A PATH TO LOW COST GYROSCOPY

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ABSTRACT

The theoretical framework for low cost, micromachined gyros and their commercial attractiveness have both been established for over a decade. However, they are still not manufactured by the millions, as had been expected. This paper illustrates some of the practical issues by tracing the development of a commercial gyro.

INTRODUCTION

Micromachining, as a means of making low cost gyroscopes, has inspired engineering imaginations for over a decade. Yet, it is only in the last year that such gyros have approached mass production. That is, with a capacity of millions of pieces each year. Their commercial attractiveness has been widely recognized [1,2,3]. Also many companies and universities have published plausible designs [3,4,5,6,7,8] but reduction to practice continues to be difficult.

This paper outlines the path taken by Analog Devices Inc. (ADI) over the past few years in pursuit of a gyro and, of course, the associated dollars. The starting position was very good. ADI was already producing micromachined accelerometers at a multi-million per year rate so that many of the process issues were understood. Further there was a deep conviction that integration with the electronics would, eventually, yield the lowest cost instrument. This provided the perseverance necessary for the undertaking.

There is generally more than one route to an objective and usually no uniquely best one. During the development ADI found it necessary to change paths in response to commercial pressures. The objective here is to share the two approaches and give an overview of their relative merits, sketching the technical issues along the way.

GYROSCOPES

These instruments measure rotation with respect to an inertial frame, an abstraction inaccessible for mechanical attachment or direct observation. This detachment is the source of their usefulness and of their difficulty in manufacture. They cannot exploit the first order effects measured in physically referenced rotation measuring devices, such as synchros or optical shaft encoders. Instead they must extract tiny, second order signals from a plethora of interfering effects.

There are at least two physical phenomena which have been demonstrated plausible for a micromachined inertial rotation sensor [9]. The rapid development in integrated optics may, one day, make it economical to use Sagnac interferometry. This is the basis of laser and fiber-optic gyros which reliably guide modern aircraft. In the meantime, Coriolis accelerometry forms the basis of the mechanical gyros which dominate the low cost market. One can regard mechanical gyros as vibrating accelerometers. Spinning gyros can even be squeezed into this definition by

decomposing their spin into a pair of orthogonal vibrations. Thus, the commercial dominance of piezoelectric gyros makes sense in the light of the long established position of piezoelectric accelerometers [10]. Similarly, the aspiration to make the lowest cost gyro by micromachining is reinforced by the spectacular success of micromachined accelerometers [11].

However, the Coriolis acceleration in a micromachine is indeed tiny. For example, take a reasonable vibration in the region of 10 microns amplitude at 16kHz giving an excitation velocity of the order 1m/s and acceleration 100km/s^2 . Then, the Coriolis acceleration corresponding to an angular rate resolution of $1^\circ/\text{s}$ would be 35mm/s^2 , about 4milligee. In absolute terms, this does not seem too difficult for a mass produced part. There are examples of much better, low cost, micromachined accelerometers [12]. The difficulty lies in that signal being about a third of a part per million of the excitation. The problem of mechanical cross coupling is formidable.

Fortunately, the mechanically coupled acceleration is 90° phase displaced with respect to the velocity induced, Coriolis acceleration and can be rejected by a synchronous demodulator to the extent of its phase accuracy [13,14]. This rejection is limited. So, the quality of the mechanical design is measured by the size of the interfering 90° , or "quadrature" signal it produces from manufacturing tolerances. High aspect ratio flexures can be very valuable in improving those tolerances and give quadrature as low as 125ppm [15]. Also, control of the flexure sidewall angles was recognized as critically important even in the bulk etched devices with very large aspect ratios [16].

A "CONVENTIONAL" APPROACH

ADI started in 1994 with tightly coupled accelerometers vibrating in vacuo, an approach which had enough previous history in discrete form [17] and micromachined [4,5] together with enough variants over the past few years [1,3,8,15,20] to call "conventional".

The integrated surface micromachining process gives a sub millimetric sensor size, restricted mostly by the curvature of the structural film. Also, for a given planar geometry and taking electrical collapse into account, the Coriolis signal varies roughly as the sixth power of the linear dimensions of the sensor. Thus, a vacuum is needed to give the vibration a high Q. That produces the most motion and, therefore, signal from the very limited electric drive available in a fully integrated structure. Even so, the differential capacitance for a given gyro input is only a millionth of that available in the preceding bulk micromachined instruments. Further, with that very small signal, the vacuum is necessary to reduce Brownian noise to an acceptable level.

The tight coupling between the devices, forcing them into perfect antiphase, enhances Q in the manner of a tuning fork, helps with the phase accuracy for quadrature rejection and helps with the rejection of external disturbances at the vibration frequency. Resonance tuning of the accelerometer was avoided because of the bandwidth conflict [13] stability difficulties and beat frequency noise.

Three very different structures were fabricated, none taking more than 1mm by 1mm. One of the more interesting is shown in figures 1 and 2.

Figure 1. Part of Gyro Die Showing Sensor

Figure 2. Detail of Sensor Showing Coupling, Drive and Flexures

The two rings vibrate rotationally in antiphase. The drive is similar to that of Howe and Tang [18] and four plates capacitively sense the Coriolis motion perpendicular to the plane of the substrate. The antiphase coupling between the opposite plates on a ring is intrinsically perfect while the fork coupling between the two rings has a stiffness ratio about 200 between antiphase and phase. The sensing capacitors are connected analogously to the "cross quad" or "common centroid" method for reducing the errors in the input transistors of operational amplifiers. This reduces the sensitivity to manufacturing process and temperature gradients. The high order of symmetry also helps with quadrature motion from tether sidewall mismatch and from drive levitation [19].

INTEGRATED ELECTRONICS

Accepting the limitations of the conventional sensor design and conservative mechanical design rules looked to ADI's strengths in precision electronics to provide good overall performance. The electronics is outlined in figure 3 and is dominated by the need to accommodate a quadrature signal of several hundred parts per million from worst-case manufacturing

tolerances. A phase accuracy requirement of a milliradian follows, together with the need to accommodate many times full scale of interfering signal.

Figure 3. Vacuum Gyro Electronics Functions

Sensitivity to the very small differential capacitances was achieved with a high frequency carrier, and a subcarrier was used to differentiate Coriolis from vibration signals. In this way, a common high frequency preamplifier and demodulator of poorly defined gain and phase could be used for both the angular rate signal and a velocity stabilizing servo, resulting in a gyro scale factor essentially insensitive to electronics gain. The carrier and subcarrier were phaselocked to the vibration frequency to avoid the large, unmodelable null errors that result from temperature variation of harmonic beat frequencies.

Headroom in the amplifiers and demodulators was eased by nulling quadrature using a purely electronic servo. Nulling by electromechanical feedback would have complicated the servo compensation circuits without tangible benefit. It is worth noting that, unlike open loop trimming, closed loop quadrature nulling does not improve the angular rate null. The same phase errors which would give rate offset in the Coriolis demodulator give an exactly corresponding Coriolis-phased error signal to a quadrature nulling servo.

The resulting architecture has four, similar, digital phase sensitive demodulators, one for the Coriolis signal, one for the quadrature servo, one for the velocity servo and one for the phase lock loop. In practice, there is also a frequency discriminator to ensure initial capture. The total chip area taken by the sensor and this, rather complex electronics is 5mm by 5mm.

PACKAGING

It was assumed that a package similar to a standard IC would be used to minimize production costs. It took nearly a man-year of intense effort to yield a reliable vacuum package with this constraint. A prerequisite was the development of a simple means of measuring, on thousands of parts, leaks far smaller than those detectable by standard equipment. This was provided by measuring the resonance Q of the ADXL05 micromachined accelerometer. It is both a sensitive and a rapid technique for the pressures of interest, around 50millitorr. Eventually, in 1995, many consecutive batches were produced which had no perceptible leaks after severe thermal cycling of the glass-sealed ceramic.

RESULTS

The resulting gyros worked to the target specification of 0.5deg/s accuracy. A typical error plot is shown in figure 4.

Figure 4. Vacuum Gyro Angular Rate Error vs. Input

THE REAL WORLD INTERVENES

During the 18 months needed for the prototype gyro development the rest of the world moved on. It had been projected that gyros with the target specification could be sold for about \$30 at which our product was nicely profitable. However, advances in piezoelectric gyros dropped the million quantity prices to about \$15 for automotive navigation grade and \$5 for camera grade. It was clear that in order to compete with this trend we had to reduce both chip size and packaging cost.

Further, it came as an unpleasant surprise to find that surface micromachined devices were not robust in vacuo. The structures shown in figure 1 can, at atmospheric pressure, be hard mounted in ceramic packages, shock tested until the packages shatter, and be recovered undamaged. However, at 50millitorr they can be destroyed by the shock of packages striking each other in normal IC test equipment. This implied that either soft mounting or a non-standard package would be needed. Each of these options seemed an unacceptable expense.

Late in 1995 a solution to these cost problems was evolved and a new sensor was put into fab. One which did not need a vacuum or the complex electronics support. Then, in 1996, commercial reality asserted itself. There was a world shortage of semiconductors. The limited fab capacity had become precious. The micromachining division could not meet the exploding demand for accelerometers in a shared facility so a dedicated micromachining fab was set up in Cambridge. All hands were needed to get the new facility to the point where it could satisfy the orders, which are about a million pieces each month in 1998. The gyro project was shut down for a year while the infrastructure needed for its manufacture was reestablished.

A "NEW" APPROACH

Faced with the economic necessity of a die shrink and the elimination of the vacuum package, it was necessary to reexamine the basic assumptions of an electronics solution. The old sensors occupied only 4% of the die area. In search of smaller die it seemed reasonable to shift some complexity from electronics to mechanics. It was apparent that by increasing the drive and accelerometer fingers the signal size limitation by air damping could be overcome. The penalty, of course, would be a larger sensor but also a temperature sensitivity of both signal size and

quadrature. While the viscosity of air is very temperature dependent, it is also very consistent so that a damping dominated gyro scale factor can be accurately compensated with minimal electronics. More significantly, signal phasing would be poorly defined, spoiling quadrature rejection. On the other hand, if the sensor itself has a few degrees of phase error then the complexities of precision phase electronics can be eliminated. Thus, both the electronics complexity and vacuum problems are soluble by a low quadrature. This can be achieved at the expense of sensor structural complexity.

The basic low-quadrature principle is to anchor an accelerometer structure to the substrate by a flexure which allows the Coriolis motion but is very stiff to both the exciting vibration and the cross-coupling angular motions. Then, the vibrating mass is suspended from the accelerometer by a flexure which is very stiff to Coriolis motion and angular motion but allows the vibration at high amplitude without stress stiffening. Coupling caused by imbalance of the flexures or drive is suppressed by stiffness. Coupling out of plane must propagate through two sets of misalignments, mostly sidewall errors, so that the already small coefficient is squared. The result is quadrature coupling significantly less than one part per million whereas the Coriolis effect is only attenuated by the vibrator to total inertia ratio.

It is still advantageous to use an antiphase pair of structures to double the signal without exceeding curvature limitations, to reject linear acceleration and to locally conserve momentum. The last increases the Q somewhat and desensitizes the system to mounting conditions. However the Q is low enough for the two vibrators to match adequately without a special coupling.

Needless to say, patents have filed and it should be noted that this is quite different from the designs of Geiger and the team at HSG-IMIT [20]. There, the vibrator is anchored to substrate and the accelerometer suspended from it so that the accelerometer moves with the vibration.

The sensor is in figure 5. It is 2microns thick, has nearly 5000 fingers and has a Q of 20 at 10kHz. It vibrates with an amplitude of 9microns at that frequency. The observed resonant frequency does not shift noticeably with amplitude and the response decays gracefully above the resonant peak giving experimental verification of the stress relief mechanism. The quadrature is so small that stray electrical coupling from vibration drive to accelerometer electronics is the dominant gyro error source. This is apparent from a linear dependency on the drive voltage. Quadrature errors have a quadratic dependence.

Figure 5. A Gyro Structure with Less than 1 ppm Quadrature

The electronics does not have any servo loops, resulting in a dramatic reduction in die size despite retaining a thermometer output and adding a digital output option to the rescaleable analog output. The die, with complete electronics, is 3mm by 3mm and the package is an IC "cerpak" 10mm by 10mm by 3mm. It takes about 2.5mA from a single ended 5V supply.

The change in approach seems to be yielding the needed results. Still, there is much work to be done for the transition of prototype into production. Amongst other things, we must run about 120,000 die through fab for qualification before releasing them.

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