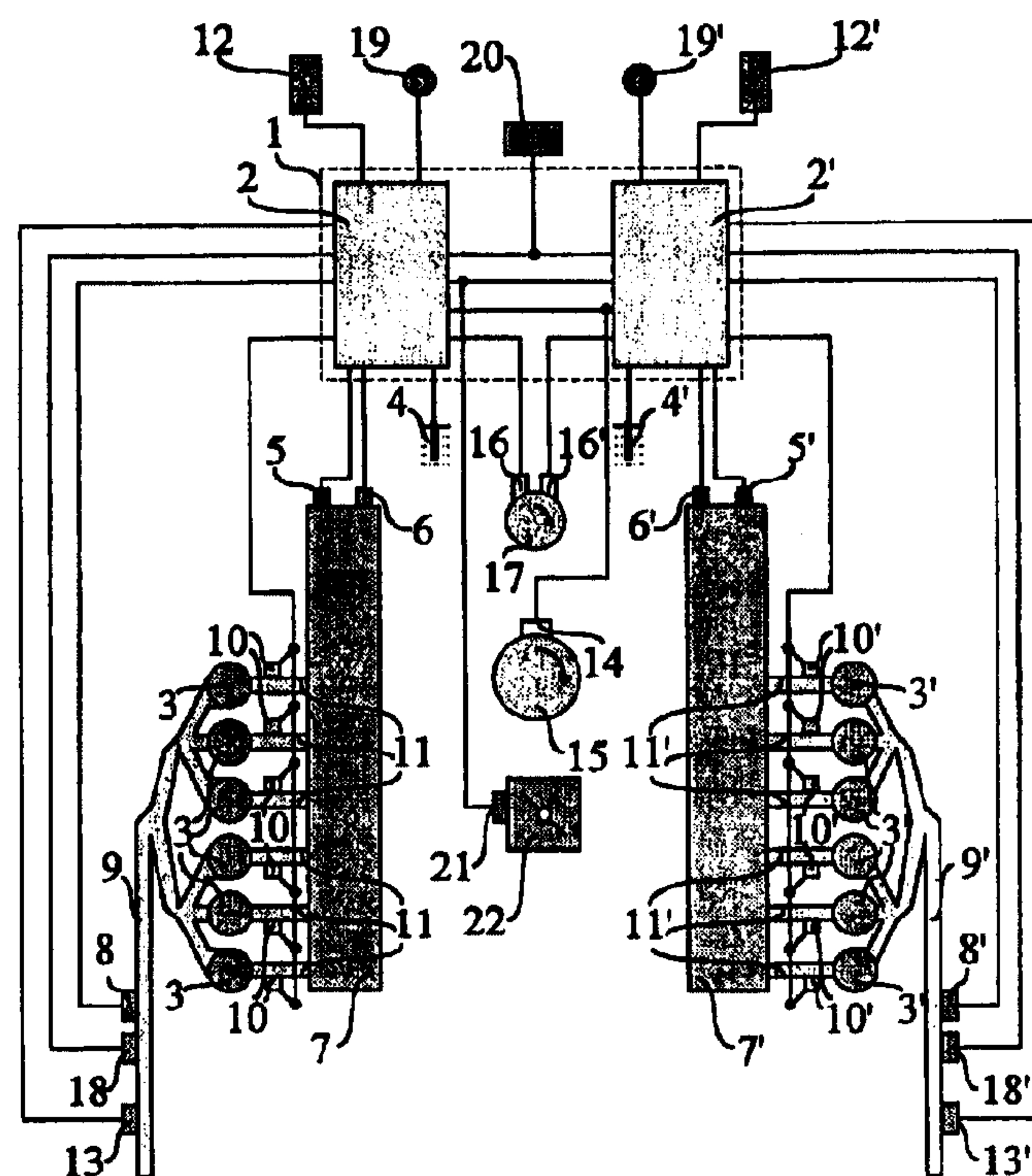




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(54) Titre : PROCEDE DE DETECTION D'UN RATE D'ALLUMAGE DANS UN MOTEUR A COMBUSTION INTERNE
(54) Title: PROCESS FOR DETECTING A MISFIRE IN AN INTERNAL COMBUSTION ENGINE AND SYSTEM FOR
CARRYING OUT SAID PROCESS



(57) Abrégé/Abstract:

A process for detecting a misfire in one or more cylinders (3, 3') of an internal combustion engine, including the following operative steps: sampling the exhaust gas pressure values during at least one engine cycle, the sampling frequency being proportional to the crankshaft rotational speed; analyzing the sampled signal in the frequency domain; calculating a misfire index as a function of the results of said analysis; comparing said index with one or more threshold values. Said frequency domain analysis preferably includes a Fourier transform of the sampled signal. The present invention also relates to a system carrying out said process.





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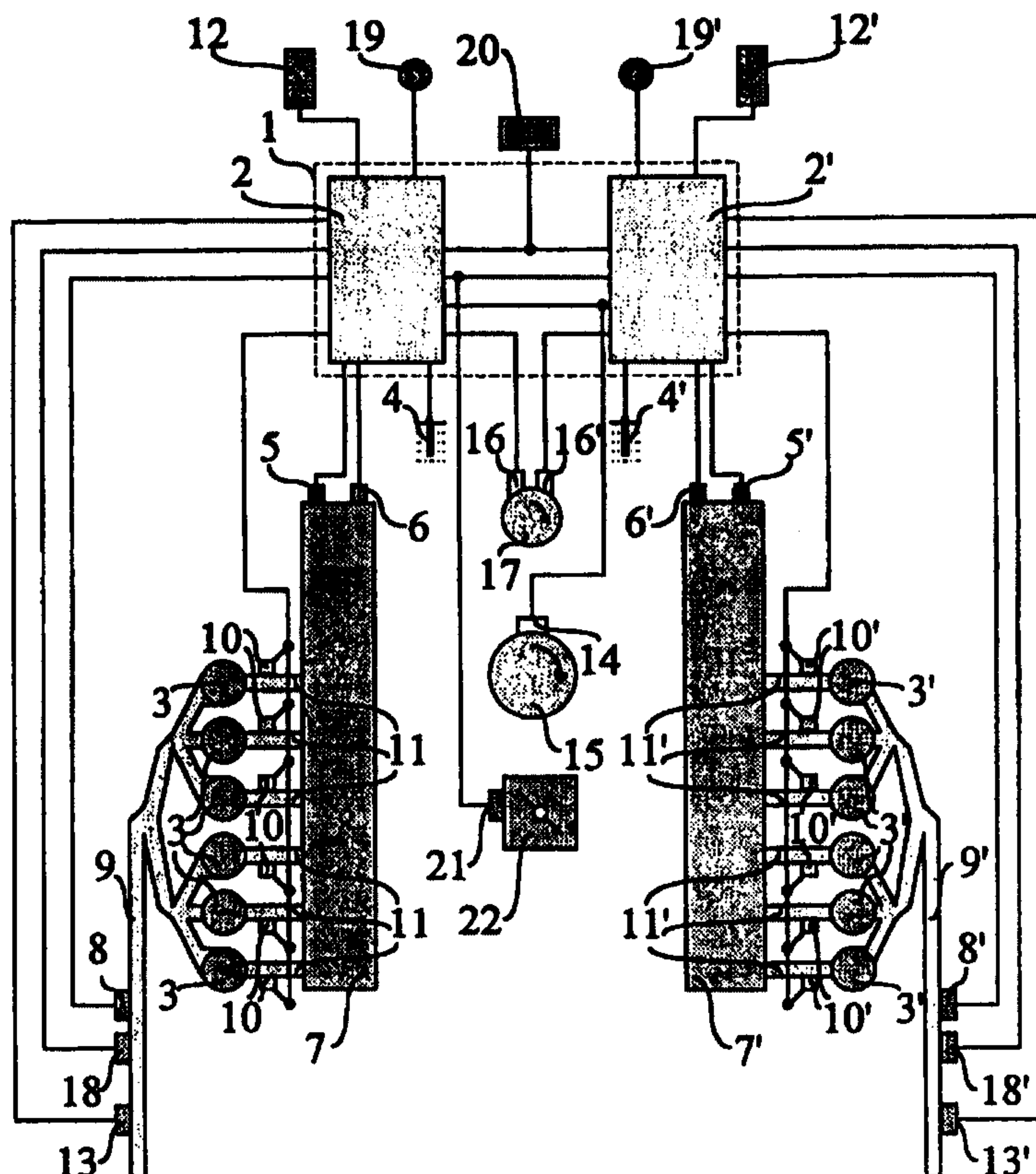
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(54) Title: PROCESS FOR DETECTING A MISFIRE IN AN INTERNAL COMBUSTION ENGINE AND SYSTEM FOR CARRYING OUT SAID PROCESS

(57) Abstract

A process for detecting a misfire in one or more cylinders (3, 3') of an internal combustion engine, including the following operative steps: sampling the exhaust gas pressure values during at least one engine cycle, the sampling frequency being proportional to the crankshaft rotational speed; analyzing the sampled signal in the frequency domain; calculating a misfire index as a function of the results of said analysis; comparing said index with one or more threshold values. Said frequency domain analysis preferably includes a Fourier transform of the sampled signal. The present invention also relates to a system carrying out said process.



“PROCESS FOR DETECTING A MISFIRE IN AN INTERNAL COMBUSTION
ENGINE AND SYSTEM FOR CARRYING OUT SAID PROCESS”

5 The present invention relates to a process for detecting a misfire in an internal combustion engine, and in particular a process which can be used for detecting a misfire in one or more cylinders of an internal combustion engine. The present invention also relates to a system for carrying out said process.

10 It is known that in order to monitor the performance of an internal combustion engine, in particular a racing engine with a high number of cylinders, it is desirable to detect the occurrence of the misfire of the fuel mixture in one or more cylinders. A process for carrying out said detection, which is known from US-5576963 and presently plays an important role with respect to the ever stricter rules for the control of polluting exhausts, consists of measuring the sudden fluctuations in the rotational speed of the crankshaft by means of an electronic sensor located close to the fly-wheel.

15 This sensor is connected to the control unit positioned inside the car, which receives all the data concerning the engine and transmitted by suitable sensors. By calculating the fluctuations in the speed according to the delivered torque it is possible to identify a possible misfire in one cylinder of the engine. However, this process does not allow to precisely identify in which cylinder the misfire occurred and moreover has a quite high

20 error probability, particularly in the case of the traveling car being subjected to sharp oscillations, e.g. caused by defects in the road surface, which temporarily affect the rotational speed of the crankshaft.

In order to overcome these drawbacks, US-5109825 devised to measure the fluctuations in time of the pressure of the engine exhaust gas. Though pressure sensors

25 available on the market are very accurate and provide a response almost in real time, the known processes for detecting the misfire on the basis of the measurement of the pressure fluctuations in the exhaust gas are still very inaccurate and poorly reliable, particularly when applied to engines with a high number of cylinders.

Therefore the object of the present invention is to provide a process for

30 detecting the misfire which is free from the above-mentioned drawbacks. Another object of the present invention is to provide a system which carries out said process.

These objects are achieved by means of a process and a system in which a misfire is identified from the analysis in the frequency domain of a signal obtained by sampling the exhaust gas pressure.

Thanks to the sampling and the subsequent frequency analysis of the pressure values detected in the exhaust pipes, the process according to the present invention provides a higher accuracy and reliability with respect to prior art processes. In fact, if the engine firing is regular, the periodical openings of the cylinder exhaust valves generate pressure pulses in the exhaust pipes having the same periodicity and similar waveforms. On the contrary, in the case of misfire in one of the cylinders, the corresponding pressure pulse is changed, thus changing the periodical pattern of the pressure values. The reference for the synchronization with the pulse frequency is readily derivable from the sensors detecting the rotational speed of the crankshaft and/or camshaft.

Another advantage of the process according to the present invention is that through the frequency analysis of the sampled signal it is possible to determine whether only one or more misfires occurred during a single engine cycle. In fact, the amplitude of the modulus of the various harmonics of the sampled signal depends on the number of cylinders wherein the misfire occurred.

A further advantage of the process according to the present invention is that through the frequency analysis of the sampled signal it is possible to determine not only the misfire, but also the position of the cylinder where it occurred. In fact, the knowledge of the cylinder firing sequence and the comparison of the phase of the first harmonic of the sampled signal with the phase of the first cylinder provide a phase difference which indicates the position of the cylinder where the misfire occurred.

These and other advantages and characteristics of the process and system according to the present invention will be clear to those skilled in the art from the following detailed description of an embodiment thereof, with reference to the annexed drawings wherein:

- Figure 1 shows a diagrammatic view of the system according to the present invention;
- Figure 2 shows a flow chart of the process according to the present invention;
- Figures 3a, 3b and 3c show three diagrams of the pressure as a function of the

crankshaft rotation;

- Figures 4a, 4b and 4c show other three diagrams of the pressure as a function of the crankshaft rotation;
- Figures 5a, 5b and 5c show three diagrams of the misfire index as a function of the number of engine cycles;
- Figure 6 shows a Fourier transform of the diagram of figure 3a; and
- Figures 7a, 7b and 7c show three diagrams in polar coordinates of the main harmonic of the pressure in the diagrams of figures 3a, 3b and 3c.

With reference to figure 1, there is seen that the system according to the present invention includes in a known manner a control unit 1 (indicated by a dotted line) which in turn includes a pair of mutually connected electronic controllers 2, 2' each of which provides the control over one of two rows of cylinders 3, 3' of the engine. In the present embodiment there is described a V12 engine having two rows of six cylinders 3, 3' each, but in other embodiments the number of cylinders and/or rows may obviously change. The controllers 2, 2' are connected in a known manner to a pair of coolant temperature sensors 4, 4' and to two pairs of sensors 5, 5' and 6, 6' respectively detecting the temperature and pressure of the air in the intake manifolds 7, 7'. The controllers 2, 2' are also connected to a pair of lambda sensors 8, 8' for analyzing the oxygen content in the exhaust pipes 9, 9', to two series of injectors 10, 10' which inject the fuel into the intake pipes 11, 11' of the cylinders 3, 3', as well as to a pair of ignition coils 12, 12'. The exhaust pipes 9, 9' are preferably provided also with a pair of temperature sensors 13, 13' connected to the controllers 2, 2'.

The system according to the present embodiment of the invention suitably includes a sensor 14 detecting the rotational speed of the fly-wheel 15 integral with the crankshaft and a further pair of sensors 16, 16' detecting the rotation of the camshaft 17. These sensors 14, 16 and 16' are connected to the controllers 2, 2' so that the latter, on the basis of the received data, can calculate in real time the speed and angle of rotation of the crankshaft during an engine cycle. The presence of the sensors 14, 16 and 16' is made necessary by the fact that the fly-wheel 15 in a four-stroke engine makes two revolutions (720°) per cycle, whereby the reference provided by the sensors 16, 16' allows to distinguish the first revolution from the second one.

In order to carry out the process according to the present invention, in the two exhaust pipes 9, 9' there are properly arranged two high-precision pressure sensors 18, 18' connected to the controllers 2, 2', said sensors transmitting in real time an electric signal whose voltage is proportional to the measured pressure. Furthermore, the controllers 2, 2' are connected to a pair of warning lights 19, 19' positioned inside the car, to a port 20 for the connection to an external processor, as well as to a sensor 21 detecting the position of the engine throttle 22.

Referring now to figure 2, there is seen that the process according to the present invention includes, after a certain period of time from the engine start, a first step of periodical check, e.g. each second, of the engine running state. In fact, in order to obtain reliable results from the process, it is preferable that the latter be carried out only if some engine parameters are within a preset range of values. In particular, the process according to the present invention is activated only when the coolant temperature measured by sensors 4, 4', the air temperature measured by sensors 5, 5' and the air pressure measured by sensors 6, 6' in the manifolds 7, 7' are above certain thresholds stored in the memory of the controllers 2, 2'. Moreover, these controllers check that the revolutions per minute (rpm) detected by sensor 14 are within a preset range of values.

Table 1 hereunder shows an example of values meeting the conditions for the start of the process.

Minimum number of revolutions	990 rpm
Maximum number of revolutions	7550 rpm
State check period	1 s
Delay from engine start	10 s
Minimum coolant temperature	20° C
Minimum air temperature	20° C
Minimum absolute pressure in manifolds 7, 7'	250 mmHg

Table 1: start conditions

5 A further condition for starting the process may be reaching a certain opening of the throttle 22 as detected by sensor 21.

10 If the conditions above are met, at the beginning of an engine cycle, corresponding to a certain position of the camshaft 17 as detected by sensors 16, 16', the controllers 2, 2' start sampling the electric signals transmitted by sensors 18, 18' and proportional to the pressure inside the exhaust pipes 9, 9'. These analogue signals are converted in a known manner into digital form and then stored in a buffer memory within each controller 2, 2'. The sampling frequency is suitably synchronized with the rotational speed of the fly-wheel 15 as detected by sensor 14, so that at the end of the engine cycle, detected through sensors 16 and 16', there is stored a preset number, e.g. 64, of pressure samples. Though the response of the pressure sensors 18, 18' is almost immediate, in order to synchronize precisely with the engine, the controllers 2, 15 2' take into account the lag, almost constant, caused by the time required by the pressure pulse to travel from the exhaust valves of the cylinders 3, 3' to the pressure sensors 18, 18' along the exhaust pipes 9, 9'. Thanks to the temperature sensors 13, 13' it is possible to compensate for the very small fluctuations in said lag caused by the 20 fluctuations in the temperature within the pipes 9, 9'.

After having been sampled, the pressure values corresponding to an engine cycle are processed by the controllers 2, 2' which, at the same time, sample another series of pressure values which are stored in a further buffer memory for a subsequent processing.

This processing carried out by each processor of the controllers 2, 2' suitably includes an analysis in the frequency domain, and in particular a Fourier transform of the sampled signal, through which there are obtained two series of coefficients corresponding to the real part and the imaginary part of the first harmonics of the signal. In particular, in the present embodiment there are calculated the coefficients of the first 32 harmonics of the sampled signal, but in other embodiments it is obviously possible to calculate a different number of harmonics according to the needs.

These coefficients are used to calculate in a known way the modulus of the first harmonics, e.g. the first three, and then, by combining the values of these moduli, to obtain an index which allows to detect a misfire in one or more of the cylinders 3, 3'. This misfire index can be calculated in various ways, e.g. by adding or multiplying the moduli of the harmonics. Prior to this addition or multiplication, the moduli may possibly be multiplied or raised to a power with a different coefficient for each harmonic, so as to obtain a weighed addition or multiplication. In the present embodiment, the misfire index is calculated by simply adding the moduli of the first three harmonics.

Once said index has been calculated, it is compared with preset threshold values stored in the controllers 2, 2'. Table 2 hereunder shows an example of threshold values of the misfire index experimentally obtained as a function of the engine rpm detected by sensor 14 and of the pressure in the manifolds 7, 7' as detected by sensors 6, 6'.

mmHg ↓	rpm ↓							
	1100	2000	3000	4000	5000	6000	7000	7500
300	110	110	124	130	144	148	156	168
450	115	120	148	156	180	188	196	204
600	130	140	180	188	236	248	256	268
760	150	162	224	264	292	300	312	320

Table 2: Threshold values of the misfire index

The controller 2 or 2' which detects the exceeding of said threshold, indicates

through the warning light 19 or 19' that a misfire occurred in the corresponding row of cylinders 3 or 3'.

At this moment, the controller 2 or 2' which detected the misfire preferably compares the modulus of each of the first three harmonics with preset threshold values also stored as a function of the engine rpm and of the pressure in the corresponding manifold 7 or 7'. If all three moduli are within a range of values between a minimum threshold and a maximum threshold, a single misfire is detected, i.e. a misfire occurred in one only of the cylinders 3 or 3', otherwise a multiple misfire is detected, i.e. a misfire occurred in at least two of the cylinders 3 or 3' belonging to a row.

The following tables 3.1, 3.2, 4.1, 4.2, 5.1 and 5.2 show examples of minimum values and amplitudes of the threshold ranges for the moduli of the first three harmonics.

mmHg ↓	rpm ↓							
	1100	2000	3000	4000	5000	6000	7000	7500
300	8	28	48	40	56	84	84	84
450	8	24	56	40	80	96	96	96
600	12	36	60	72	116	104	104	104
760	24	44	72	108	160	144	144	144

Table 3.1: Minimum threshold values for the modulus of the first harmonic

mmHg ↓	rpm ↓							
	1100	2000	3000	4000	5000	6000	7000	7500
300	128	108	92	180	144	188	192	196
450	120	140	148	184	168	192	196	200
600	96	128	176	144	192	200	224	244
760	68	144	196	188	244	224	228	232

Table 3.2: Range amplitude for the modulus of the first harmonic

mmHg ↓	rpm ↓							
	1100	2000	3000	4000	5000	6000	7000	7500
300	20	8	8	4	12	16	24	28
450	24	12	8	8	16	16	28	36
600	20	12	8	16	24	16	24	32
760	24	16	8	28	40	36	36	36

Table 4.1: Minimum threshold values for the modulus of the second harmonic

mmHg ↓	rpm ↓							
	1100	2000	3000	4000	5000	6000	7000	7500
300	48	64	72	96	80	72	56	52
450	48	80	112	92	104	68	52	48
600	72	108	140	124	136	96	80	60
760	96	124	172	168	160	136	88	72

5

Table 4.2: Range amplitude for the modulus of the second harmonic

mmHg ↓	rpm ↓							
	1100	2000	3000	4000	5000	6000	7000	7500
300	0	0	0	0	0	0	0	0
450	0	0	0	0	0	0	0	0
600	8	4	4	4	8	4	0	0
760	4	4	4	12	12	8	4	4

Table 5.1: Minimum threshold values for the modulus of the third harmonic

mmHg ↓	rpm ↓							
	1100	2000	3000	3000	5000	6000	7000	7500
300	92	72	52	124	40	132	144	152
450	92	88	84	88	64	84	64	60
600	88	104	112	68	96	48	28	24
760	88	124	160	136	160	80	80	80

Table 5.2: Range amplitude for the modulus of the third harmonic

5 If a misfire is detected in only one of the six cylinders 3 or 3', the relevant
 controller 2 or 2' can determine the position of the cylinder where the misfire occurred
 by first calculating in a known manner the phase of the first harmonic. Thereafter, by
 subtracting the phase of the first harmonic from the phase of the first cylinder of the
 engine cycle, stored in the controllers 2, 2' by means of a table as a function of the
 10 engine rpm, there is obtained a phase difference which approximately corresponds to
 the phase of the cylinder where the misfire occurred.

For example, if at given engine rpm the phase of the first cylinder of the engine
 cycle is 210° , a misfire occurred in the first, second, third, fourth, fifth or sixth cylinder
 in firing order when the phase of the first harmonic is respectively between 180° and
 15 240° , 120° and 180° , 60° and 120° , 0° and 60° , 300° and 360° or 240° and 300° .

Table 6 hereunder shows the relationship between the engine rpm and the phase
 of the first cylinder in order to determine the position of the cylinder where the misfire
 occurred.

- 10 -

rpm	phase
510	164°
990	140°
1500	106°
2010	80°
2490	58°
3000	36°
3510	16°
3990	0°
3990	360°
4500	348°
5010	338°
5490	328°
6000	320°
6510	312°
6990	302°
7500	292°

Table 6: relationship between engine rpm and phase of the first cylinder

Each detection of a misfire in one of the engine cylinders, as well as the
 5 corresponding cylinder position in case of single misfire, is stored in suitable counters
 in the memory of controllers 2, 2'. This memory can be read through port 20 by an
 external processor during the car servicing, so as to diagnose possible engine failures.

Referring now to figures 3a to 3c, there is seen, through measurements made in
 experimental tests where misfires were caused in the tested engine, how the signal
 10 transmitted by sensors 18, 18' changes as a function of the misfire in one of the
 cylinders 3, 3'. In particular, figure 3a shows that at about 2000 rpm with an engine
 load around 15%, the voltage (given in Volts) at the terminals of the pressure sensors
 18, 18' proportional to the pressure in the exhaust pipes 9, 9' is almost regular with
 six periodical oscillations during an engine cycle (indicated by the crankshaft rotation

angle from -180° to 540°). This voltage is indicated by a thin line, whereas a thick line indicates the voltage in the case of misfire in the first cylinder. In this case, it is clearly seen that the voltage pattern has a first irregularity around 240° and a second irregularity around 480° . However, figure 3b shows that at about 4000 rpm with an engine load approximately at 100%, the voltage pattern in case of regular firing is more complicated with respect to the preceding case. Nonetheless, the voltage pattern in case of misfire in the first cylinder (still indicated by the thick line) moves away around 400° from the regular firing voltage pattern (still indicated by the thin line). Also figure 3c shows that at about 6000 rpm with an engine load approximately at 100%, the voltage pattern of the pressure sensors 18, 18' is different in the case of misfire in the first cylinder, in particular around 470° .

Similarly, with reference to figures 4a to 4c, there is seen, still through measurements made in experimental tests, how the signal transmitted by the pressure sensors 18, 18' changes as a function of the misfire in one of the cylinders 3, 3', regardless of the misfire being caused by a lack of fuel injection or ignition in the cylinder. In fact, there is seen that the voltage pattern in case of lack of injection (indicated by the thick line) is substantially equal to the voltage pattern in case of lack of ignition (indicated by the dotted line). This correspondence can be found both at low rpm, i.e. at about 2000 rpm with an engine load around 15% (figure 4a), at intermediate rpm, i.e. at about 4000 rpm with an engine load around 55% (figure 4b), and at high rpm, i.e. at about 6000 rpm with an engine load approximately at 100% (figure 4c).

Referring now to figures 5a to 5c, there is seen that the misfire index measured as a function on the engine cycles (indicated on the horizontal axis) shows readily detectable peaks, which correspond to the moments when a misfire was experimentally caused in one of the engine cylinders. This can be found both at low rpm, i.e. at about 1000 rpm with an engine load around 15% (figure 5a), at intermediate rpm, i.e. at about 3000 rpm with an engine load around 55% (figure 5b), and at high rpm, i.e. at about 5000 rpm with an engine load approximately at 100% (figure 5c).

With reference to figure 6, there is seen that the modulus of the first ten harmonics of the signal (in Volts) transmitted by sensors 18, 18' changes quite

apparently from the case of regular firing in all cylinders (indicated by the white bars) to the case of misfire in the first cylinder (indicated by the grey bars). The figure shows the modulus of the first ten harmonics calculated with the engine at 2000 rpm and a load around 15%, i.e. the case shown in figure 3a and figure 4a. The figure clearly shows that in the case of regular firing the modulus of the sixth harmonic is much higher than all other moduli, whereas in the case of misfire in the first cylinder there is also a significant contribution of the moduli of the first harmonics, in particular of the first three. It is clear that the contribution of the modulus of each harmonic depends on some factors which have to be considered when setting the threshold values of the misfire index. These factors include, for example, the shape of the exhaust pipes 9, 9', the number and the firing sequence of the cylinders 3, 3' of each row.

Finally referring to figures 7a to 7c, there is seen that the phase of the first harmonic changes as a function of the position of the cylinder where the misfire occurred. In fact, it is possible to identify six separate areas, each area corresponding to an engine cylinder, where the polar coordinates of the modulus and phase of the first harmonic at the moment of the misfire are concentrated. In particular, there is seen that said coordinates concentrate in six sectors having an extension of 60° each, whose sequence is defined by the cylinder firing sequence, which in the present embodiment is 1-4-2-6-3-5 for the row of cylinders 3. Taking into account the engine phase, this correspondence can be found both at low rpm, i.e. at about 2000 rpm with an engine load around 15% (figure 7a), at intermediate rpm, i.e. at about 4000 rpm with an engine load approximately at 100% (figure 7b), and at high rpm, i.e. at about 6000 rpm with an engine load approximately at 100% (figure 7c).

Possible additions and/or modifications may be made by those skilled in the art to the above-described and illustrated embodiment, yet without departing from the scope of the invention. In fact it is obvious that the type of sampling, frequency analysis and particularly the method for calculating the misfire index may change according to the type of engine to be monitored. Similarly, also the threshold values may change according to the experimental tests carried out on each type of engine.

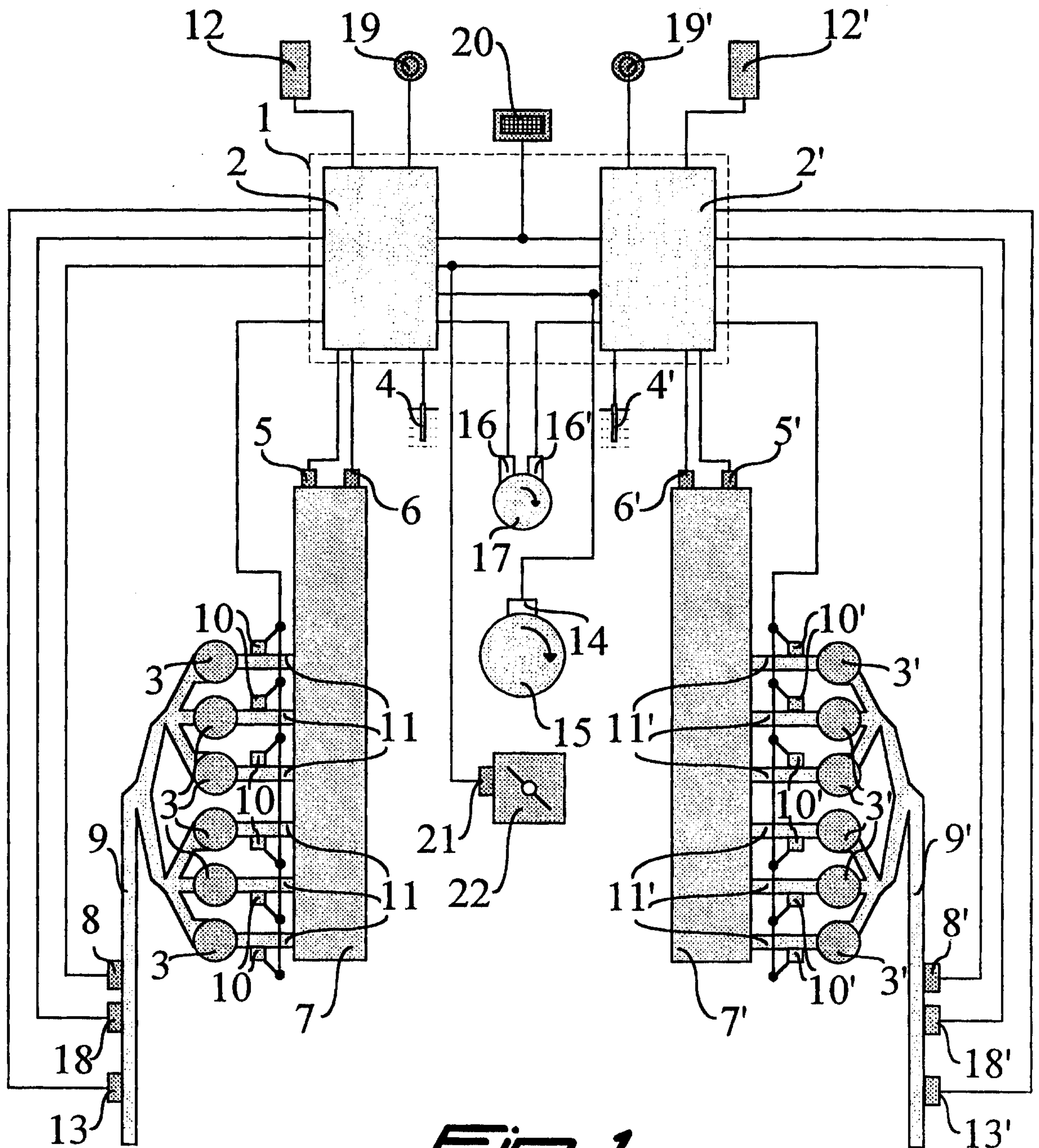
Finally, it is obvious that the process according to the present invention can be used in combination with one or more prior art processes.

CLAIMS

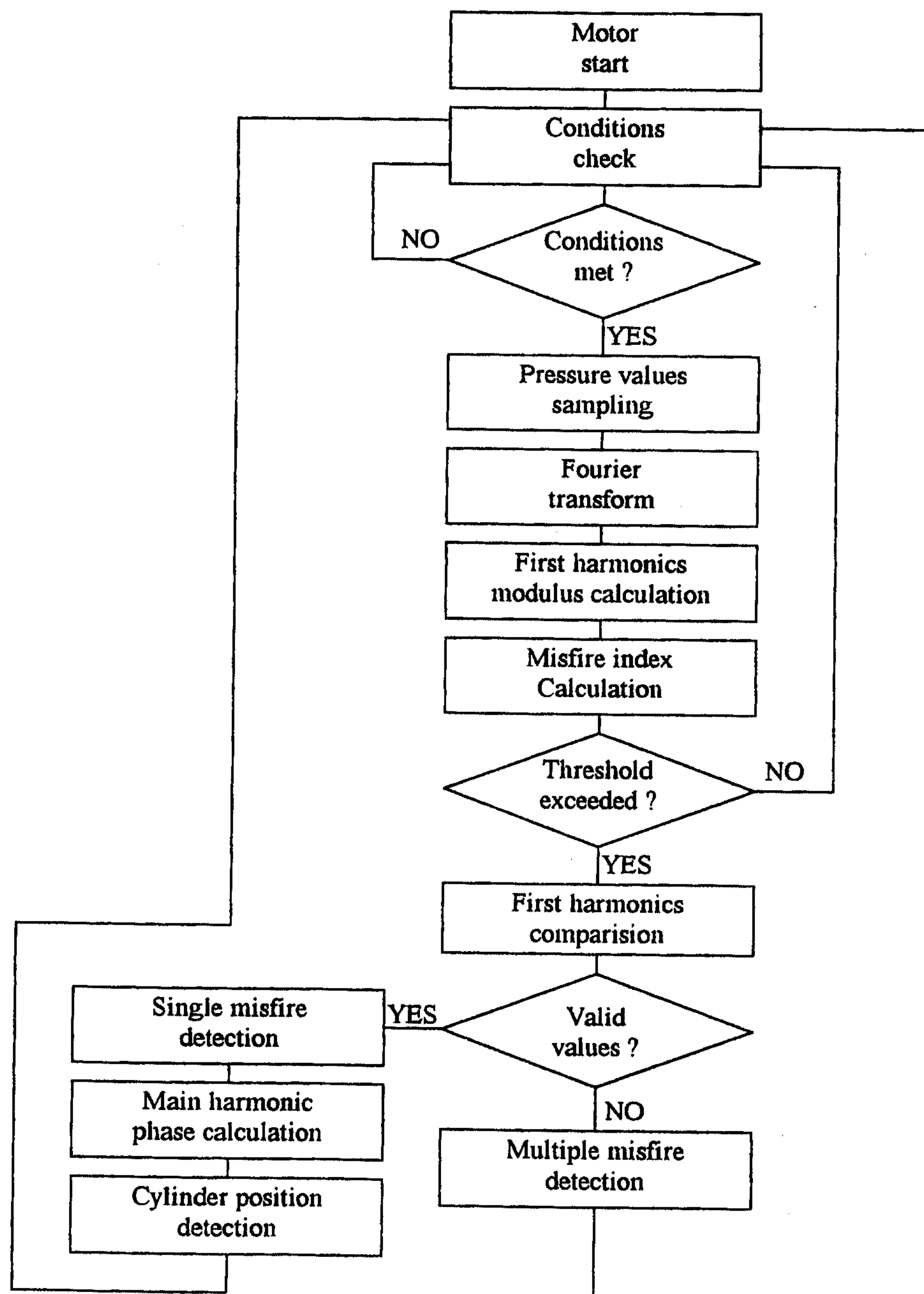
1. A process for detecting a misfire in one or more cylinders (3,3') of an internal combustion engine, characterized in that it includes the following operative steps:
 - 5 - generating a sampled signal by sampling an exhaust gas pressure during at least one engine cycle at a sampling frequency proportional to rotational speed of a crankshaft;
 - analyzing said sampled signal in the frequency domain;
 - calculating a misfire index from said analysis;
 - 10 - comparing said index with at least one threshold value; and
 - identifying a misfire based on said comparison of said index with said at least one threshold value.
2. A process according to claim 1, characterized in that said frequency domain analysis includes a Fourier transform of the sampled signal.
- 15 3. A process according to claim 2, characterized in that the calculation of the misfire index includes the combination of the modulus of some harmonics of the sampled signal.
4. A process according to claim 3, characterized in that the calculation of the misfire index includes the addition of the modulus of at least the first three harmonics of
20 the sampled signal.
5. A process according to any one of claims 1 to 4, characterized in that the sampling of the pressure values is started at the beginning of an engine cycle.
6. A process according to any one of claims 1 to 5, characterized in that it includes the comparison of the modulus of at least one harmonic of the sampled signal with
25 one or more threshold values.
7. A process according to claim 6, characterized in that it includes the calculation of the phase of the first harmonic of the sampled signal, and the calculation of the difference between said phase and the phase of at least one engine cylinder (3,3').
8. A system for carrying out the process according to any one of claims 1 to 7,
30 characterized in that it includes at least one sensor (18,18') detecting the pressure in the exhaust pipes (9,9') and at least one sensor (14) detecting the crankshaft rotation, said sensors (14, 18, 18') being connected to at least one control unit

- (1,2,2') including means for the analogue-to-digital conversion of the electric signal transmitted by the sensor (18, 18') detecting the pressure in the exhaust pipes (9, 9'), means for sampling the signal converted into digital form, memory means for storing the sampled signal, as well as means for analyzing the sampled signal in the frequency domain, calculating a misfire index as a function of the results of said analysis and comparing said index with one or more threshold values.
- 5
9. A system according to claim 8, characterized in that it includes at least one sensor (16,16') detecting the camshaft (17) rotation.
- 10
10. A system according to claim 8 or 9, characterized in that it comprises means for controlling the sampling frequency of said sampling means according to the signal transmitted by the sensor (14) detecting the crankshaft rotation.
11. A system according to any one of claims 8 to 10, characterized in that it comprises at least one sensor (4, 4') detecting the coolant temperature, and at least two sensors (5, 5', 6, 6') respectively detecting the temperature and pressure of the air in the intake manifolds (7, 7'), said sensors (4, 4', 5, 5', 6, 6') being connected to said control unit (1, 2, 2').
- 15
12. A system according to any one of claims 8 to 11, characterized in that it comprises at least one warning light (19, 19') indicating a misfire in at least one engine cylinder, said warning light (19, 19') being connected to said control unit (1, 2, 2').
- 20
13. A system according to any one of claims 8 to 12, characterized in that it comprises a sensor (21) detecting the position of the engine throttle (22), said sensor (21) being connected to said control unit (1, 2, 2').
14. A system according to any one of claims 8 to 13, characterized in that it comprises at least one sensor (13, 13') detecting the temperature in the exhaust pipes (9, 9'), said sensor (13, 13') being connected to said control unit (1, 2, 2').
- 25
15. A car characterized in that it includes a system according to any one of claims 8 to 14 for detecting a misfire in one or more engine cylinders (3, 3').

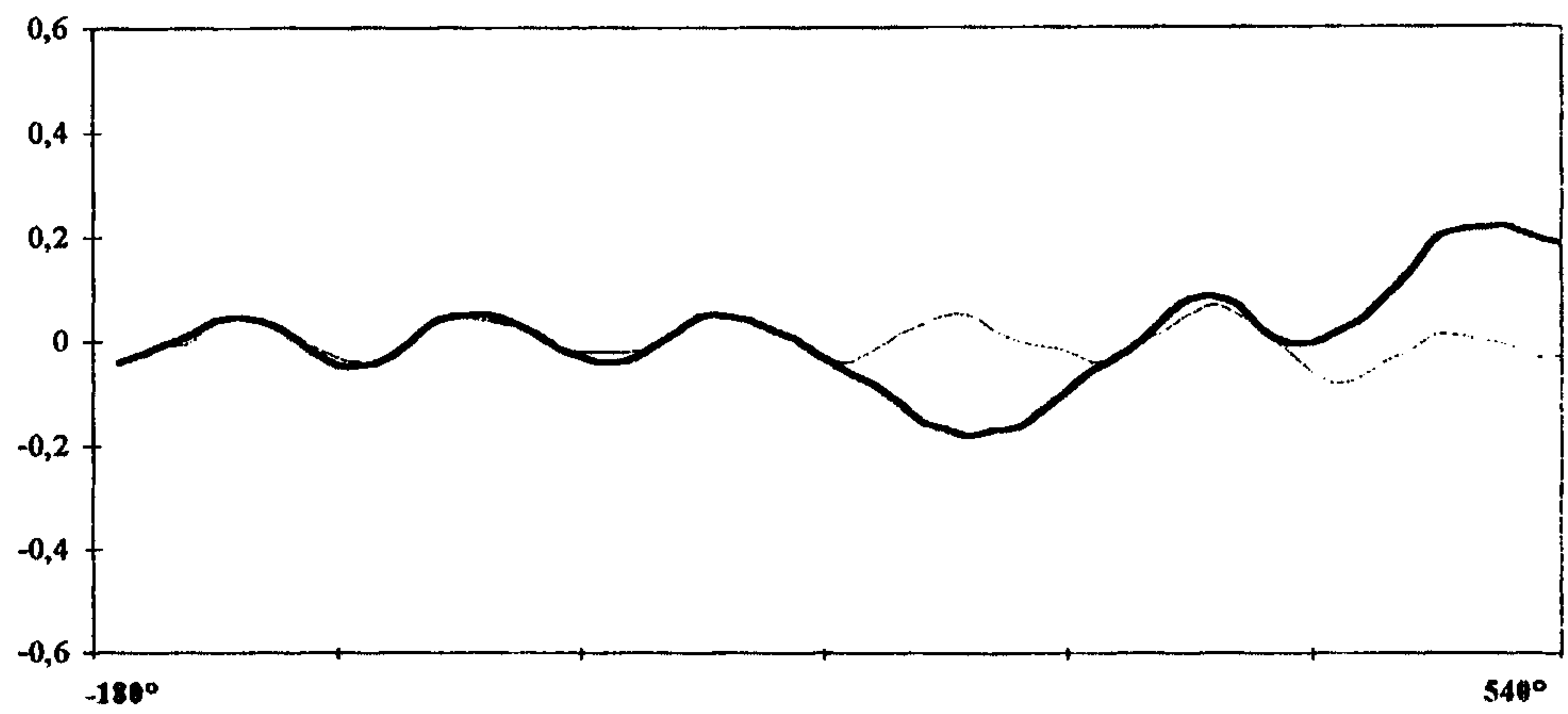
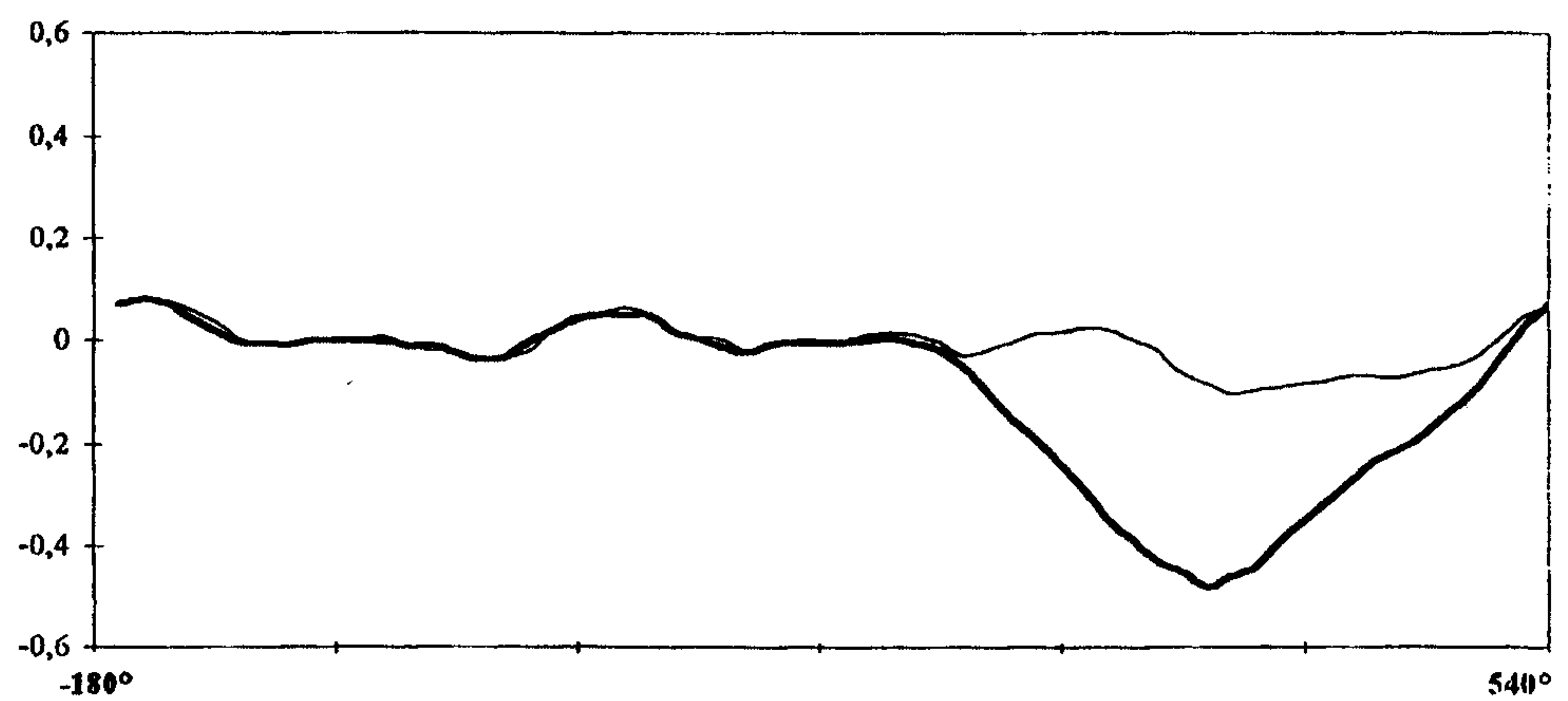
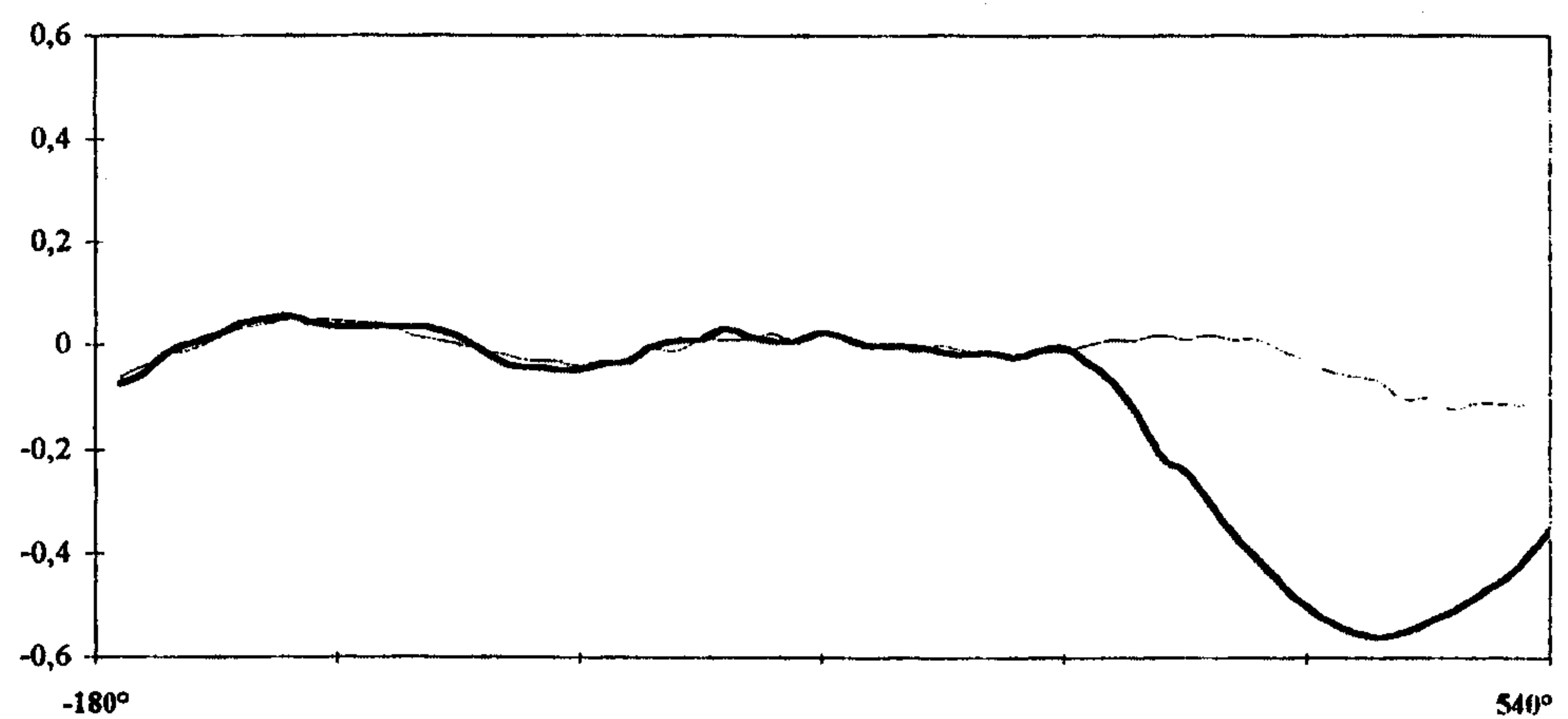
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Fig. 1

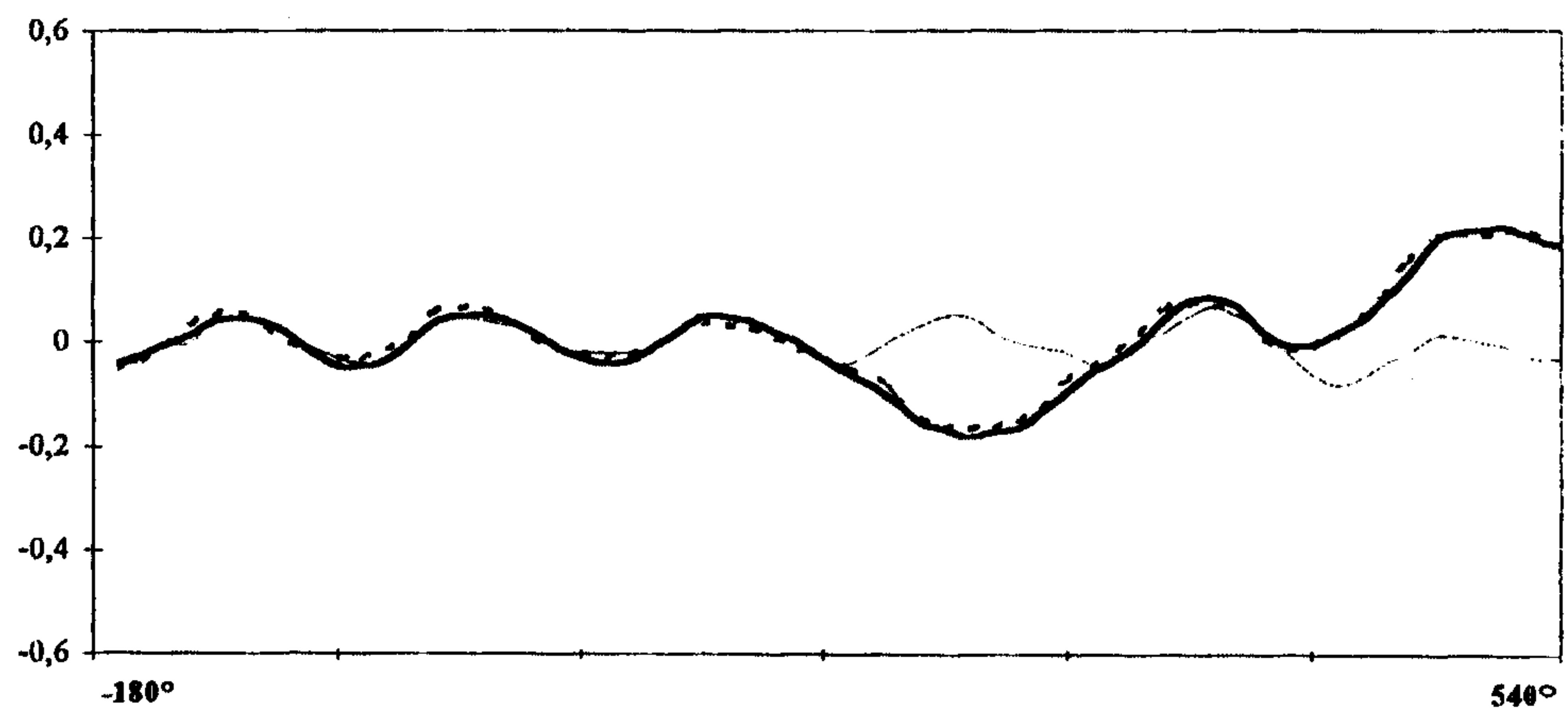
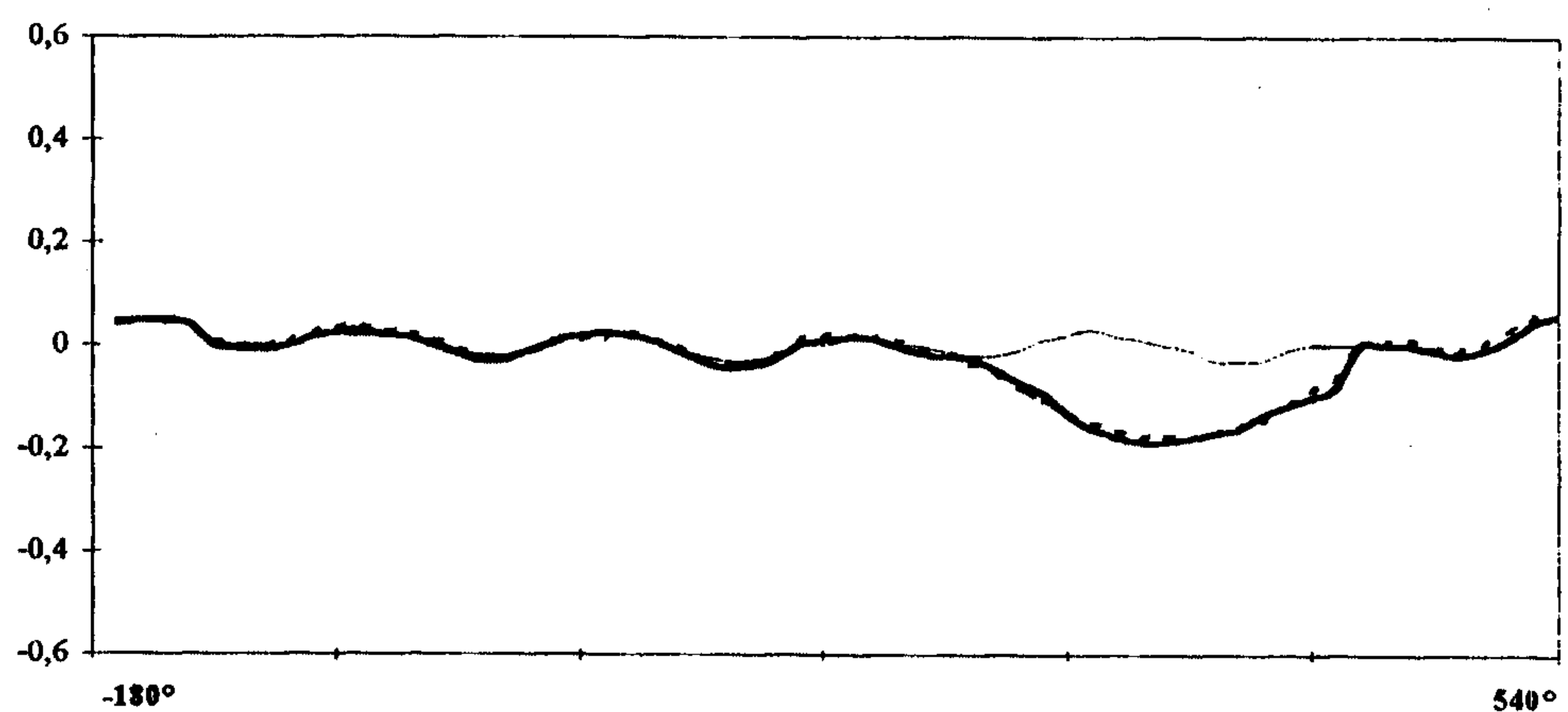
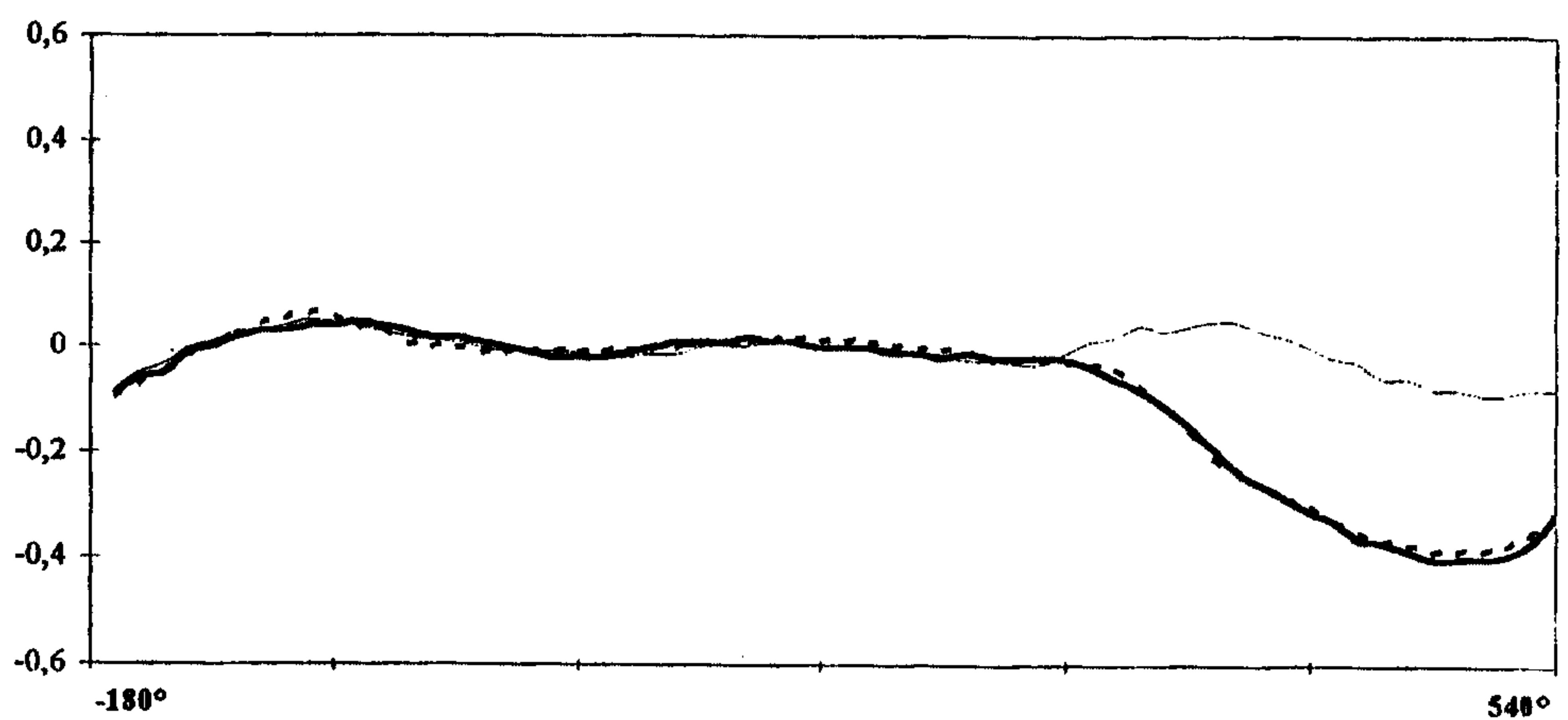
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Fig. 2

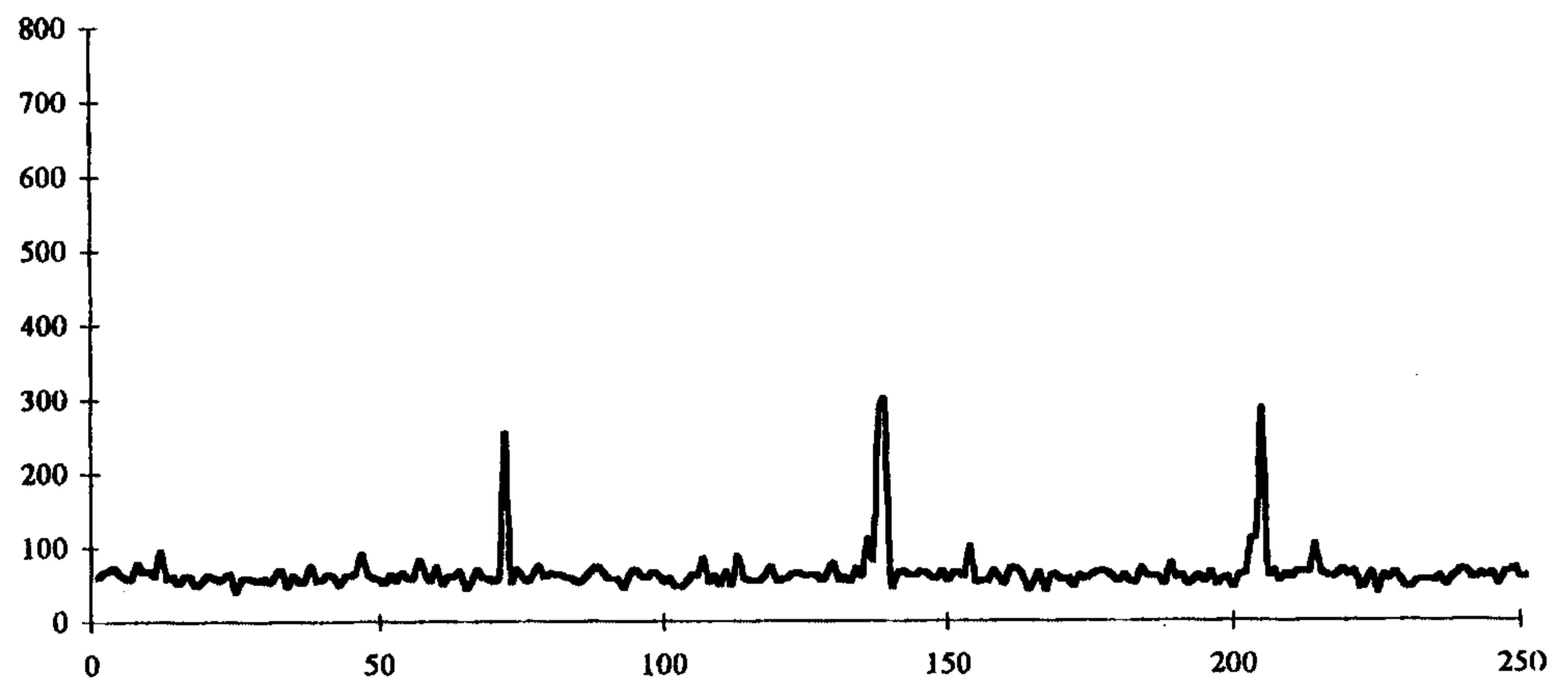
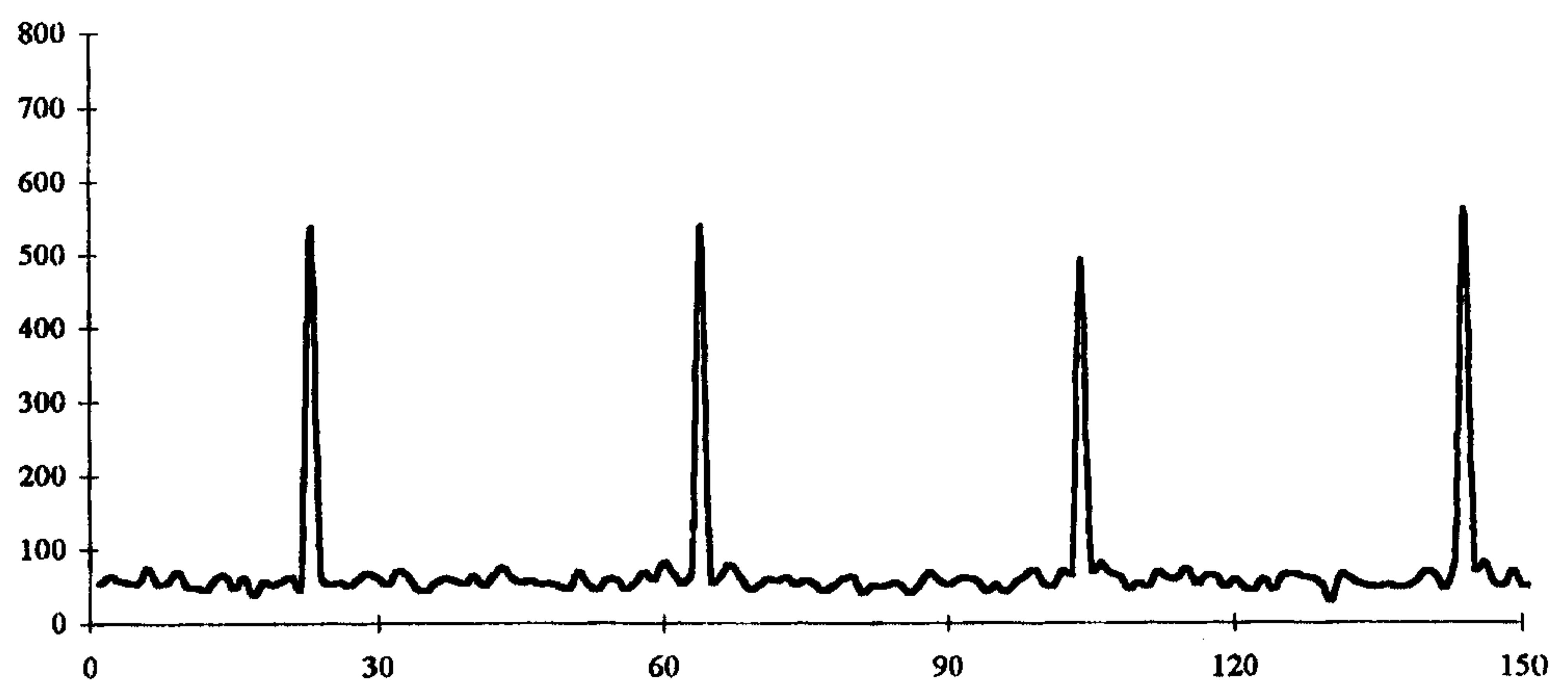
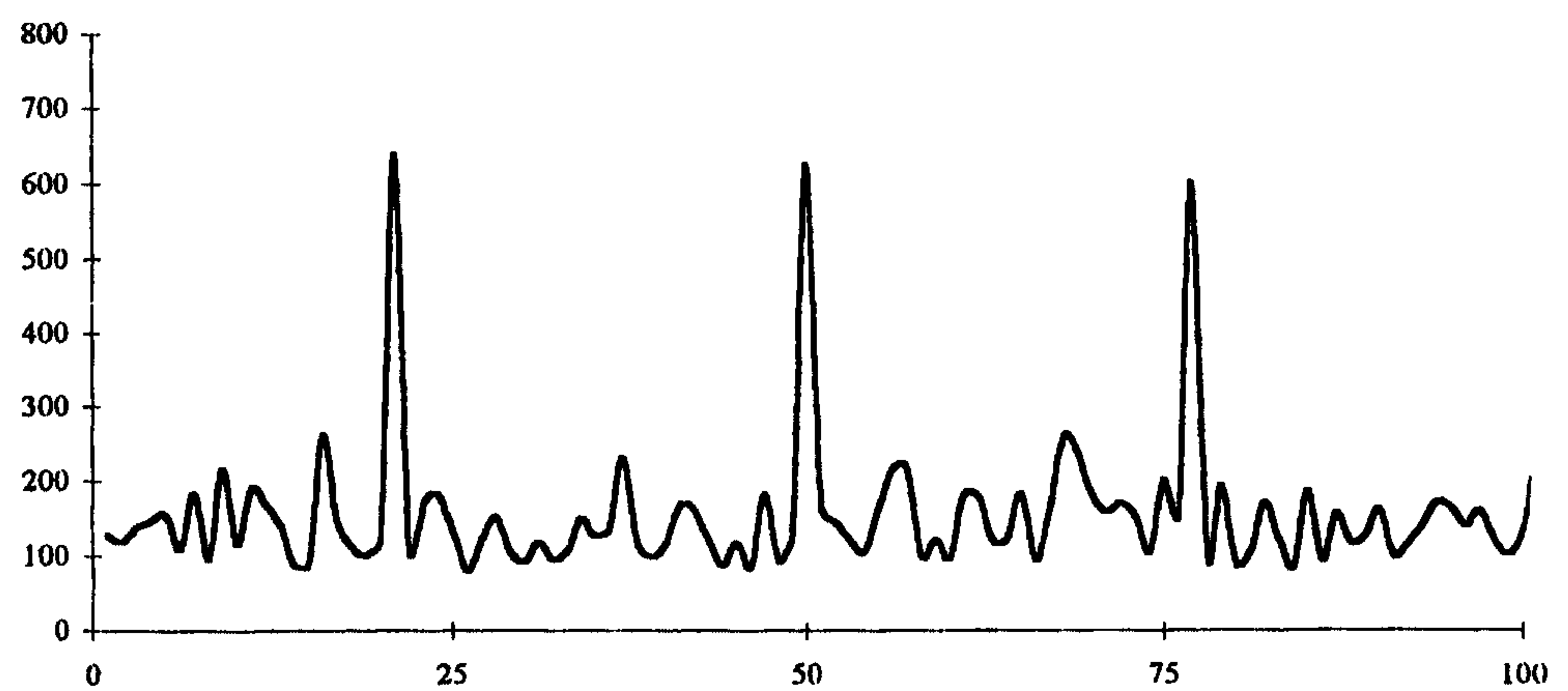
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Fig. 3aFig. 3bFig. 3c

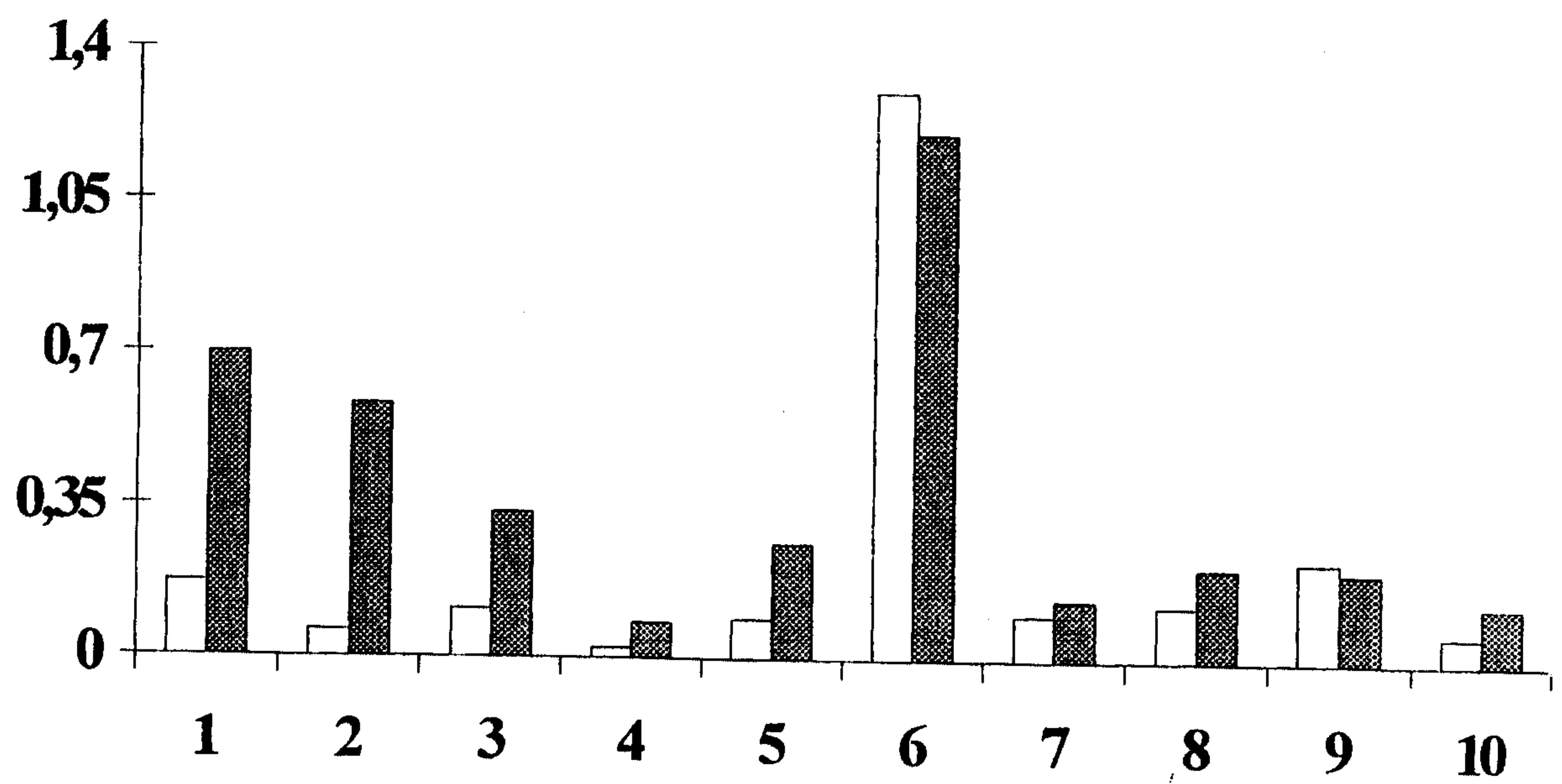
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Fig. 4aFig. 4bFig. 4c

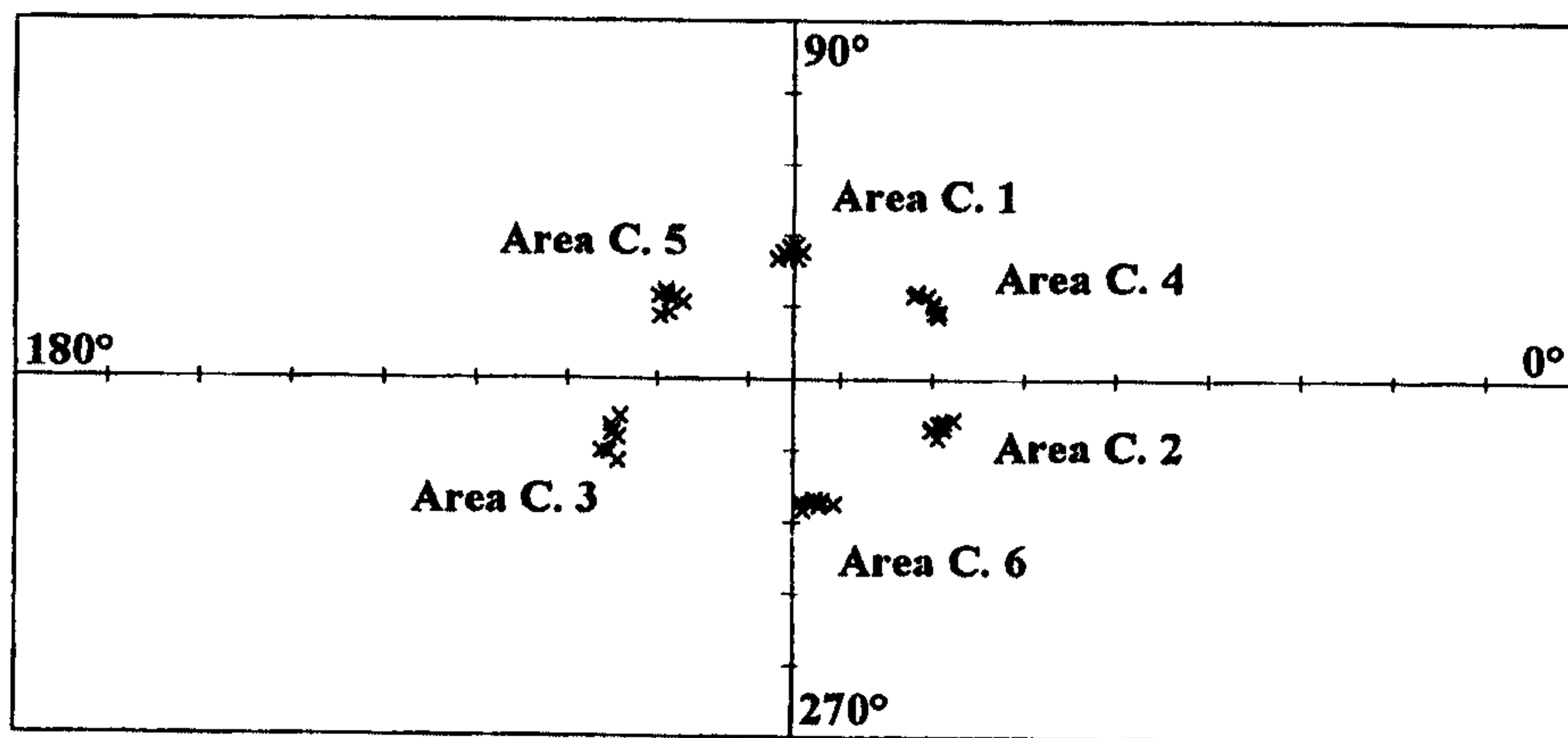
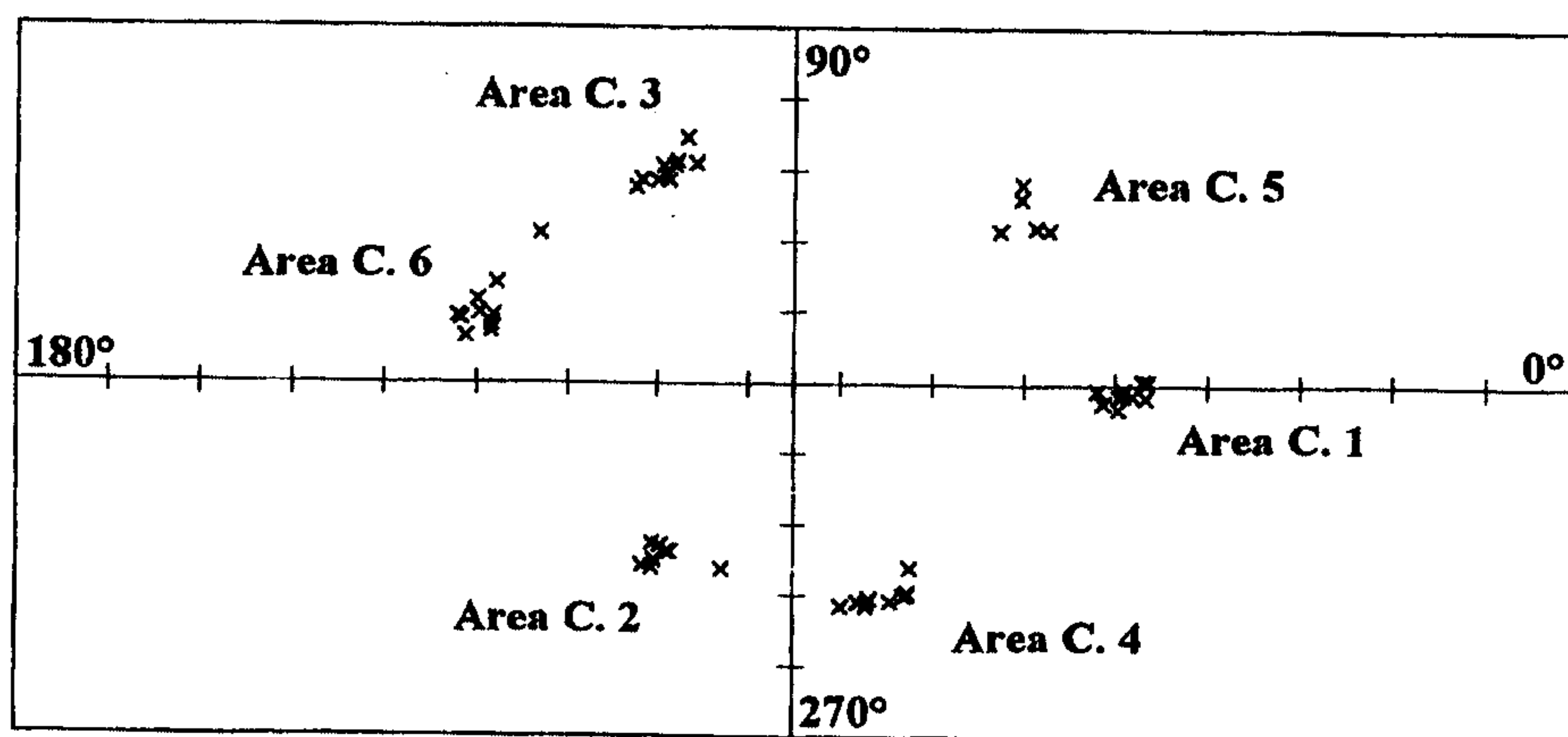
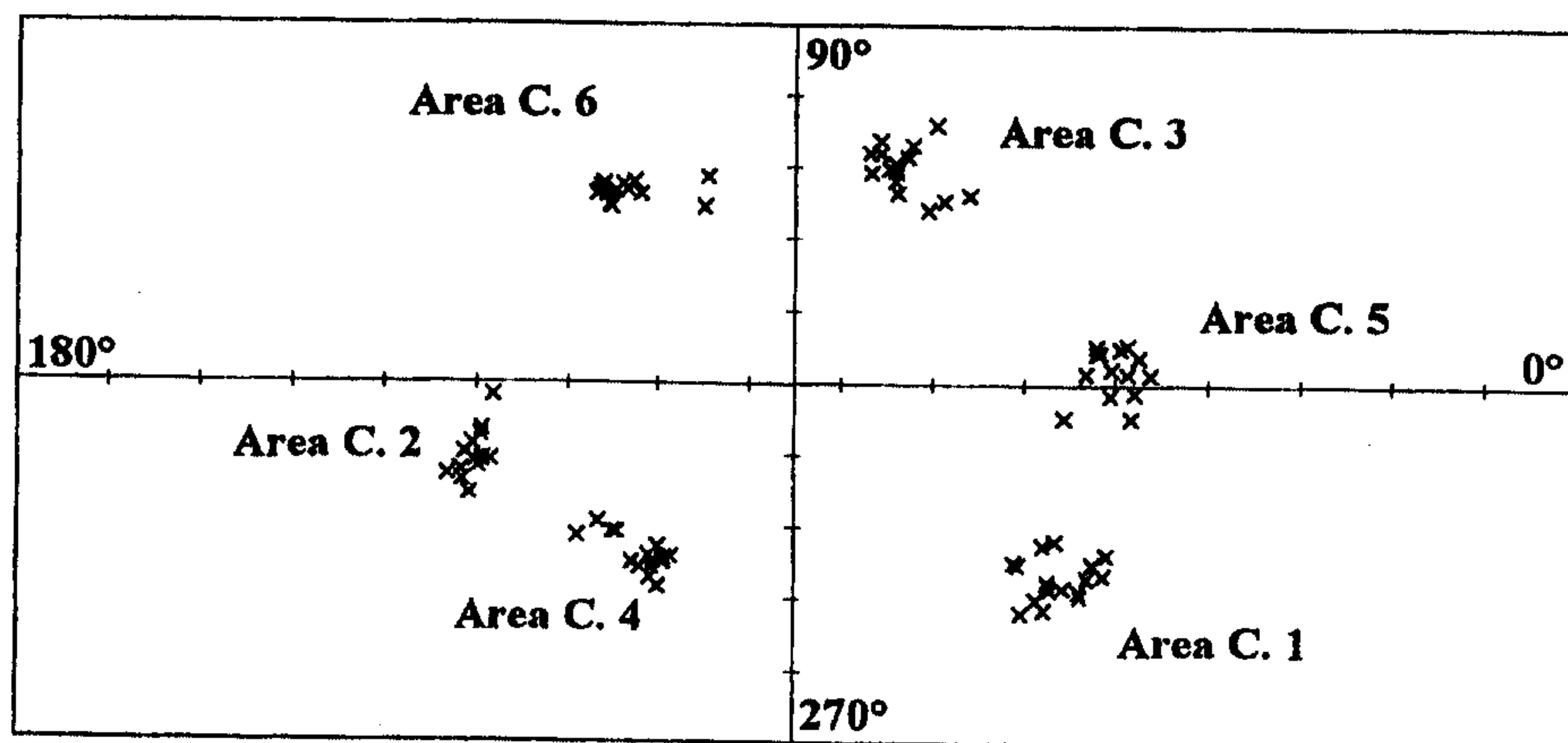
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Fig. 5aFig. 5bFig. 5c

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Fig. 6

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Fig. 7aFig. 7bFig. 7c

