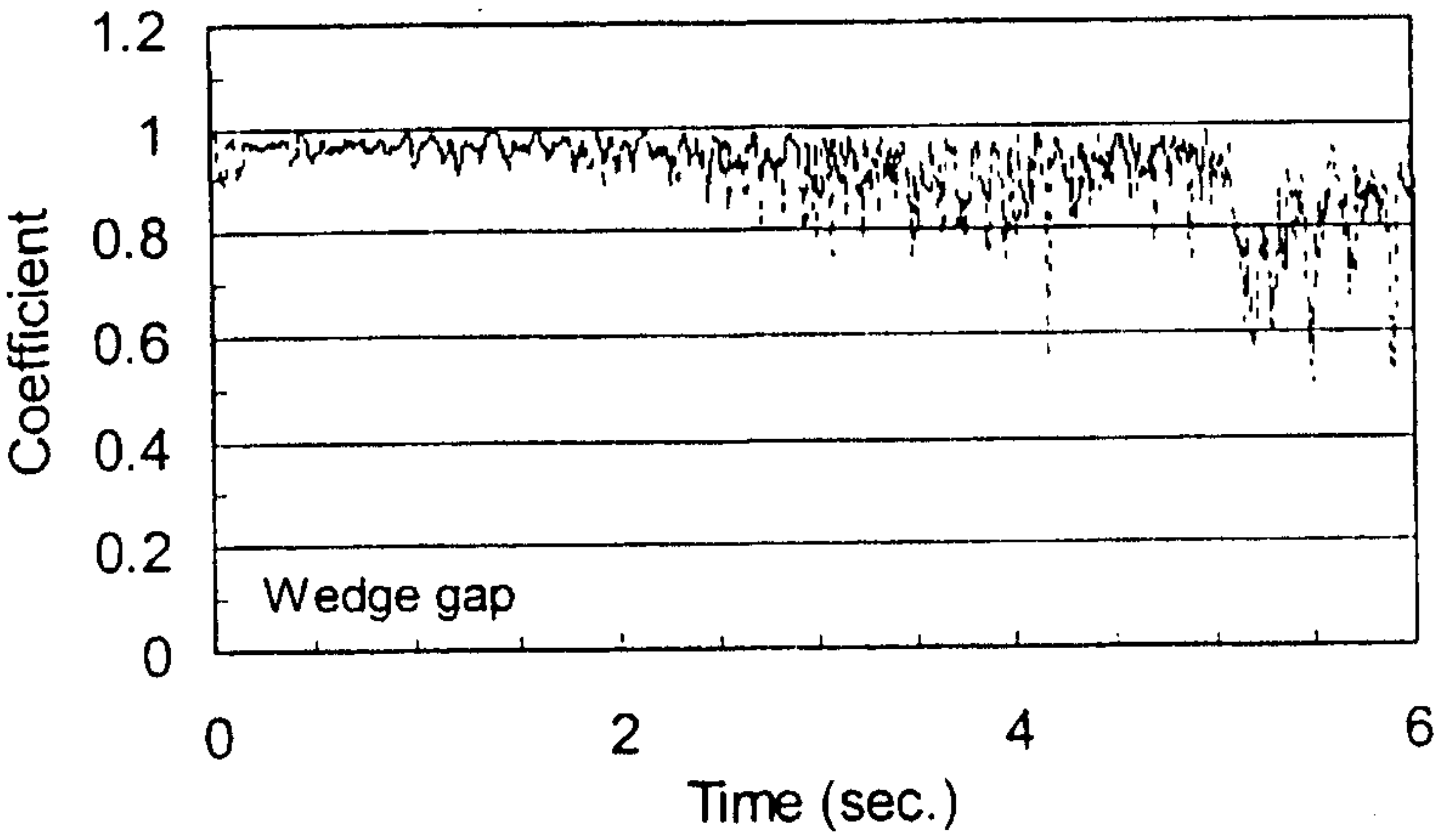


Fig.8(b)

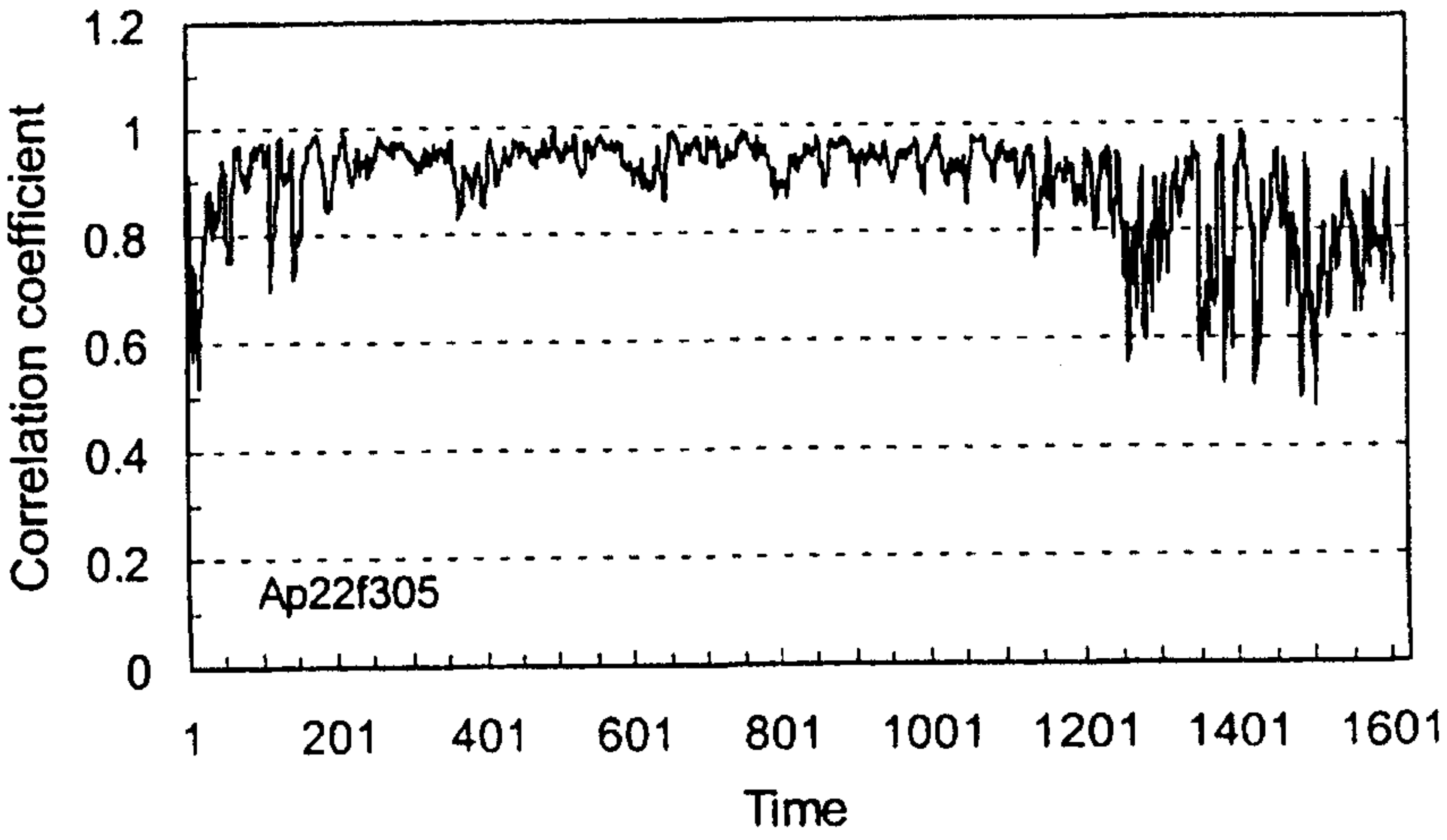

1.2
1
0.8
0.6
0.4
0.2
0
Correlation coefficient
Ap22f305
1
201
401
601
801
1001
1201
1401
1601
Time

Fig. 9b

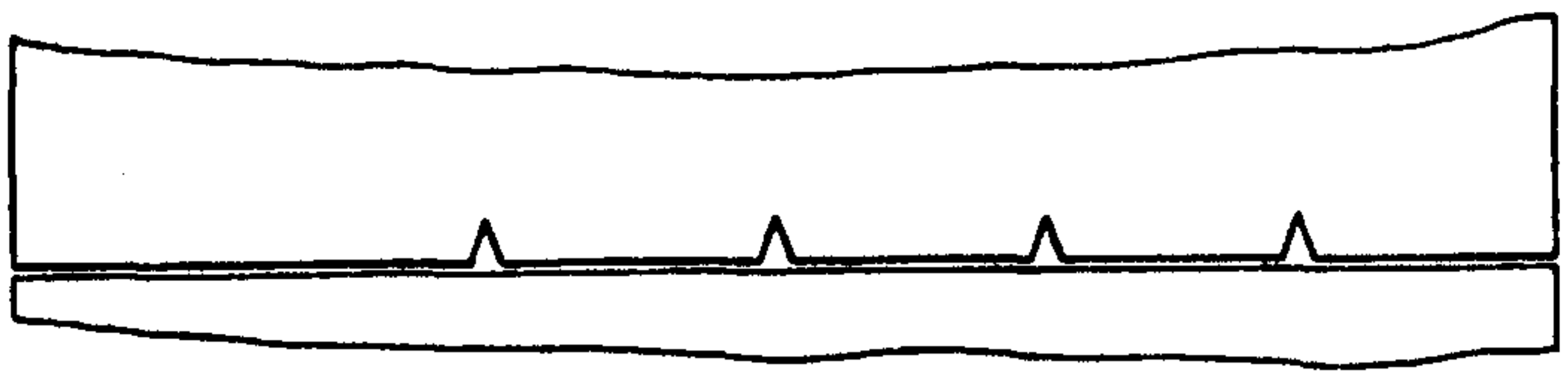


FIG. 10a

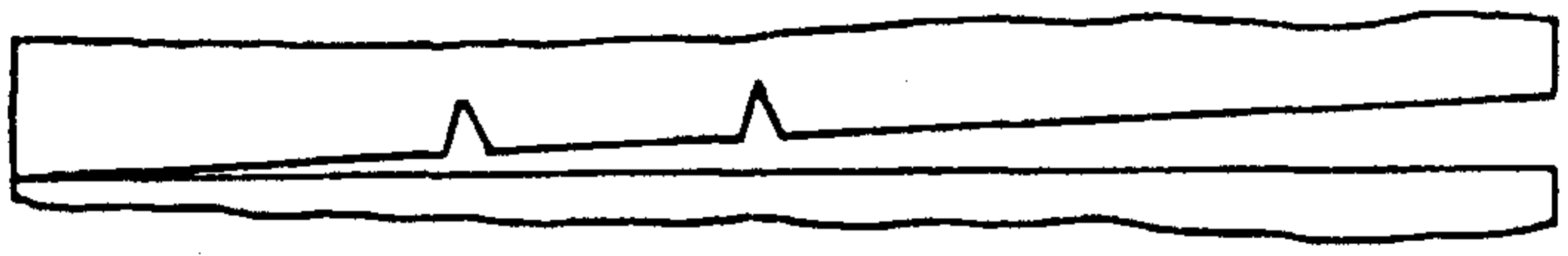


FIG. 11a

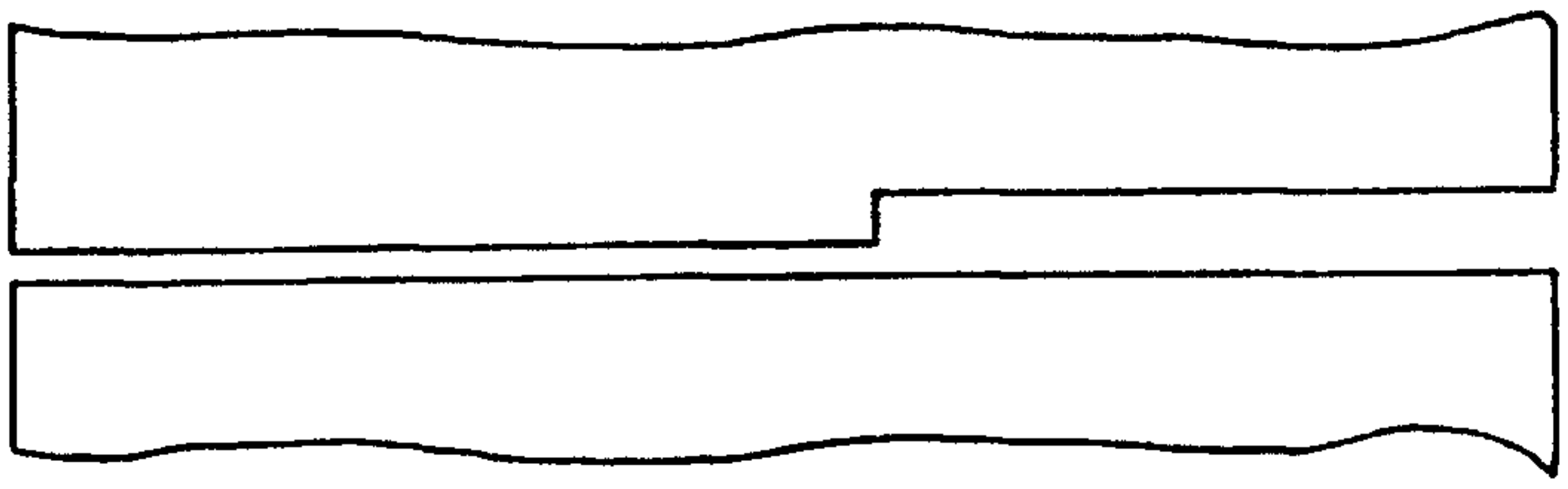


FIG. 12a

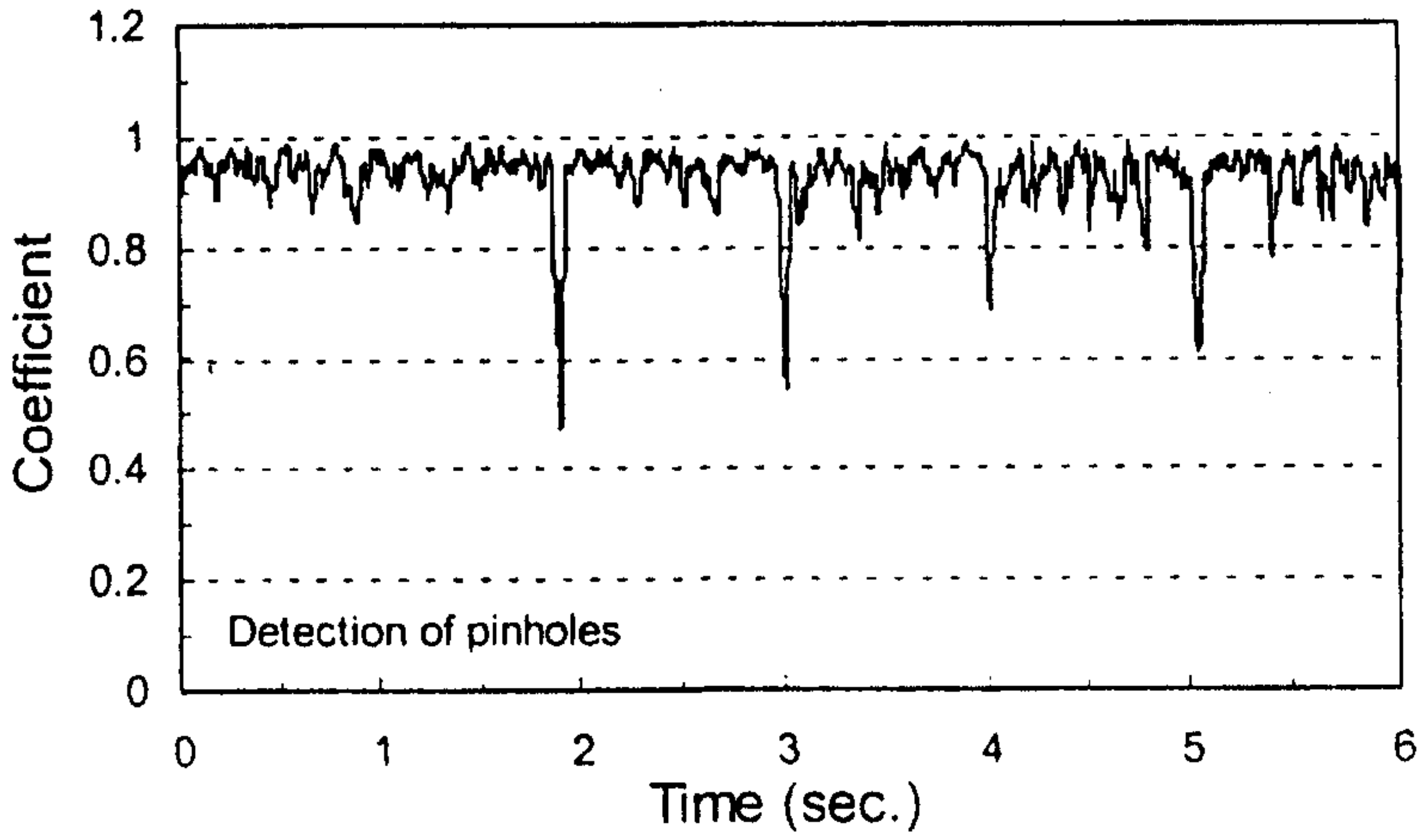

1.2
1
0.8
0.6
0.4
0.2
0
Coefficient
Detection of pinholes
0
1
2
3
4
5
6
Time (sec.)

Fig.10(b)

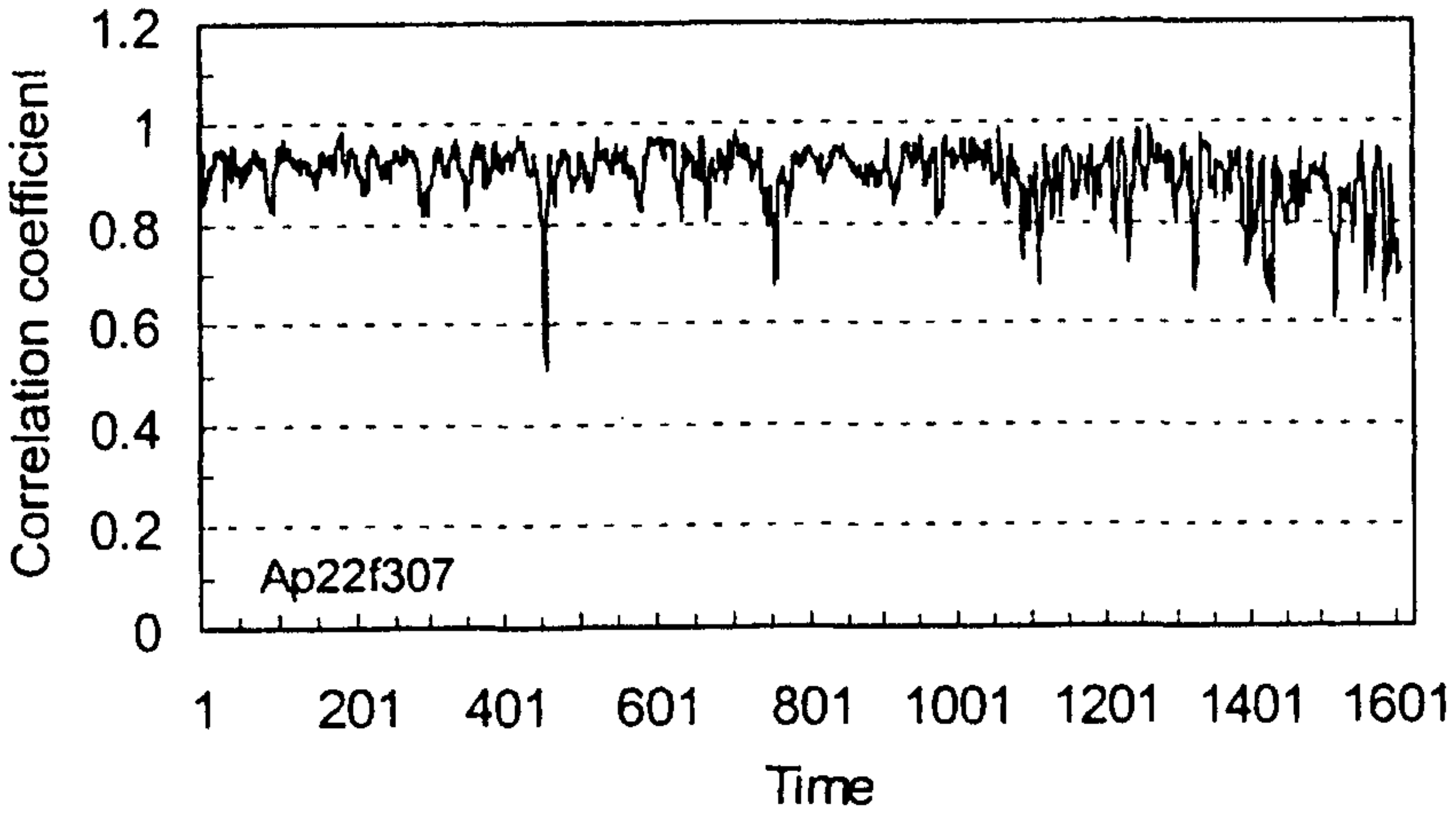

1.2
1
0.8
0.6
0.4
0.2
0
Correlation coefficient
Ap22f307
1
201
401
601
801
1001
1201
1401
1601
Time

Fig.11b

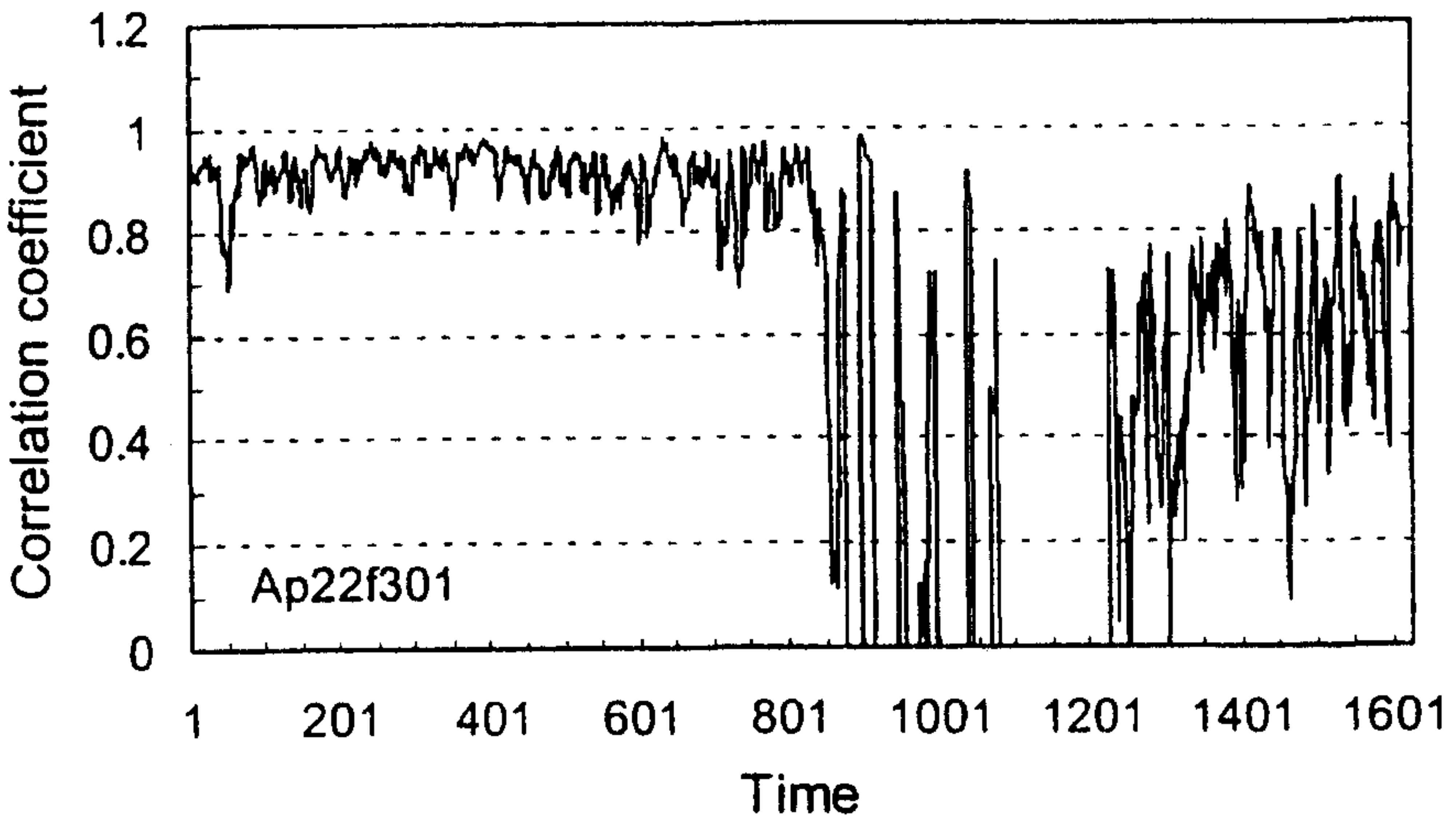
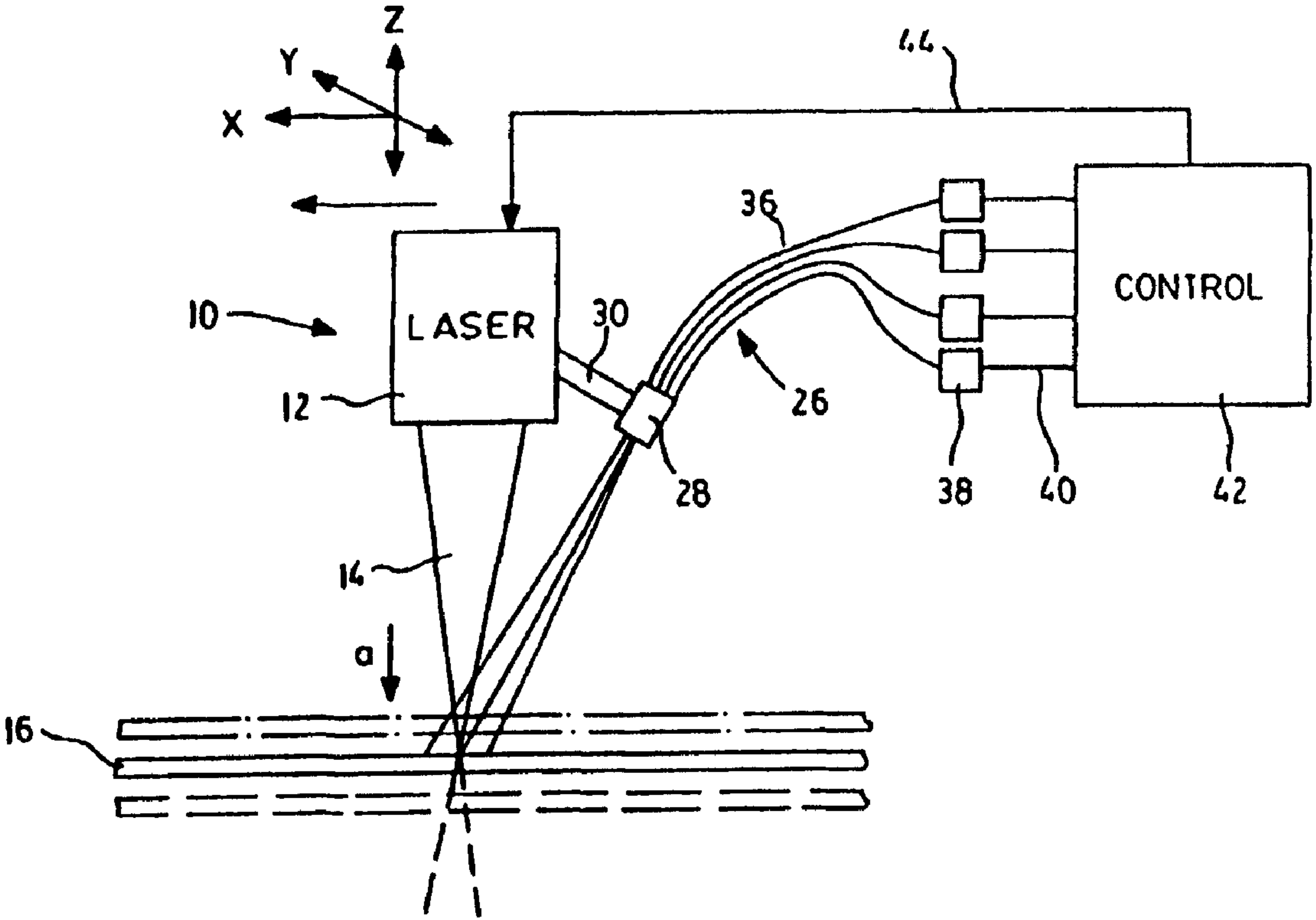

1.2
1
0.8
0.6
0.4
0.2
0
Correlation coefficient
Ap22f301
1
201
401
601
801
1001
1201
1401
1601
Time

Fig. 12b


Z
Y
X
44
36
CONTROL
10
LASER
30
12
26
28
38
40
42
14
a
16