

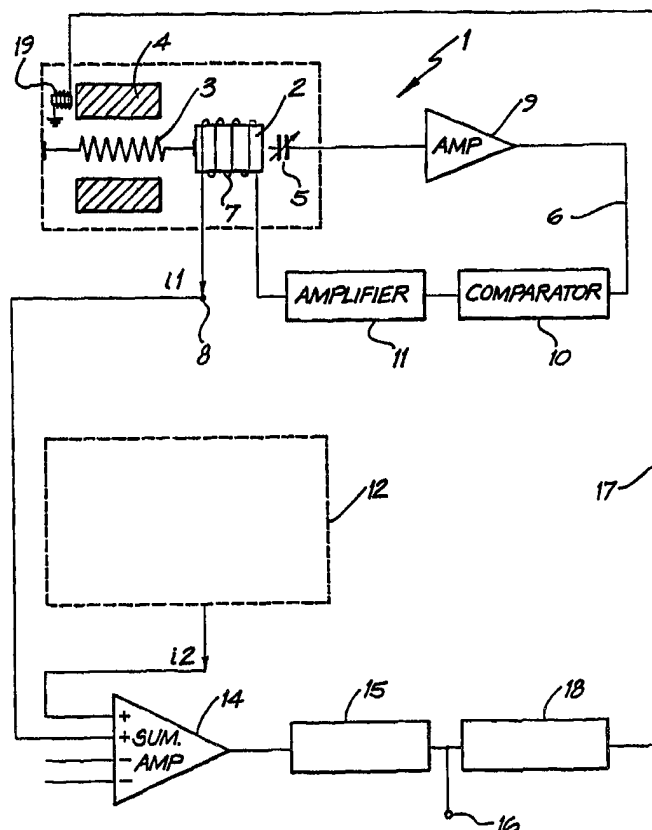


INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

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(21) International Application Number: PCT/AU98/00442 (22) International Filing Date: 11 June 1998 (11.06.98) (30) Priority Data: PO 7319 11 June 1997 (11.06.97) AU PO 7315 12 June 1997 (12.06.97) AU (71) Applicant: THE BROKEN HILL PROPRIETARY COMPANY LIMITED [AU/AU]; 600 Bourke Street, Melbourne, VIC 3000 (AU). (72) Inventors: O'KEEFE, Graeme, Joseph; 20 Parry Road, Eltham, VIC 3095 (AU). LEE, James, Beresford; 11 Marshall Street, New Lambton Heights, NSW 2305 (AU). TURNER, Robert, John; 402 Lemon Tree Passage Road, Salt Ash, NSW 2318 (AU). ADAMS, Gregory, John; 20 Springfield Avenue, Kotara, NSW 2289 (AU). GOODWIN, Graham, Clifford; 68 Atherton Close, Rankin Park, NSW 2287 (AU). (74) Agent: F.B. RICE & CO.; 605 Darling Street, Balmain, NSW 2041 (AU).		(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GE, GH, GM, GW, HU, ID, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, TJ, TM, TR, TT, UA, UG, UZ, VN, YU, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG). Published <i>With international search report.</i>

(54) Title: GRAVITY GRADIOMETER ACCELEROMETERS**(57) Abstract**

This invention concerns improvements to gravity gradient instruments (GGI) and in particular to the accelerometers that are paired within these instruments. Accelerometers (1) have a proof mass (2) suspended by a spring (3) within a magnetic field. An internal feedback loop (6) provides a signal related to movement of the proof mass back through a reaction coil (7) retaining the proof mass in the magnetic field, to maintain the proof mass stationary. An external feedback loop (17) adjusts the accelerometer scale factor. The internal feedback loop provides second order compensation to the proof mass and the spring stiffness. In a further aspect the invention is a method of matching accelerometer pairs.



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GRAVITY GRADIOMETER ACCELEROMETERS

Technical Field

This invention concerns improvements to gravity gradient instruments (GGI), and in particular to the accelerometers that are paired within these instruments.

Background Art

The GGI consists of two pairs of high quality, low noise, matched accelerometers mounted on a block. Each of the accelerometers has an internal feedback loop for proper operation, and an external feedback loop for trim adjustment of the accelerometer scale factor and alignment of the accelerometer sensitive axis.

The normal configuration has the accelerometers mounted in opposing pairs, and equally spaced around the circumference of a circle, with their sensitive axes tangential to the circle. In use the block is rotated about a spin axis which is perpendicular to the plane of the circle, and passes through the centre of the circle. The outputs of the accelerometers of each pair are differenced and the difference signals are then combined. The overall effect is that the large common mode accelerometer output signals cancel to a high degree of precision, so that the residual differences which constitute the gradient signal are observable.

The accelerometers must be matched in their pairs so that the current/acceleration transfer function is matched in amplitude and phase at all frequencies of interest, to an accuracy of 1 part in 10^{10} . The mismatch in accelerometer pairs is a result of the difference of the internal feedback closed loop errors, and thus the mismatch is also inversely proportional to the open loop gain. The existing external feedback scale factor adjustment can degrade, by an order of magnitude, the high frequency ($> 1\text{Hz}$) lateral sensitivity for a

2% mismatch within the accelerometers. The influence of vertical acceleration on the accelerometers is an additional complicating factor.

Summary of the Invention

5 The invention, as currently envisaged, is an accelerometer having a proof mass suspended by a spring within a magnetic field. An internal feedback loop provides a signal related to movement of the proof mass back through a reaction coil retaining the proof mass in the magnetic field, to maintain the proof mass stationary. An external feedback loop adjusts the
10 accelerometer scale factor. Wherein, the internal feedback loop provides second order compensation to the proof mass and the spring stiffness.

The internal feedback path may include high gain to reduce errors in the accelerometer transfer function.

15 A compensator in the internal feedback loop may provide double pole and double zero compensation:

$$\frac{m_1 s^2 + k_1}{m_0 s^2 + k_0}$$

20 where:

m_1 is the mass of the proof mass

k_1 is the spring constant of the spring

m_0 is a nominal proof mass and

k_0 is a nominal spring constant.

25

The nominal proof mass and spring constant represent the accelerometer characteristics to which both accelerometers of a pair are to be matched in order that the two accelerometers are closely matched to each other.

In a GGI the compensation provided by the internal feedback loop may correct for the mass ratio (or F_0 frequency ratio) mismatch between two paired accelerometers by providing the s^2 loop gain term as a mass compensator. The compensation may also correct for the spring ratio by providing a loop gain
5 term which lumps together variations in pick-off gain, integrator capacitors and spring constant, as a spring stiffness k compensator.

The components of the compensation network are typically resistors and capacitors. Variable components are introduced so that the break frequencies can be tuned over a $\pm 5\%$ range to match the masses m and the
10 spring stiffnesses k of the accelerometer pairs to better than 0.5%. The closed loop gain blocks are trimmed in pairs to match the time constants to within 0.5%.

In a further aspect the invention is a method of matching accelerometer pairs, comprising the steps of :

15 Testing the pair of accelerometers in back to back fixtures on a horizontal shaker which is aligned to the same vertical angle as in the GGI.

Selecting the accelerometers on the basis of the best scale factor match at 0.5Hz and the lowest lateral sensitivity at 10Hz.

Applying horizontal excitation at 0.25Hz, 1Hz and 10Hz (or higher)
20 and detecting the system response with synchronous demodulation at the frequencies. A scale factor loop may be driven from the 0.25Hz signal or it may be adjusted manually while the excitation is applied.

Adjusting second order mass compensation to minimise the in phase (I) and the quadrature (Q) components of the signal at 10Hz.

25 Adjusting second order spring stiffness compensation to minimise the components at 1Hz.

Iteratively repeating the adjusting steps to achieve matches better than 0.5%.

The external feedback path may provide the output signal,
30 demodulated at the spin frequency Ω by a demodulator, to correct for

mismatches in the strength B of the magnets in accelerometers. This feedback loop may also compensate for some part of the mismatches in proof mass and spring stiffness.

5 **Brief Description of the Drawings**

An example of the invention will now be described with reference to figure 1 which is a schematic diagram of a modified accelerometer pair embodying the present invention.

10 **Best Modes for Carrying out the Invention**

Accelerometer 1 comprises a proof mass 2 suspended by a spring 3 in a magnetic field provided by magnet 4. The proof mass 2 is associated with a position sensor 5 which provides a feedback signal through feedback loop 6 to a reaction coil 7 that retains the proof mass 2. The current i_1 flowing through coil 7 is taken as an output from output port 8.

Feedback loop 6 includes a position sensor amplifier 9, a compensation network 10 and another amplifier 11 arranged in series. In use an external acceleration causes a force to be applied to the proof mass 2 within accelerometer 1. Any tendency to movement of the proof mass 2 causes a current to flow in feedback loop 6 and through coil 7. The current flowing through retaining coil 7 in the magnetic field provided by magnet 4 causes an equal and opposite force to be applied to the proof mass 2 to compensate for the tendency to movement. The current i_1 flowing through the coil 7 is therefore a measure of the acceleration applied to the proof mass.

In a GGI the accelerometers are arranged in opposing pairs and the output i_1 from accelerometer 1 is added to the output i_2 from its paired accelerometer 12 and is combined with the output signals from the other pair of accelerometers in the GGI, in a summing amplifier 14, and the output is then filtered 15 to provide a signal to the instrument output 16.

An external feedback path 17 provides the output signal, demodulated at the spin frequency Ω by demodulator 18, to be applied to a small electromagnet 19 associated with the magnet 4. This feedback signal corrects for mismatches between the strength B of the magnet 4 in accelerometer 1 and the strength of the magnet in accelerometer 12. This feedback loop will also compensate for some part of the mismatches in proof mass m and spring stiffness k; in particular the compensation matches the real component of the mismatch at the spin frequency, but it cannot match at any other frequency or match the imaginary component of the mismatch. Below 2Hz the dominant parameters affecting mismatch are the spring constant k differences. Above 2Hz the dominant parameters are the proof mass m differences. At the preferred frequency of operation, below 1Hz, the external feedback loop can be thought of as providing dynamic correction for the magnetic field ratio B/k where B is the magnetic field strength and k is the spring stiffness.

The internal feedback path 6 includes high gains from the two amplifiers 9 and 11 to reduce errors in the accelerometer transfer function. This error reduction, as a function of frequency, is inversely proportional to the loop gain at that frequency. It follows that the mismatch in accelerometer pairs is a result of the difference of the closed loop errors.

The compensator 10 in the feedback loop 6 provides double pole and double zero compensation:

$$\frac{m_1 s^2 + k_1}{m_0 s^2 + k_0}$$

where:

m_1 is the mass of the proof mass

k_1 is the spring constant of the spring

m_0 is a nominal proof mass and

k_0 is a nominal spring constant.

This compensation corrects for the mass ratio (or F_0 frequency ratio) by providing an s^2 loop gain term as a mass compensator. The compensation also corrects for the spring ratio by providing a loop gain term which lumps together variations in pick-off gain, integrator capacitors and spring constant, as a spring stiffness k compensator.

The components of the compensation network 10 are typically resistors and capacitors. Variable components are introduced so that the break frequencies can be tuned over a $\pm 5\%$ range to match the masses m and the spring stiffnesses k of the accelerometer pairs to better than 0.5%. The closed loop gain blocks are trimmed in pairs to match the time constants to within 0.5%.

The accelerometer pairs are then tested in back to back fixtures on a horizontal shaker.

The accelerometers are selected on the basis of the best scale factor match at 0.5Hz and the lowest lateral sensitivity at 10Hz. Horizontal excitation at 0.25Hz, 1Hz and 10Hz (or higher) is input and the system response is detected with synchronous demodulation at these frequencies. A scale factor loop may be driven from the 0.25Hz signal or it may be adjusted manually while the excitation is applied. The mass compensation is adjusted to minimise the in phase (I) and the quadrature (Q) components of the signal at 10Hz, while the spring stiffness compensation is adjusted to minimise the components at 1Hz. The compensations are adjusted iteratively to achieve matches better than 0.5% since there is some interaction between the parameters.

It should be appreciated that although the invention has been described with reference to a particular example it could be embodied in many other forms. For instance, alternative parameterisation is possible besides the magnetic field ratio B/k , mass ratio and spring ratio. However the compensation must provide second order correction.

It will be appreciated by persons skilled in the art that numerous variations and/or modifications may be made to the invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be
5 considered in all respects as illustrative and not restrictive.

CLAIMS

1. An accelerometer comprising; a proof mass suspended by a spring within a magnetic field; an internal feedback loop provides a signal related to movement of the proof mass back through a reaction coil acting in the magnetic field, to maintain the proof mass stationary; an external feedback loop to adjust the accelerometer scale factor; wherein, the internal feedback loop provides second order compensation to the proof mass and the spring stiffness.

2. An accelerometer according to claim 1, wherein the internal feedback path includes high gain to reduce errors in the accelerometer transfer function.

3. An accelerometer according to claim 1, wherein there is a compensator in the internal feedback loop to provide double pole and double zero compensation as follows:

$$\frac{m_1 s^2 + k_1}{m_0 s^2 + k_0}$$

where:

m_1 is the mass of the proof mass

k_1 is the spring constant of the spring

m_0 is a nominal proof mass and

k_0 is a nominal spring constant

and,

the nominal proof mass and spring constant represent the accelerometer characteristics to which both accelerometers of a pair are to be matched in order that the two accelerometers are closely matched to each other.

4. In a gravity gradient instrument compensation is provided by the internal feedback loop to correct for the mass ratio (or Fo frequency ratio) mismatch between two paired accelerometers by providing a s^2 loop gain term as a mass compensator.

5. Compensation according to claim 4 wherein the compensation also corrects for the spring ratio by providing a loop gain term which lumps together variations in pick-off gain, integrator capacitors and spring constant, as a spring stiffness k compensator.
- 5 6. Compensation according to claim 5 wherein the components of the compensation network include variable resistors or capacitors so that the break frequencies can be tuned over a $\pm 5\%$ range to match the masses m and the spring stiffnesses k of the accelerometer pairs to better than 0.5%.
7. Compensation according to claim 6 wherein the closed loop gain
10 blocks are trimmed in pairs to match the time constants to within 0.5%.
8. A method of matching accelerometer pairs, comprising the steps of:
testing the pair of accelerometers in back to back fixtures on a
horizontal shaker which is aligned to the same vertical angle as in the GGI;
selecting the accelerometers on the basis of the best scale factor match
15 at 0.5Hz and the lowest lateral sensitivity at 10Hz;
applying horizontal excitation at a range of frequencies above 0.25Hz,
and detecting the system response with synchronous demodulation at those
frequencies;
adjusting second order mass compensation to minimise the in phase (I)
20 and the quadrature (Q) components of the signal at 10Hz;
adjusting second order spring stiffness compensation to minimise the
components at 1Hz; and
iteratively repeating the adjusting steps to achieve matches better than
0.5%.
- 25 9. Compensation according to claim 8 wherein a scale factor loop may be driven from the horizontal exit action or it may be adjusted manually while the excitation is applied.
10. Compensation according to claim 9 wherein the external feedback path provides the output signal, demodulated at the spin frequency Ω by a

demodulator, to correct for mismatches in the strength B of the magnets in accelerometers.

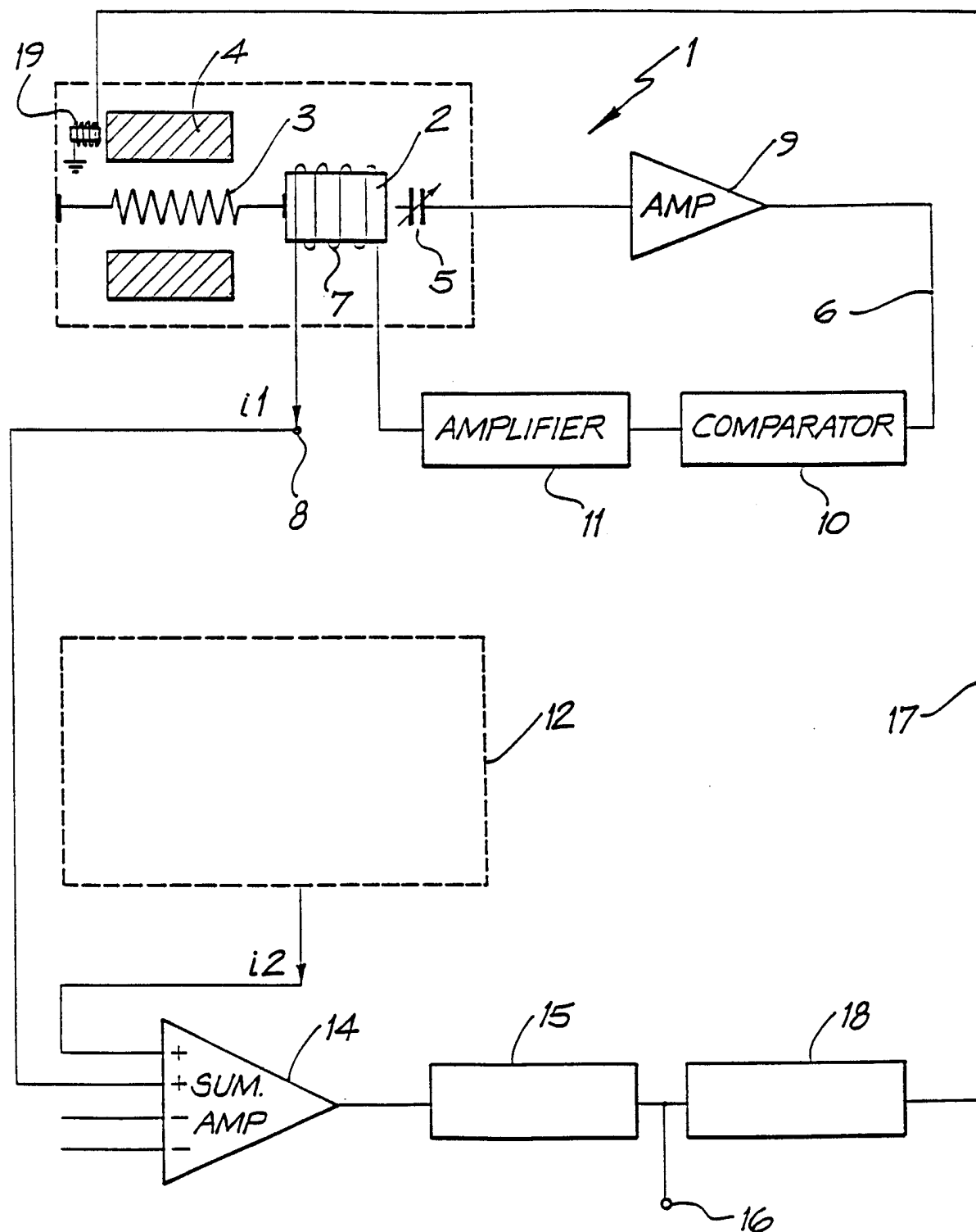


FIG. 1

INTERNATIONAL SEARCH REPORT

International Application No.
PCT/AU 98/00442

A. CLASSIFICATION OF SUBJECT MATTER		
Int Cl ⁶ : G01V 7/02, 7/04		
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) IPC: G01V 3/-, 7/-, G01P 15/-		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched AU: IPC as above		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) WPAT, JAPIO (GRAVI:, GRADI:, ACCELER:, COMPENSAT:, FEEDBACK, BALANC:, SPRING#, PROOF#, MASS:)		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	Derwent Abstract Accession No: B6043D/08, Class S03, SU 741221 A (BELENKII V A) 15 June 1980	1-10
A	Derwent Abstract Accession No: 97-041553/04, Class S03, RU 2059272 C1 (PERM POLY) 27 April 1996	1-10
A	Derwent Abstract Accession No: 96-250143/25, Class S03, RU 2046380 C1 (PERM POLY) 20 October 1995	1-10
A	US 3926054 A (BUCK) 16 December 1975 See Abstract	1-10
☒ Further documents are listed in the continuation of Box C ☒ See patent family annex		
* Special categories of cited documents: "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier document but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search 31 July 1998		Date of mailing of the international search report 11 AUG 1998
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200 WODEN ACT 2606 AUSTRALIA Facsimile No.: (02) 6285 3929		Authorized officer STEPHEN CLARK Telephone No.: (02) 6283 2164

INTERNATIONAL SEARCH REPORT

International Application No.
PCT/AU 98/00442

C (Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4457077 A (LAUTZENHISER) 3 July 1984 See Abstract	1-10
A	US 4841772 A (PAIK) 27 June 1989 See Abstract	1-10
A	US 5341681 A (MOLNY et al) 30 August 1994 See Abstract	1-10

INTERNATIONAL SEARCH REPORT

International Application No.
PCT/AU 98/00442**Box I** Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a)

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

Claim 1 relates to an accelerometer with a proof mass suspended by a spring in a magnetic field, an internal feedback loop to maintain the proof mass stationary, an external feedback to provide second order compensation.

Claim 4 relates to gravity gradient compensation provided by internal feedback loop to correct for mass ratio mismatch between two paired accelerometers by providing S^2 loop gain.

Claim 8 matches accelerometer pairs by testing, selecting, applying horizontal excitation and adjusting compensation.

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims
2. ☒ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest.
- ☐ No protest accompanied the payment of additional search fees.

Information on patent family members

PCT/AU 98/00442

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report			Patent Family Member				
SU	741221	NONE					
RU	2059273	NONE					
US	3926054	NONE					
US	4457077	CA	1215246	DK	3270/84	EG	16579
		GB	2143047	NL	8402029	NO	842694
US	4841772	AU	31910/89	CA	1321482	WO	89/05462
US	5341681	NONE					