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Hulsing et al.
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[54] ANGULAR RATE SENSOR WITH PHASE SHIFT CORRECTION

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[73] Assignee: **Sundstrand Data Control, Inc.**, Redmond, Wash.

[21] Appl. No.: **72,235**
[22] Filed: **Jul. 10, 1987**
[51] Int. Cl.⁴ **G01P 9/04**
[52] U.S. Cl. **73/505**; 73/510
[58] Field of Search .... 73/505, 510, 517 R; 364/453

[56] **References Cited**

U.S. PATENT DOCUMENTS

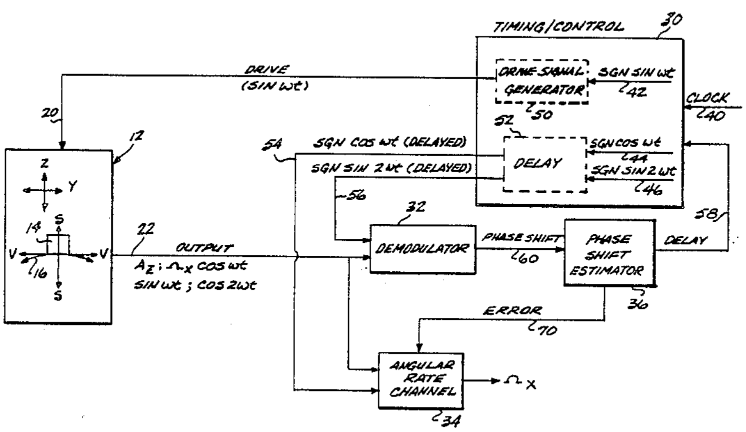
4,445,376	5/1984	Merhav	73/510
4,510,802	4/1985	Peters	73/505
4,590,801	5/1986	Merhav	73/510
4,665,748	5/1987	Peters	73/505

Primary Examiner—John Chapman
Attorney, Agent, or Firm—Christensen, O'Connor, Johnson & Kindness

[57] **ABSTRACT**

A Coriolis rate sensor comprising first and second accelerometers mounted with their force sensing axes parallel to a common sensing axis. The accelerometers are vibrated along arcs in response to a periodic drive signal at a first frequency, each arc being tangent to a vibration axis normal to the sensing axis. The accelerometer output signals are demodulated to determine angular rate, as well as to detect the phase shift between the drive signal and the periodic compounds of the output signals. In one arrangement, the detected phase shifts are used to drive a phase servo that tends to reduce the bias error caused by interaction between the phase shifts and misalignments of the accelerometers with respect to the sensing axis. In another arrangement, the phase shifts are used to calculate a bias term for correcting the measured angular rate. A single accelerometer embodiment is also described.

19 Claims, 3 Drawing Sheets



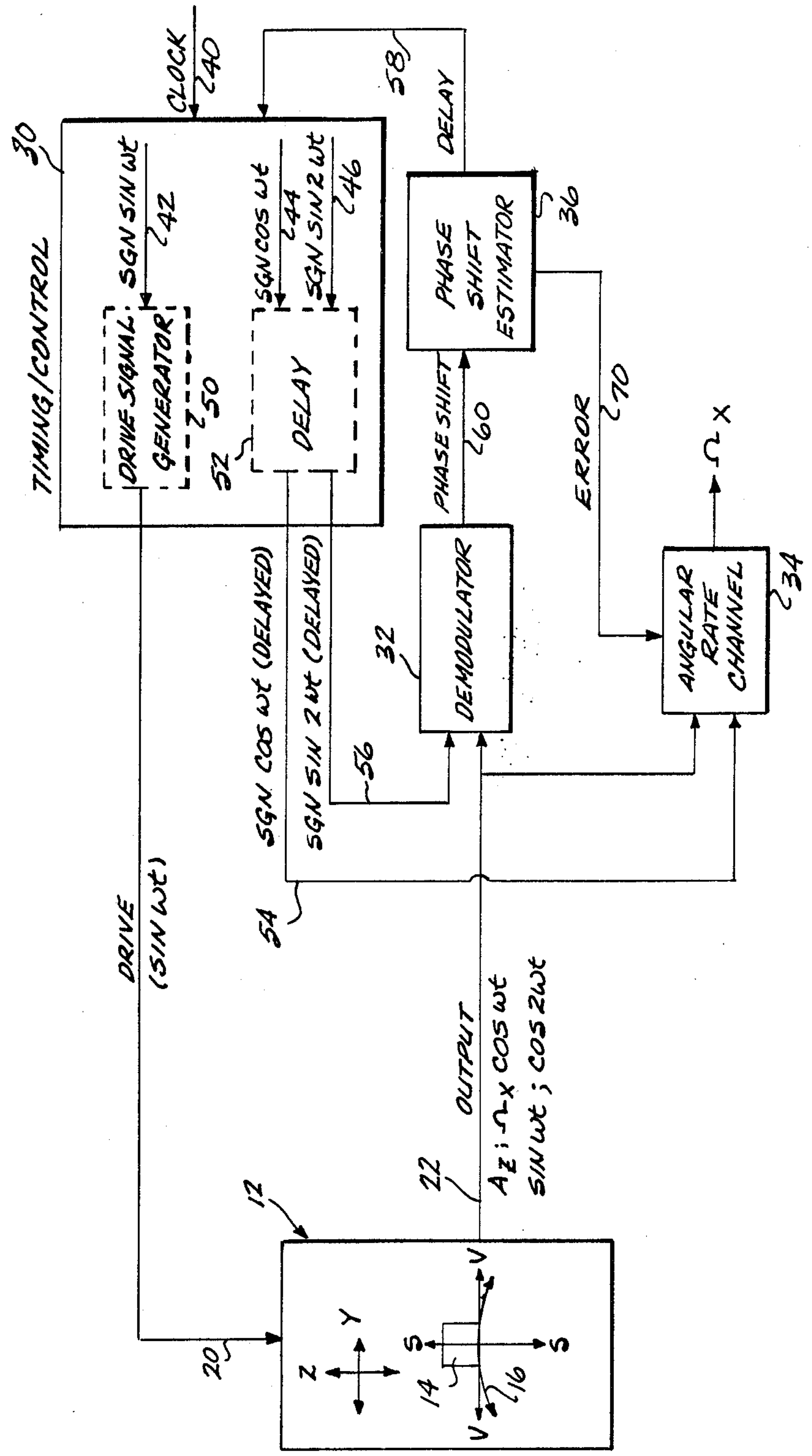

CLOCK
40
58
DELAY
30
TIMING/CONTROL
SGN SIN ωt
42
SGN COS ωt
44
SGN SIN 2ωt
46
DRIVE SIGNAL GENERATOR
50
DELAY
52
PHASE SHIFT ESTIMATOR
36
PHASE SHIFT
60
ERROR
70
Ω X
ANGULAR RATE CHANNEL
34
DEMODULATOR
32
SGN COS ωt (DELAYED)
SGN SIN 2ωt (DELAYED)
56
54
DRIVE
(SIN ωt)
OUTPUT
AZ ; Ω X COS ωt
SIN ωt ; COS 2ωt
22
12
20
Z
Y
S
S
V
V
14
16

Fig. 1.

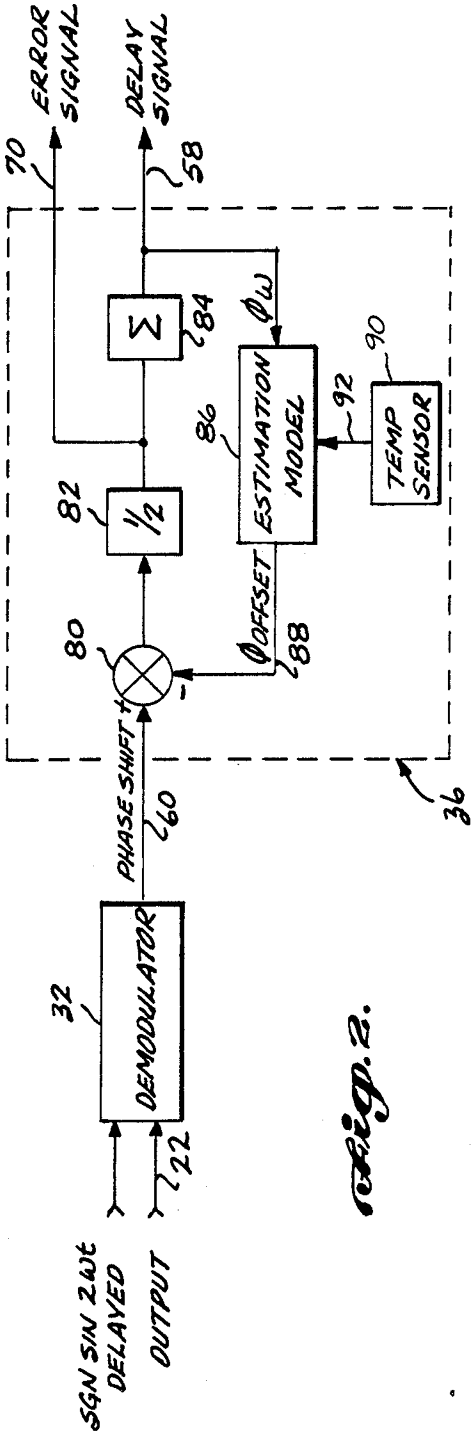

ERROR SIGNAL
DELAY SIGNAL
70
58
84
90
92
86
ESTIMATION MODEL
TEMP SENSOR
82
1/2
80
PHASE SHIFT
OFFSET
88
60
36
32
DEMODULATOR
22
SGN SIN 2ωt DELAYED
OUTPUT

Fig. 2.

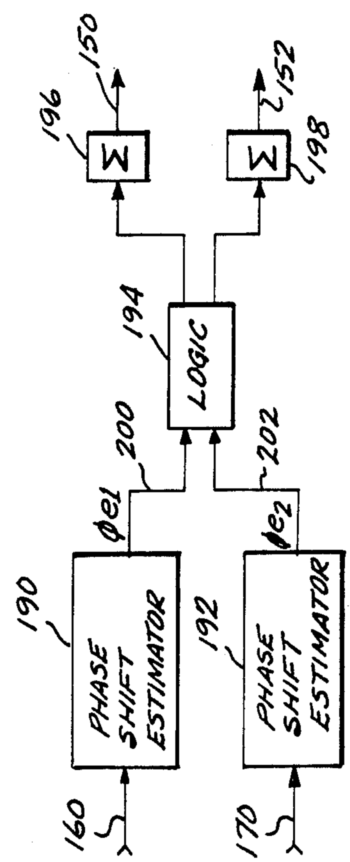

196
150
152
198
194
LOGIC
200
202
190
PHASE SHIFT ESTIMATOR
192
PHASE SHIFT ESTIMATOR
160
170

Fig. 4.

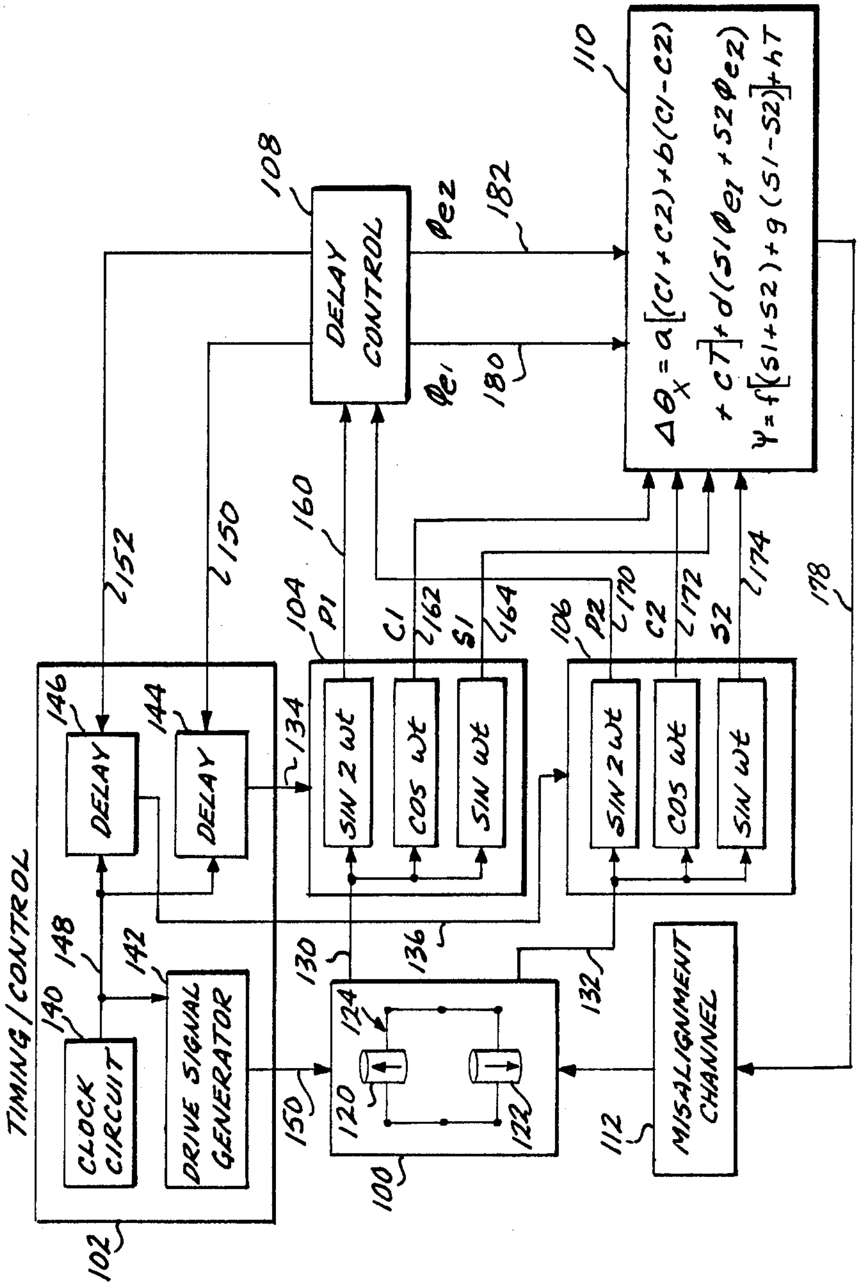

TIMING/CONTROL
CLOCK CIRCUIT
DRIVE SIGNAL GENERATOR
DELAY
DELAY
SIN 2 ωt
COS ωt
SIN ωt
SIN 2 ωt
COS ωt
SIN ωt
DELAY CONTROL
MISALIGNMENT CHANNEL
$\Delta\theta_x = a[(C1+C2)+b(C1-C2)+cT]+d(S1\phi_{e1}+S2\phi_{e2})$
$\Psi = f[(S1+S2)+g(S1-S2)]+hT$
P1
C1
S1
P2
C2
S2
ϕ_{e1}
ϕ_{e2}
100
102
104
106
108
110
112
120
122
124
130
132
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Fig. 3.

ANGULAR RATE SENSOR WITH PHASE SHIFT CORRECTION

TECHNICAL FIELD

The present invention relates to an apparatus for determining angular rate of rotation utilizing accelerometers.

BACKGROUND OF THE INVENTION

Angular rate of rotation about a given coordinate axis may be measured by moving (e.g., vibrating) an accelerometer along an axis normal to the accelerometer's sensitive axis and normal to the rate axis about which rotation is to be measured. For example, consider a set of X, Y, Z coordinate axes fixed in a body whose rotation rate is to be measured, and an accelerometer also fixed in the body with its sensitive axis aligned along the Z axis. If the angular rotation vector of the body includes a component along the X axis, then periodic motion of the accelerometer along the Y axis will result in a periodic Coriolis acceleration acting in the Z direction that will be sensed by the accelerometer. The magnitude of the Coriolis acceleration is proportional to the velocity along the Y axis and the rotation rate about the X axis. As a result, the output of the accelerometer includes a DC or slowly changing component that represents the linear acceleration of the body along the Z axis, and a periodic component that represents the rotation of the body about the X axis. The accelerometer output can be processed, along with the outputs of accelerometers that have their sensitive axes in the X and Y directions and that are moved along the Z and X axes, respectively, to yield linear acceleration and angular rate about the X, Y and Z axes. Such signal processing is described in U.S. Pat. Nos. 4,445,375 and 4,590,801.

As described in U.S. Pat. No. 4,590,801, one preferred embodiment of a rotation rate sensor comprises, for each axis, two accelerometers oriented with their sensitive axes parallel or antiparallel to one another, and means for vibrating the accelerometers along an axis normal to their sensitive axes. A suitable method for vibrating such accelerometer pairs is described in U.S. Pat. No. 4,510,802. In the system described in that patent, a parallelogram structure is used to vibrate the accelerometers along a common vibration axis. In such an arrangement, it may be demonstrated that a bias error is produced by interaction between misalignment of the accelerometers with respect to the desired sensitive axis, and the phase shift between the motion of the accelerometers and their resulting output signals. This bias error results from the fact that the misalignment causes the accelerometer to sense a component of the acceleration used to vibrate the accelerometers. In the absence of any phase shift, this component is synchronous with the acceleration caused by the vibration, and therefore 90° out of phase with the vibration velocity and therefore with the Coriolis acceleration. The vibration acceleration therefore would be cancelled in the rate channel. However because of the phase shift introduced by the accelerometer between its vibration velocity and the Coriolis component of its output signal, the vibration acceleration component is phase shifted so that it includes a subcomponent that is in phase with the vibration velocity, and that therefore shows up in the rate channel. This interaction between misalignment and phase shift is the largest source of bias error in an angular rate sensor of this type.

An approach to eliminating the above-described rate bias is set forth in U.S. Pat. No. 4,665,748. In the system described in that patent, the angular rate output of the accelerometers is demodulated by a signal in phase with the accelerometer motion, to produce a feedback signal that is used to drive the components of the accelerometer output signal that are synchronous with the accelerometer motion toward a null value. The present invention relates to an improved technique for reducing the bias error caused by interaction between misalignment and phase shift of the accelerometers.

SUMMARY OF THE INVENTION

The present invention provides an angular rate sensor with an improved bias reduction technique. In a preferred embodiment, the angular rate sensor includes a phase servo that operates to reduce the phase shift between the accelerometer output signal and the demodulation time reference.

In one preferred embodiment, the angular rate sensor comprises an accelerometer assembly, timing/control means, first and second demodulation means, rate channel means, and delay control means. The accelerometer assembly comprises first and second accelerometers mounted such that their force sensing axes are parallel to a common sensing axis, and means for vibrating the accelerometers along arcs, each of which is tangent to a vibration axis normal to the sensing axis. In this context, the term "parallel" should be understood to include "antiparallel." In a preferred embodiment, the force sensing axes of the accelerometers are antiparallel to one another. The accelerometer assembly also includes drive means for vibrating the accelerometers along their respective arcs at a first frequency in response to a periodic drive signal at the first frequency. Thus the output signal of each accelerometer includes a component at a second frequency equal to twice the first frequency.

The timing/control means generates a periodic master timing signal from which the drive signal is derived. The master timing signal is also used to generate first and second timing signals. The first timing signal represents a first rate component at the first frequency in quadrature phase with respect to the drive signal, and a first phase shift component at the second frequency in phase with the drive signal, the first timing signal being delayed by a first time delay that is a predetermined function of a first delay signal. In a similar manner, the timing/control means generates a second timing signal that represents second rate and phase servo components, and that is delayed by a second time delay that is a predetermined function of a second delay signal. The first demodulation means demodulates the first output signal using the first rate component to produce a first rate signal, and demodulates the first output signal using the first phase shift component to produce a first phase shift signal. Similarly, the second demodulation means demodulates the second output signal using the second rate component to produce a second rate signal, and demodulates the second output signal using the second phase shift component to produce a second phase shift signal. The rate signals are used by the rate channel means to provide a measure of angular rate about an axis normal to the sensitive vibration axes.

The delay control means receives the first and second phase shift signals, and produces the first and second

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