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History of Key Technologies

Blazing Gyros: The Evolution of Strapdown Inertial Navigation Technology for Aircraft

Paul G. Savage
Strapdown Associates, Inc., Maple Plain, Minnesota 55359

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Introduction

INERTIAL navigation is the process of autonomously calculating the position and velocity of a moving vehicle from measurements of angular rotation and linear acceleration provided by vehicle-mounted inertial sensors (gyros and accelerometers). The first inertial navigation system (INS) was developed at the Massachusetts Institute of Technology (MIT) Instrumentation Laboratory (eventually becoming the Charles Stark Draper Laboratory) for ballistic missile guidance [1]. (The INS includes velocity, attitude, heading, etc. outputs. In commercial application parlance, it also includes guidance steering outputs based on an input waypoint-defined flight profile.) Soon thereafter, the technology was applied to aircraft navigation, with four companies eventually dominating the U.S. aircraft inertial navigation industry in the 1960s: Honeywell Aerospace and Defense Group with gyro design and manufacturing in Minneapolis, Minnesota, and INS design, development, and manufacturing in Clearwater, Florida; Kearfott in Wayne, New Jersey; Litton Guidance and Control Division in Woodland Hills, California; and Delco Electronics Division of General Motors in Milwaukee, Wisconsin. Honeywell specialized in high-accuracy systems and introduced a new electrostatically suspended gyro (ESG) technology for precision applications. Delco concentrated on transoceanic commercial and military cargo/tanker aircraft applications using the Carousel IV system (a variation of the Titan II ballistic missile inertial guidance set). Litton and Kearfott focused on medium-accuracy military tactical aircraft and airborne missile applications. To achieve required gyro accuracy, each of the aforementioned inertial navigation systems was configured with gimbaled platforms to isolate the inertial sensors from aircraft angular rates.

INS advanced development at Litton and Kearfott in the 1960s centered on improving accuracy, reducing size, weight, and cost, and improving reliability of gimbaled INS products (important requirements for expanding military aircraft and airborne missile applications). A key contribution was the introduction of dry tuned-rotor-gyro (TRG) technology. Delco focused on reliability improvement for transport applications. Honeywell focused on improved accuracy and reliability of ESG gimbaled systems.

For future cost, reliability, and size reduction based in part on projected advances in computer technology, several companies (most prominently, Honeywell) focused a significant portion of company resources on a radically new strapdown approach to inertial navigation: replacing the gimbaled platform with a computerized analytical equivalent and mounting ("strapping down") the inertial sensors directly to the user vehicle. Based on technical books, journals, internet archives, discussions with past colleagues, but mostly from direct experience and personal records, this paper describes the curious and sometimes convoluted path by which the Honeywell strapdown program eventually led to development of the ring laser gyro (RLG) strapdown INS and conversion from gimbaled to strapdown technology throughout the airborne inertial navigation industry.

For technical background, the paper first discusses the concept of inertial navigation using gimbaled versus strapdown system

Paul G. Savage is an internationally recognized expert in the design and testing of strapdown inertial navigation systems, and is the President of Strapdown Associates, Inc., a company he founded in 1980. Strapdown Associates has provided software and engineering services to government agencies and aerospace companies for strapdown inertial system configuration definition, flight software development, system simulation, and testing. Mr. Savage has published and presented several papers on strapdown inertial navigation systems and associated computational elements. From 1974 to 2009, he served as an author/speaker on several NATO AGARD and Research and Technology Organisation technology transfer lecture series tours. From 1981 to 2009, Mr. Savage provided his *Introduction to Strapdown Inertial Navigation Systems* course to the aerospace industry. Since 2011, he has provided a two-day focused version of the *Intro to Strapdown* course onsite at host facilities in the continental United States. He has written and published the textbook *Strapdown Analytics* (available from Strapdown Associates), detailing the analytical aspects of strapdown inertial navigation system design. From 1963 to 1980, Mr. Savage was employed at Honeywell Avionics Division as Senior Principal Engineering Fellow, where he led engineering design teams and provided technical consultation to Honeywell engineering managers for system design, analysis, software development, simulation, and integration/test in the evolutionary development of laser gyro strapdown inertial navigation systems for military and commercial aircraft. From 1971 through 1975, he was the Engineering Manager and System Design Engineer for the strapdown Honeywell Laser Inertial Navigation System (LINS), the first to prove the readiness of laser gyro strapdown inertial navigation technology for aircraft applications, as demonstrated during a landmark flight-test series at Holloman Air Force Base in 1975. Mr. Savage is a graduate from the Massachusetts Institute of Technology, where he received his BS and MS degrees in aeronautical engineering in 1960. He is a Senior Member of the AIAA.

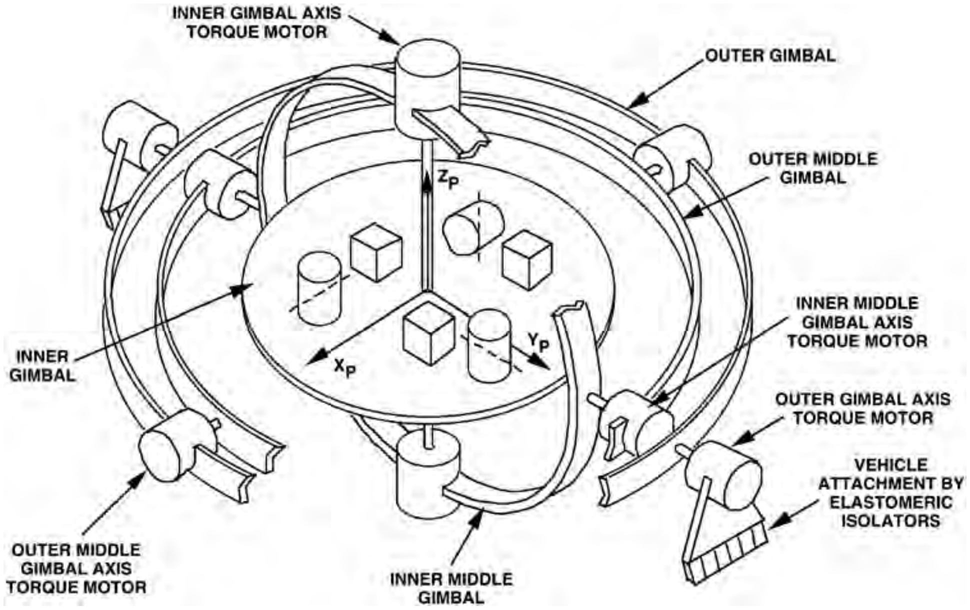


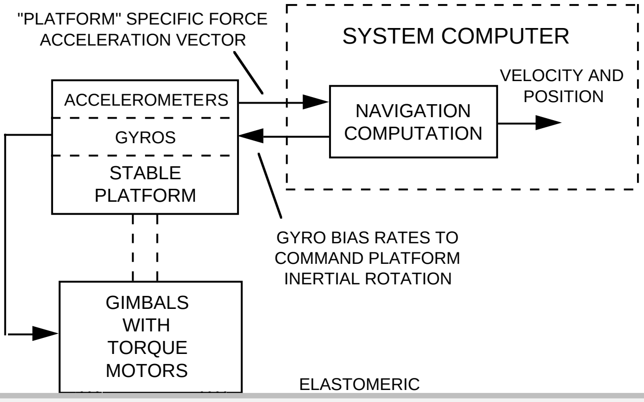
Fig. 1 Gimbaled platform schematic.

implementations. Angular rotation sensors (gyros), the key instruments in inertial systems, are briefly described and compared for the strapdown approaches considered along the way. The Honeywell GG1300 RLG is described in more detail, the first RLG to meet aircraft strapdown INS accuracy and reliability requirements. Most of the paper focuses on the interrelationships and testing of four Honeywell strapdown inertial systems developed in the early through mid-1970s: the Advanced Tactical Inertial Guidance System (ATIGS), the Laser Inertial Navigation System (LINS), the Ring Laser Gyro Navigator (RLGN), and the Laser Inertial Reference System (IRS) Prototype using a new, smaller size Honeywell GG1342 RLG, the latter known at Honeywell as the 7 × 7 Laser IRS Prototype system. Flight testing of the four Honeywell systems is described: ATIGS by the U.S. Navy's Naval Weapons Center (NWC), LINS by the U.S. Air Force Central Inertial Guidance Test Facility (CIGTF) at Holloman Air Force Base, the RLGN by the U.S. Navy's Naval Air Development Center (NADC), and the 7 × 7 Laser IRS Prototype by The Boeing Company. The proposal process for the new Boeing 757/767 commercial airplane strapdown IRS is also discussed, which, with 7 × 7 Laser IRS Prototype flight-test results, led to the selection of Honeywell for the multiyear 757/767 IRS large-scale procurement contract, the first for both aircraft strapdown inertial systems and for RLGs. The paper concludes with an epilogue of how the Honeywell and Boeing programs soon led to the general conversion from gimbaled to strapdown system technology throughout the entire aircraft inertial navigation industry.

Gimbaled Versus Strapdown System Implementation Approaches

Inertial sensors in a gimbaled INS are orthogonally mounted to a common base (platform) surrounded by concentric gimbals, interconnected to the platform and each other through ball-bearing shafts (depicted schematically in Fig. 1, the cylinders representing gyros, cubes accelerometers, and input axes are dashed). Nonrotation of the Fig. 1 sensor platform is actively controlled by torque motors mounted on the gimbal shafts, driven by gyro output measurements of platform rotation. Four-gimbal platforms (Fig. 1) were typically used in aircraft applications for operation at any vehicle angular orientation, while maintaining the three inner gimbal shafts near perpendicularity (the optimum orientation for minimum gimbal torque-motor size/power requirements under dynamic angular maneuvering).

INS computer to calculate velocity and position. Feedbacks from the navigation computer bias the platform gyros (when allowable for the gyro configuration), commanding the platform to follow prescribed small angular rotation rates (e.g., to maintain a locally vertical platform orientation relative to the Earth in the presence of Earth's rotation rate and aircraft translational motion over the Earth). Figure 3 depicts the classical strapdown approach to inertial navigation. Unlike Fig. 2, the inertial sensor mount in Fig. 3 is directly connected (usually through silicone elastomeric isolators) to the vehicle structure ("strapdown"), thereby eliminating the Fig. 2 intermediate gimbal/torque-motor assembly. With minor differences, the navigation computations in Fig. 3 are the same as for the gimbaled INS configuration of Fig. 2. The basic difference is that the specific force acceleration components, provided directly from platform accelerometers in Fig. 2 to the navigation computations block, are calculated in Fig. 3 with a vector-transformation operation performed in the system computer. This analytically converts the strapdown accelerometer outputs to the values that would be measured from accelerometers mounted on a Fig. 2 gimbaled platform. The second input to the vector transformation block in Fig. 3 is the angular orientation (attitude) of the gyro/accelerometer strapdown mount relative to the equivalent Fig. 2 gyro-stabilized platform. The attitude data are calculated by high-speed digital integration operations on strapdown rate-gyro inputs. The feedback gyro biasing operation in Fig. 1 for commanding platform rotation rates is also present in Fig. 3,



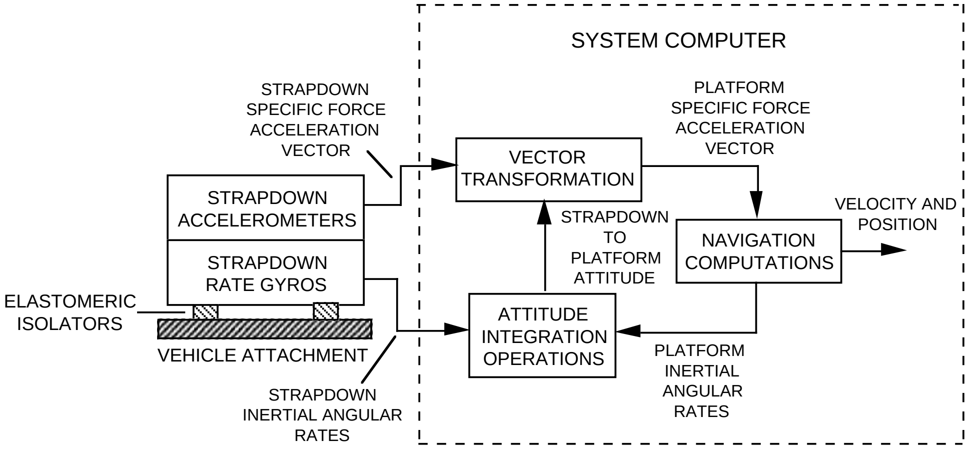


Fig. 3 **Rate-gyro-based strapdown inertial navigation system.**

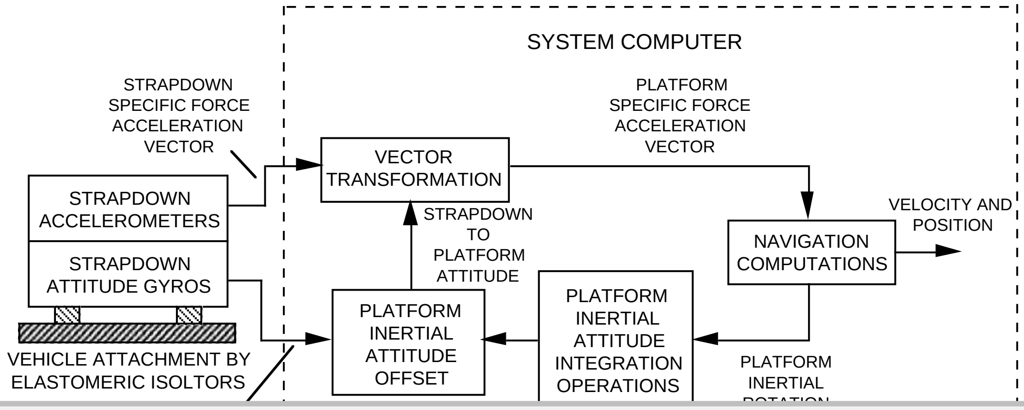
but as part of the attitude computational process, so that computed attitude outputs become referenced to Fig. 2 stable "platform axes."

Prior to engaging the inertial navigation function, the initial angular orientation of the Fig. 2 platform (or Fig. 3 computed attitude) must be established during "initial alignment" operations. Under quasi-stationary conditions, this is a self-alignment function in which the physical gimbaled platform (or strapdown computed attitude) is controlled to a locally level orientation, based on accelerometer measurements in Fig. 2 (or transformed acceleration measurements in Fig. 3). Simultaneously, accelerometer heading relative to true north is ascertained from gyro controlled platform accelerometer rates in Fig. 2 (or transformed acceleration rates in Fig. 3) in response to earth's rotation rate, based on the fundamental characteristics that the horizontal component of earth rate points north.

An alternative to the Fig. 3 rate-gyro strapdown approach is to use attitude gyros whose output represents the angular orientation relative to nonrotating inertial space, of the gyro case (hence, the sensor mount to which the gyros are attached). The concept is depicted in Fig. 4. Comparing Fig. 4 with Fig. 3 shows the principal advantage afforded by use of attitude gyros: eliminating Fig. 3 high-speed computation requirements for integrating strapdown angular rates into attitude. For 1960 and early 1970 computer technology limitations, this was an important advantage. The penalty was the attitude-gyro requirement for accurate readout capability at any angular orientation of the strapdown sensor mount (fixed to the vehicle). Other operations in Fig. 4 parallel those in Fig. 3, but with the integration of platform inertial rotation rates executed at a low rate in a separate computation block, then combined with gyro data to form the Fig. 3 strapdown-to-platform attitude data for acceleration transformation. In the 1960–1970 time frame, only the ESG (with modification for wide-angle readout) had the accuracy potential for aircraft strapdown INS application.

Compared with the traditional gimbaled INS approach, strapdown technology promised future cost reduction and improved reliability through elimination of mechanical parts, gimbal shaft-angle transducers, slip-ringed electrical connections to/from platform components, and high-power gimbal-motor-drive electronics [2–4]. Another strapdown advantage was touted in redundant applications (particularly for the Fig. 3 rate-gyro approach) by using skew-aligned sensor input axis geometries (mounting the inertial sensors in a nonorthogonal arrangement, having no three input axes coplanar) [3,5–8]. Figure 3 orthogonal axis angular rates/acceleration components are then obtained from any set of three or more skewed gyros/accelerometers by analytical conversion operations in the system computer. As a result, only one additional gyro/accelerometer is required for each level of system redundancy (in contrast with classical redundant gimbaled INS configurations requiring a duplicate INS for each redundancy level). For the Fig. 3 rate-gyro implementation, strapdown sensor outputs can also be used for other vehicle functions (e.g., aircraft axis angular rate/acceleration for flight control/stability augmentation), thereby reducing the multiplicity of dedicated aircraft inertial sensors normally required for non-INS related functions. (Note, to achieve a consistent redundancy level throughout a system, skewed redundant sensors must also be interfaced with equivalent redundancy level computers, power supplies, and cabling designed to also block single failure propagation between redundant channels.)

Before strapdown technology could be considered viable, two major technological advances were required to achieve accuracy levels already attained in gimbaled INS high-volume production: 1) computer advances to handle new rate-gyro strapdown INS throughput requirements and, most important, 2) never-yet-achieved gyro accuracies in a nongimbaled strapdown dynamic rate environment.

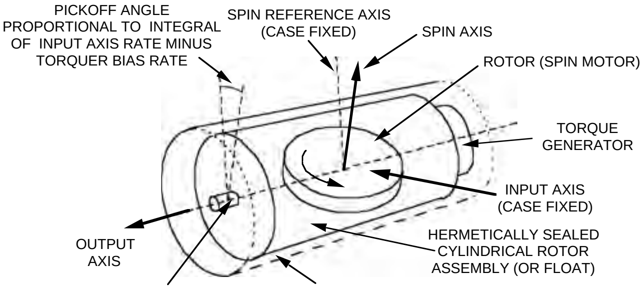


The gimbaled platform in an INS exists for two basic reasons: to reduce gyro error (as noted previously) induced by high-input angular rates and to create a stable mount for the accelerometers at a known angular orientation relative to the Earth (for Earth-based position/velocity determination) [9]. By eliminating the stabilized platform, performance requirements for strapdown gyros dramatically increase in scale-factor accuracy and sensor-to-sensor alignment for reduced error buildup under attitude changes. A more subtle requirement for aircraft systems is the need for long-term stability of critical inertial sensor performance parameters due to the lack of built-in rotation test equipment (used to measure and compensate inertial sensor performance parameters in a test facility). In a gimbaled INS, rotation calibration can be provided by the gimbal assembly during a special test mode. (For the Delco Carousel gimbaled system, the stable platform is used as a base for mounting a synchronously controlled rotating "table," which houses the horizontal sensors. By continuously rotating the table relative to the stabilized platform at 1 rpm, horizontal accelerometer and gyro biases become averaged, effectively canceling their impact on position/velocity error buildup.) Additionally, normal self-alignment operations before navigation mode engagement implicitly compensate critical sensor errors in a gimbaled INS. During self-alignment, all inertial navigation systems develop platform tilt and heading errors that cancel horizontal accelerometer and east gyro bias. For gimbaled systems, the cancellation remains after navigation mode entry because the sensor platform remains at its self-alignment orientation under subsequent vehicle maneuvering. In contrast, strapdown sensors rotate with the vehicle during navigation, altering their orientation from the alignment attitude (the worst case being a 180 deg heading rotation following initial alignment, effectively doubling the impact of the sensor errors).

To meet the strapdown performance challenge, major design changes had to be incorporated in conventional angular-momentum-based gyros, and a new angular rate sensor was introduced, the RLG, based on the relativistic properties of light [10]. (The term "gyro" is now commonly used for all angular rate sensing inertial instruments. It is derived from "gyroscope," the term originally used for angular rate sensing based on the gyroscopic angular-momentum properties of rotating mass.)

Conventional Strapdown Gyro Development

The distinguishing characteristic between angular-momentum-based gyro configurations is the method used to contain the spinning rotor without inducing error from spurious torques on the rotor assembly. Angular-momentum gyros considered during the 1960s for strapdown application were the single-degree-of-freedom floated rate integrating gyro (RIG), the two-axis dynamically compensated dry TRG, and the ESG ([11–13], Chaps. 7–9 in [14], Chap. 4 in [15]). The RIG (Fig. 5) supports the rotor assembly by the buoyancy of surrounding viscous fluid. The TRG (Fig. 6) supports the rotor by flexure pivots connected through an intermediate gimbal to the spin-motor shaft. Pivot-flexure spring torques on the rotor, developed under off-null operation, are thereby compensated by dynamic motion of the spinning gimbal. The two-axis ESG (Fig. 7) supports the free rotor with an electrostatic field applied by case-mounted electrodes.



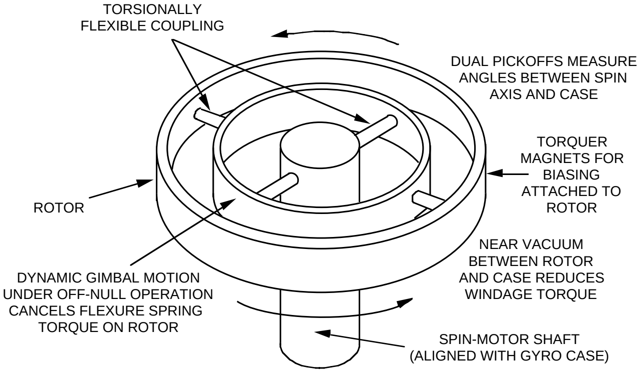
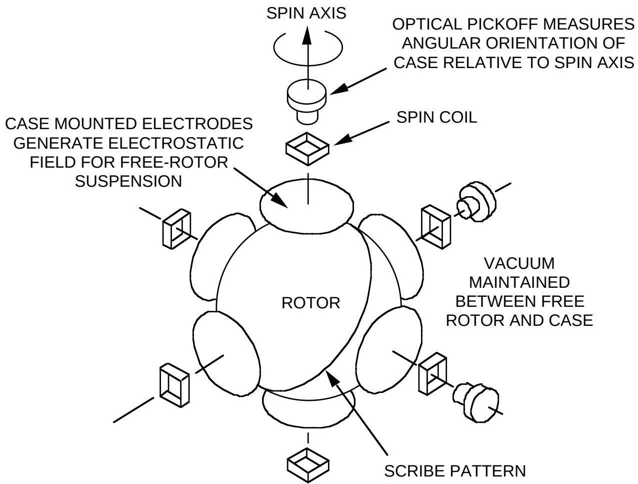


Fig. 6 Two-axis dry TRG.

The RIG (Fig. 5) measures the integrated difference between input axis angular rate and applied bias rate, the latter provided by an electrical torquer. The TRG (Fig. 6) measures the two-axis angular orientation between the gyro case and rotor. The TRG also contains a torquer assembly for intentionally precessing the spinning rotor axis relative to inertial space. To meet the strapdown gyro performance challenge, closed-loop TRG and RIG configurations had to be developed, in which electrical input to the torquers are provided in feedback fashion to maintain pickoff output null. The torquer input command thereby becomes proportional to gyro case angular rate and the strapdown rate-gyro output in Fig. 3.

The ESG (Fig. 7) measures the two-axis angular orientation of the case relative to the rotor which, having no accurate torquing means, maintains a fixed angular orientation relative to inertial space. The angular orientation of the case relative to the rotor is determined with the Fig. 7 Honeywell hollow-shell ESG rotor approach by measuring the time interval between pickoff sensed light reflections from a scribe pattern etching on the rotor. Rockwell Autonetics Division (Anaheim, California), a latecomer to ESG technology, used a small solid mass-unbalanced rotor to generate a detectable modulation signature in the suspension electrodes for readout: mass unbalance modulation (MUM). ([11,13], Chap. 8 in [14]). In gimbaled applications, ESG case-to-rotor angular orientation is maintained at the pickoff null by gimbal command rotation. For strapdown applications, ESG pickoffs have to be accurate at any case orientation relative to the rotor (wide-angle readout) for Fig. 4 attitude-gyro measurements.

Both RIGs and TRGs required enlarged high-rate torquer assemblies and associated precision electronics to precess the spinning rotors at high angular rates [11,16]. Strapdown RIG pivots,



originally used for delicate unstressed centering of the floatation supported rotor assembly (Fig. 5), now had to withstand severe lateral bearing loads under output axis rotation, thereby distorting output axis integration response. Gas bearings for improved RIG spin-motor reliability required stiffening for high dynamic angular rate, increasing startup stiction under successive on–off cycles. The inevitable result was added bias and scale-factor error from mechanical stresses under dynamic angular rates, high-rate torquer heating, and on–off/cooldown, with long-term bias stability remaining a major limitation in aircraft strapdown INS applications. ESG modification for strapdown operation introduced new error mechanisms as a function of vehicle attitude; precision wide-angle readouts generated scale-factor error, and increased bias error was induced from suspension-field forces acting at different case-mounted-electrode/rotor orientations, both effects requiring complicated calibration procedures and increased production cost. With these changes, aircraft strapdown INS requirements also dictated two orders-of-magnitude improvement in RIG/TRG torquer-loop scale-factor accuracy (compared with gimbaled system requirements), and 2 arcseconds ESG readout accuracy for arbitrary rotor/case attitude.

By the end of the 1960s, strapdown conventional gyros were incapable of meeting general aircraft strapdown INS requirements without performance specification relief or limiting usage to application areas where reduced INS accuracy was acceptable (e.g., operation with inertial aids to mitigate navigational error buildup or limiting strapdown technology to lower angular rate applications). Additionally, as with gimbaled system conventional gyros, strapdown versions required active temperature control (with heaters) to stabilize thermally sensitive performance parameters at compensation-calibrated values. The associated warm-up requirement precluded a desirable faster INS reaction time, the time from system turn-on to entry into the navigation mode (including platform initial north alignment determination). Ironically, accelerometer thermally sensitive bias trending during heading alignment was actually the warm-up time determining factor. For conventional gyros and accelerometers mounted in close proximity, gyro heating becomes a dominant accelerometer thermal input driver, requiring accelerometer temperature control (and warm up) for heated gyro compatibility.

RLG Development

To directly meet the Fig. 3 strapdown rate-gyro challenge from a different perspective, the RLG was introduced in 1963. Unlike traditional angular-momentum gyros whose operation is based on the Newtonian inertial properties of rotating mass, the operating principle for the RLG is based on the relativistic properties of optical standing waves generated by oppositely directed laser beams contained in a closed optical path ([11,12], Chap. 13 in [14], Chap. 8 in [15], [17,18]).

Figure 8 depicts the basic operating elements in an RLG: a closed optical cavity containing two independent beams of light, both of the same single frequency. The beams travel continuously between the reflecting surfaces of the cavity in a closed optical path, one in the clockwise direction and the other counterclockwise, each occupying the same physical space. The light beams are sustained by the lasing action of a helium-neon gas discharge within the optical cavity. The reflecting surfaces are dielectric mirrors designed to selectively reflect the frequency associated with the particular helium-neon transition being used. The counter-rotating beams combine into a standing wave of light that remains inertially fixed as the gyro cavity rotates. A small fraction of each beam escapes the cavity, one reflected through a corner prism, both recombined on photodiode readout detectors. The corner prism is designed to produce a small angle between the recombining beams, thereby creating an optical interference fringe pattern on the photodiodes, each fringe equivalent to a magnified image of the standing wave within the gyro. As the cavity rotates, the fringes traverse the diodes, each fringe

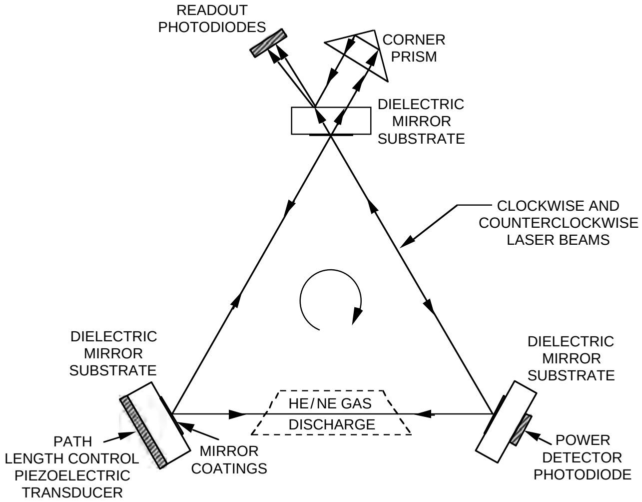


Fig. 8 RLG operating elements.

Photodiode readout logic generates digital output pulses for each fringe quarter-wave passage. Two diodes are used, separated from each other by one-quarter of a photodiode-sensed fringe, so that resulting diode sinusoidal outputs are 90 deg phase separated. Comparison between diode outputs determines the direction of rotation, positive or negative, depending on whether one diode output is leading or lagging the other.

Laser stands for light amplification by the stimulated emission of radiation. In an RLG, the emission process is provided by the helium/neon gas discharge that generates light waves at a discrete atomic transition wavelength when impacted by photons of the same wavelength. For lasing to occur, the RLG mirrors must reflect the emitted light around the closed beam path, so that it returns in phase with itself. The beam intensity will then be amplified into resonance until the light emitted ("gain") balances all cavity losses, which then also maximizes beam power. The gain is set by the current magnitude applied to the gas discharge. To satisfy the return-in-phase condition for lasing, the beam path length must be controlled to an integral multiple of discrete lengths, corresponding to the optical wavelength of the helium/neon discharge. This is achieved implicitly in the RLG by mirror adjustment to a position for peak beam power. Beam power is measured by a photodiode power detector attached to one of the mirror substrates (Fig. 8). Piezoelectric transducers attached to the outer mirror substrates (Fig. 8) provide the means for actively controlling mirror position, enabling minute adjustments by an electrically applied voltage. The control voltage is generated in closed-loop fashion to sustain maximum output from the power detector. In addition to enabling lasing, the path-length control process also produces two very important angular rate sensing operational benefits: 1) stabilization of RLG performance parameters and 2) elimination of path-length changes from gyro block thermal expansion.

The RLG concept bypassed many of the conventional gyro design issues. Piezoelectric transducer path-length control eliminated the principle source of thermal error sensitivity without requiring direct temperature control. This important characteristic eliminated the warm-up time penalty experienced with conventional gimbaled inertial systems. Stable high scale-factor accuracy, the critical performance parameter for strapdown applications, was an inherent quality, independent of bias-producing mechanisms. Simple wide-angle readouts could be used with minimum impact on accuracy (because 360 deg laser signal detector scaling corresponds to arcseconds actual gyro input axis rotation). However, the RLG has a unique "lock-in" error mechanism of its own that cannot be eliminated and had to be circumvented before RLGs could be considered for high-accuracy INS application [19].

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