

Inertial Guidance Sensors

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Preface

IN GENERAL, a navigational or guidance system will include instruments for sensing or measuring some physical variable or variables; the means for computing, from such measurements, the direction of travel, speed and position of the vehicle; and auxiliary equipment (power supplies, environmental controls, etc.) for ensuring proper functioning of the measuring and computing means.

In the inertial method of navigation or guidance, the essential sensors or measuring means take the form of an orthogonal set of *accelerometers*, stabilized by *gyros* so as to sense components of vehicle acceleration in a frame of reference having a definite spatial orientation. The accelerometer signals are integrated and processed in a computer to yield components of vehicle velocity and position in a selected coordinate system. In many cases *optical trackers* are provided to supplement or correct the gyro directional information.

Inertial and inertial-optical methods are based on measurements made with respect to an earth-independent frame of reference (so-called inertial space, defined in the Introduction), rather than with respect to earth-fixed objects or fields. By reason of this fact they are remarkably versatile—more so than any other kind of method. Basically similar assemblages of sensors, computers, and auxiliary equipment are used for navigation of ships and aircraft, guidance of ballistic vehicles, and for certain phases of extraterrestrial navigation. Moreover, the measurements are made in accordance with physical laws of extreme exactness—the Newtonian laws of motion and of gravitation. This fact implies an accuracy potential superior to that which is expected for methods based on such empirical relationships as are involved in air speed measurement and magnetic compass indications, for example. The features of versatility of application, independence of need for radiating energy to or from the earth, and virtually unlimited potential accuracy, have made inertial methods of the highest military importance. In fact, development

and applications so far have been almost exclusively for military purposes. However, the features mentioned are attractive in any kind of navigation, military or civilian. The subject of inertial guidance must not be thought of merely as a branch of military engineering, but rather as a branch of navigational engineering.

Inertial guidance theory and practice has been the subject of extensive treatment in the U.S. and Soviet literature, with emphasis generally on dynamics, kinematics, error propagation, alignment and similar topics of primary interest to the designer and analyzer of systems.

The present work is restricted to the sensing instruments; the gyros, accelerometers and optical trackers. It may be thought of as a supplement to general treatises on inertial guidance. Only so much of inertial guidance theory is outlined (in the Introduction) as to give meaning to the requirements and specifications to be met by the sensing instruments. The body of the text is confined, so far as possible, to discussion of the instruments as such.

Furthermore, the approach emphasizes aspects of the subject other than mere dynamic analysis. In dealing with the sensors, there have been kept in mind the needs not only of those who invent and design the instruments but also of those who use them, in the broad sense of the word, that is, incorporate them into systems. The objective of the work is to describe the principles of operation of the instruments, to explain how the various kinds work, and to indicate the factors which determine their accuracy and other important properties.

As already stated, the laws on which inertial guidance is based are simple and accurate. The instruments for mechanizing the laws are basically simple, but they are not basically accurate. The latter quality is not a law of nature but something which must be built in. The problems and difficulties encountered in providing satisfactory inertial guidance equipment are not due to any shortcomings in theory. Instead, they are a consequence of the extremely high accuracy which is required of the sensing instruments in order to achieve even marginal system accuracy. This apparent paradox will be explained in the Introduction. For the present it is sufficient to point out that the provision of satisfactory inertial guidance sensors has taxed, and continues to tax, the instrumentation art to the abso-

lute limit, and has forced the introduction of methods and means which were unheard of even a few years ago.

In the early postwar years, the technology of inertial guidance sensors was essentially a branch of machine design, handled by classical mechanical, electrical and optical engineering methods. The instruments were mechanisms built up of wheels, pendulums, gears and other such familiar elements. At present the technology of the sensing instruments for inertial and optical navigation is in a state of flux or transition analogous to the invasion of the traditional electronics field by "molecular electronics." The instrumentation engineer relies increasingly on discoveries and applications in the fields of solid-state physics and molecular engineering.

One aspect of such dependence is to seek solutions for problems in precision mechanism design which were largely ignored in classical engineering, such as achieving microstability of materials of construction or meeting critical surface-condition requirements for one purpose or another.

Another aspect of the transition is the development of instruments, exemplified by the free-rotor type of gyro, the electrostatically supported type of accelerometer, and the computed-scan type of optical tracker, in which extreme mechanical simplification is achieved by relying completely upon electronic circuits to perform functions previously performed by mechanical elements.

A third aspect is the conception of radically new kinds of instruments in which the sensing functions are to be performed by taking advantage of the inertial properties of atomic nuclei or other subatomic systems or particles, with the intention of entirely circumventing the problems associated with instruments based on the inertial properties of bulk material. (It must be emphasized that the subject of instrumentation of the Newtonian laws at the subatomic level is in such an early stage of thought that even potential practicability has not yet been established. The subject is in the province of the research physicist, rather than the instrumentation engineer, and will receive only brief notice in the present text.)

The state of flux of the inertial guidance sensor art necessarily makes impossible the presentation of a definitive treatise. Nevertheless, by examining the whole field of inertial guidance sensors, as is done in the present text, it is possible to reveal common principles

and to show a unity which is not readily discernible by unconnected studies of isolated instruments. Such background will be of aid in understanding existing instruments and their limitations, in relating proposals for novel instruments to the existing state of the art, and in choosing the most practical lines of attack in research and development.

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Contents

Preface	iii
Introduction	1

Part A: GYRO

1 Principles of Operation and Classification	15
2 Gyros Utilizing Gimbaled Rigid Rotors (Dynamics)	22
Dynamics and Stabilization, Single-axis Gyros	23
Dynamics and Stabilization, Double-axis Gyros	36
Sources of Error	40
Acceleration-dependent Torques	42
Acceleration-independent Torques	49
Trigonometrical Sources of Errors (Misalignments)	50
Autocompensation Methods	51
Case Rotation Method	52
Rotor Speed Modulation Method	52
Dynamical Quantities, Table	53
3 Gyros Utilizing Gimbaled Rigid Rotors (Design Features)	55
Mechanical Components	56
Spin Bearings	57
Gimbals	66
Output-axis Bearings	69

Electrical Components	72
Gyro Drive Motors	72
Pick-offs	72
Torquers	75
Lead-ins	75
Magnetic Shields	76
4 Gyros Utilizing “Ball-and-Socket” Supported Rigid Rotors	78
Dynamics and Stabilization	79
Sources of Error	82
Acceleration-dependent (Mass-unbalance) Torques	83
Torques Associated with Faulty Geometry	85
Torques Due to Viscous Coupling of Rotor and Stator	89
Motion of Spin Axis Relative to Axis of Figure	94
Design Features	97
Gas-film Support (Hydrodynamic Bearing)	98
Electrostatic Support	101
Magnetic Support (Superconductive Rotor Type)	104
Magnetic Support (Ferromagnetic Rotor Type)	107
5 Gyros Utilizing Vibratory Bodies	109
The Foucault Pendulum Re-examined	109
Vibratory Gyros, Displacement Type	113
Vibratory Gyros, Rate Type	114
6 Gyros Utilizing Moving Bodies of Fluid (Liquid or Gas)	119
Gyros Utilizing the Angular Momentum of a Spinning Liquid Body	120
Gyros Utilizing Coriolis-force Measurements	127
7 Gyros Utilizing the Inertial Properties of Particles	134
Nuclear Angular Momentum Instruments	136
Instruments Utilizing Translational Momentum of Electrons	138
Conclusions	140

CONTENTS

ix

Part B: ACCELEROMETERS

8 Accelerometers: Introduction, Classification and Nomenclature	140
Introduction	140
Acceleration of Gravity	149
Units of Acceleration	151
Classification and Nomenclature	151
Classification in Terms of Nature of Output-vs-input Function	151
Classification in Terms of Physical Principles	153
9 Accelerometers, Mechanical Types	156
Accelerometers Making Use of Spring Distortion Force	156
Accelerometers Making Use of Viscous-shear Force	160
Accelerometers Making Use of Inertial Force (Newton's Second Law of Motion)	162
Gyropendulum Type	162
Reaction-rotor Type	163
Vibrating-string Type	165
Centrifugal-force-balance Type	166
Accelerometers of Kinematic Type	167
Transit-time ("Falling-ball") Type	167
Physical Pendulum ("Clock-pendulum") Type	168
10 Accelerometers, Electrical Types	170
Electrostatically Restored Accelerometers	170
Electromagnetically Restored Accelerometers	172
Coil-and-magnet Type	173
Accuracy as Affected by Servo System Performance	176
Induction (Cup-and-magnet) Type	181
Eddy-current Induction Torque Generation, Principles	182
Permanent Magnets as Precision Instrument Components	186
Precision Measurement of Permanent Magnet Fields	187
Permanent Magnet Materials	189
Minimizing the Temperature Coefficient of Magnetic Field Intensity	191

Stabilization of Instrument Magnets	191
Geometrical Considerations	193
11 Gravitational Field Measurements with Accelerometers (on Unstable Bases)	195
Gravimetry	195
Gravitational Gradient Measurements	197
 Part C: OPTICAL TRACKERS	
12 Optical Trackers	201
Introduction	201
Searching and Tracking Operations	206
Angle Measurement	207
Photosensitive Devices	210
Accuracy Requirements	211
Special Features of Optical Trackers for Terrestrial Use	212
Special Features of Optical Trackers for Extraterrestrial Use	214
Camera-type Devices	215
Concluding Remarks	215
Index	217

Introduction

NAVIGATION OR GUIDANCE of a vehicle on the earth always presupposes measurements made with respect to frames of reference, independent of the vehicle, with respect to which the vehicle moves. This is most readily visualized in celestial navigation. The starry sky constitutes a frame of reference which is independent of the ship and, for that matter, also independent of the earth. It presents a sort of natural map containing a large number of known points. By observing the ocean horizon and applying corrections for dip, the navigator finds the direction of the line to the center of the earth (earth oblateness being ignored for the present). Then, in effect, he projects this line to the sky map and, taking time into account, determines position in latitude and longitude. He must take time into account because the celestial frame of reference is angularly fixed whereas the earth is rotating.

The vehicle-independent frames of reference are perfectly tangible in the foregoing example. The observer actually sees the stars and the horizon. Other examples of navigational methods utilizing tangible frames of reference are radio methods based on receipt of signals from shore stations of known position, and position-finding with the aid of an odometer and a magnetic compass. In these cases the earth itself provides the vehicle-independent frames of reference.

Inertial guidance or navigation is basically akin to these more familiar methods but differs in that the frames of reference are intangible and the methods of measurement are of a self-contained nature in the sense that receipt of energy or determination of direction of fields outside the vehicle is not required.

Inertial guidance or navigation is the process of directing the movements of a rocket, ship, aircraft or other vehicle, from one point to another, which is based on sensing components of acceleration of the vehicle in known spatial directions, by instruments which

Electrical Components

The principal electrical components are the gyro drive motor, the transducers* (pick-offs and torquers) and the electrical connections for energizing these devices. Magnetic shielding is also taken up, since it is in some cases a necessary adjunct to the electrical components.

Gyro Drive Motors. Gyro motors are critical from a structural point of view, because of their substantial mass. The principal requirement is mechanical rigidity and stability, under conditions of vibration and also of thermal changes. Monolithic ferrite (as distinguished from laminated iron armatures) and ceramic insulation and "potting" are coming into use to achieve those conditions. The motors ordinarily are of the polyphase hysteresis synchronous type, run from a controlled-frequency power supply. Constancy of speed is desirable because some sources of disturbing torque are speed-dependent; it is needed to insure a constant angular momentum so that a given applied control torque will produce a predetermined angular velocity of precession. Short-period speed variations, as in the "hunting" of a synchronous motor for example, ordinarily are of no importance. The nonconstant nature of the power input, characteristic of the hysteresis type of motor, can have some troublesome side effects, but the simplicity of this type makes it prevail over others with which constancy could be assured.

Pick-offs. The pick-offs for output-axis gimbals or floats have the requirements of high angular sensitivity (typically one second of arc or better), a correspondingly low value for drift or shift of null, and essentially zero coercion. Since the pick-off is used in a null-seeking system, constancy of scale factor is of subordinate importance, though symmetry of the scale factor function about null is important. Design for adequate mechanical rigidity to avoid null shift under acceleration, as well as mass-shift torques, must not be overlooked. Typical pick-offs are as follows.

Capacitor pick-off systems typically include as the sensing element a differential-type capacitor of variable effective area or (and more usually) variable gap. The capacitor may be used in a bridge

* A broad and useful survey of pick-offs and torquers, for various kinds of instruments, is presented by Lion.¹⁰

circuit or in a resonant circuit to control either the frequency or the impedance of the circuit. The carrier voltage excitation for the pick-off may be either in the audio- or radio-frequency range. Figure 3.6 shows two representative capacitor pick-off circuits. In

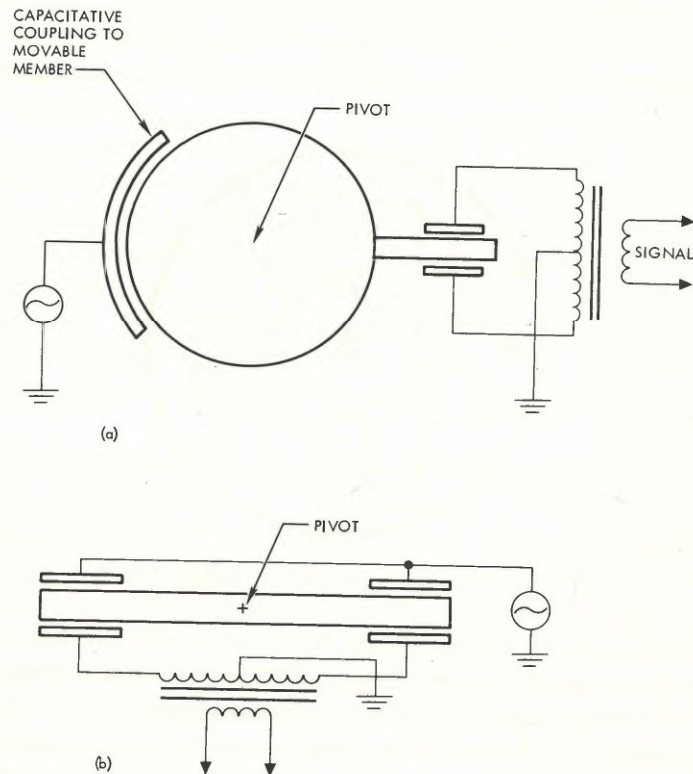


Figure 3.6. Capacitor pick-off circuits.

form (a) the movable electrode is excited, via capacitive coupling; this is the system shown for the gas-film supported free-rotor gyro described in a later section. Form (b), with the movable electrodes electrically floating, is employed when for any reason it is not desired to apply excitation to the movable member. The gyro of Figure 3.1 is provided with this form of pick-off; only the movable electrodes are shown, for the sake of clarity.

The high impedance characteristic of the capacitor type of pick-off generally requires the use of a step-down impedance-matching

transformer or the use of closely-adjacent preamplifiers. Advantageous features are mechanical simplicity and ruggedness, elimination of need for a lead-in wire to the moving element, noncritical material requirements, high sensitivity, high signal-to-noise ratio, and low coercion.

"Microsyn"-type pick-offs (Figure 3.7) have found extensive use. The primary is energized with audio-frequency alternating cur-

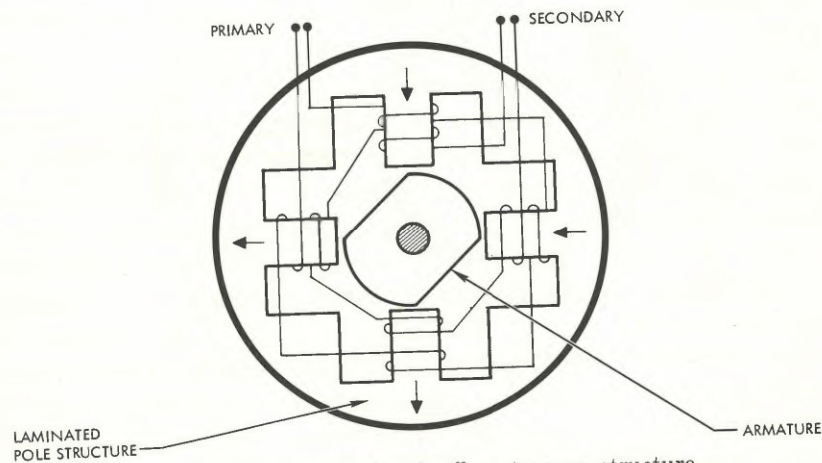


Figure 3.7. "Microsyn" pick-off or torquer structure.

rent. Departure of the armature from null (the position shown) results in a voltage across the secondary due to a change in the reluctance of the magnetic circuit of phase depending on the direction or rotation and amplitude proportional to angle over a limited range. Close control of geometry and of magnetic properties of the materials is required to bring the coercive torque to a tolerable level.

The moving-coil type of electromagnetic pick-off (not illustrated) makes use of a signal coil (iron-free) usually of discoidal shape mounted at a radius on the gimbal which is adjacent to a fixed two-pole iron armature energized with alternating current at audio frequency. Displacement of the coil from null results in a phase- and amplitude-sensitive voltage signal. Sensitivities equaling that of the capacitor type are readily obtained. The moving-coil type is relatively noncritical with regard to configuration. The chief practical limitations are in the requirement for flexible leads to the

moving element and in the need for selecting coil-potting materials which are inert with respect to the flotation liquid if such is used. This type of pick-off is falling into disuse for gyros and accelerometers. However, it remains a very useful device for laboratory instrumentation, its low-impedance characteristic making for simpler circuitry than for the capacitor type.

Torquers. Gyro torquers, sometimes called torque motors or torque generators, have only moderate requirements as regards linearity and constancy of scale factor if used merely for trimming, i.e., compensation of a small fixed bias torque. Torquers of variable-electromagnet type are adequate for such purposes. One such type takes the form essentially of the "Microsyn" pick-off structure already described, but with the primary winding energized from a constant a-c or d-c supply, the signal (alternating or direct current, respectively) being applied to the secondary. The torque output is a function of the in-phase product of the currents in the two windings.

Torquer requirements are very severe when the torquer is required to produce high, variable precession velocities in inertial space, such as a component of earth rate Ω , variable with latitude. Types which have found practical use are based on the force associated with a d-c-carrying conductor disposed within a permanent-magnet field. The torquer may have a configuration essentially like that of a d'Arsonval galvanometer movement, as indicated in Figure 3.1, the coil being mounted on the gyro gimbal and the magnet structure on the gyro case. Alternatively it may take the form of a coil mounted on a lever arm on the gimbal, and a permanent-magnet structure on the case, as in the form shown in Figure 2.7 or as illustrated and described in the section on electromagnetic accelerometers. A third alternative makes use of a conductive drag cup on the gimbal, concentric with the output axis, and a rotating magnet on the case.¹¹ In all forms, accuracy is determined ultimately by the stability and constancy of the magnetic field. The problems involved in establishing accurate permanent-magnet fields are discussed in the section on Permanent Magnets as Precision Instrument Components in Chapter 10.

Lead-ins. Lead-in wires or ribbons are required to bring current to the gyro motor and to the pick-offs and torquers when moving-