SAND2010-5710C

Effects of high G-loading on MEMS structure and die attachment

R. T. Marinis[1], P. Hefti[2], J. W. Soucy[3], P. B. Ruffin[4], M. Zwiener[5], and R. J. Pryputniewicz[2]

[1]Sandia National Laboratories*, PO Box 5800, Albuquerque, NM 87185-1452, rtmarin@sandia.gov
[2]Worcester Polytechnic Institute, ME/CHSLT-NEST, Worcester, MA 01609
[3]Draper Laboratory, Cambridge, MA 02139
[4]US Army, Huntsville, AL
[5]University of Alabama Huntsville, Aerophysics Research Center, Huntsville, AL

ABSTRACT

In harsh-environment and high-performance (military) guidance applications inertial sensors must be sensitive to low rates of rotation yet survive the high blast loads associated with the initial launch. In this study a set of tuning fork gyroscopes (TFG's) were subjected to a series of increasing g-loads (culminating at approximately 60,000 G's) with measurements of shape made after each test. High G-testing was conducted within the large impact chamber using a custom fabricated mini powder gun with a 1.2" bore x 3.5" barrel. The test sample was contained within a 2" diameter x 1.25" block located at the muzzle bonded to a 1.2" diameter shaft within the barrel. Acceleration loading on the sample was provided by accelerating the shaft within the barrel which transferred the load to the test sample at the muzzle. Varying the powder type and load determined the peak loading on the test sample. A custom set of test sample packages were hermetically sealed with glass lids to allow optical inspection of components while preserving the operating environment. Optical and interferometric measurements have been made prior to and after each shock G-loading. Full field shape was determined and traces of pertinent structures were extracted for comparison. Failure of the die is observed in the form of fractures below the chip surface as well as fractures in the glass lid sealing the package. Potential causes of the failure are discussed as well as a proposal for modified packaging techniques to mitigate future component failures.

INTRODUCTION

Military grade MEMS gyroscopes are critical for navigation in guided munitions. In such applications the sensor must survive extremely harsh launch environments and maintain integrity, often requiring sensitivity to loads many orders of magnitude lower than those experienced during launch. Previous inertial measurement units (IMUs) have proven to remain functional at loads up to 20,000 G's [1]. In other works gyroscopes (as well as other MEMS) have proven to survive loading up to 60,000 G's [2, 3]. In these works performance is examined exclusively by electrical means. Current study aims to monitor the mechanical effects that such loading will have on the die and structure.

A custom set of gyroscopes has been fabricated at Draper Laboratory to allow for optical measurements, Fig. 1. A glass lid, Corning Pyrex® 7740 metalized with a seal ring, provides a hermetic seal while allowing optical inspection of the device. The MEMS structure is fabricated using Silicon on Insulator (SOI) processing and anodically bonding the structure onto a Hoya glass substrate [4]. The individual die have been brazed into the package with AuSn eutectic and electrical connections were made by wire bonding.

*Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

A total of four test articles were received by WPI in 2005, referred to herein as test articles g01 through g04. Initial testing monitored the shape of the component as a function of time, with static shape measurements made upon receipt and repeated in 2007 and 2009. Inertial loading was performed in 2009, with comparison made after various loads. Optical inspection was also performed to identify failures in chips and/or packages.

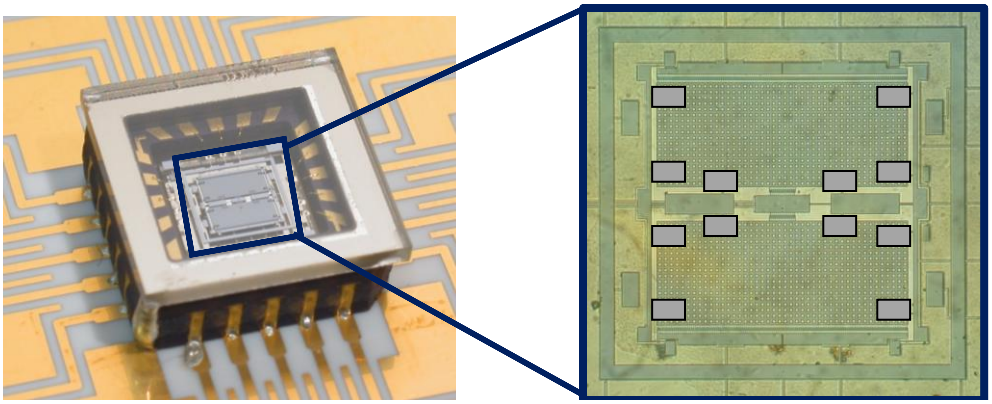

Fig. 1. Tuning fork gyroscope (TFG): (a) packaged component, (b) MEMS die.

EXPERIMENTAL PROCEDURE

Shape of the tuning fork gyroscope (TFG) test articles is measured at the Center for Holographic Studies and Laser micro-mechaTronics (CHSLT) facilities of Worcester Polytechnic Institute (WPI). Measurements are based off a phase shifting Michelson interferometer with compensation for package cover glass using a LED ($\lambda \approx 640$ nm) illumination. The shape measurements extracted are a function of the interferometer geometry as well as the illumination wavelength. Throughout the duration (4.5 years) of this investigation an improved microscope configuration was developed [5]. To account for the use of multiple microscopes the wavelength of each LED is characterized over the full current range. The driving current was recorded for each measurement and used during analysis.

Light emitting diode (LED) illumination was selected to prevent the observation of fringes on multiple surfaces of the TFG. Complex masking is required for surface selection with the use of laser illumination due to the long coherence length. This process was avoided with the use of a modulation threshold filter in which only the focused surface modulates, such as with the LED illumination because of its short coherence. Due to the short coherence length a compensation glass was placed in the reference arm of the interferometer to match the temporal path to that of the object beam of the interferometer. Details of the illumination source are discussed in [6].

A five phase step algorithm is applied using 90 degree phase steps to analyze the surface of the gyroscope. Rigid body motion is compensated by subtraction of a plane fit through three supporting posts of the gyroscope. Line traces are then extracted from pertinent structures to clearly examine changes in the TFG. Careful selection into which areas of the TFG are extracted and compared is used as much of the gyroscope is supported above the substrate, Fig. 2. In this figure the three posts used to generate the plane for rigid body corrections are identified by the X marks. A line representing the extracted trace is also indicated in this image. The islands which this trace is made through are connected directly to the substrate.

To account for slight differences in magnification (by the use of multiple optical systems as well as slight zoom differences) the linear trace through the center of the TFG was normalized to be a length of 100 units. Rigid body transformations were applied during post processing to level and align the traces (first order corrections).

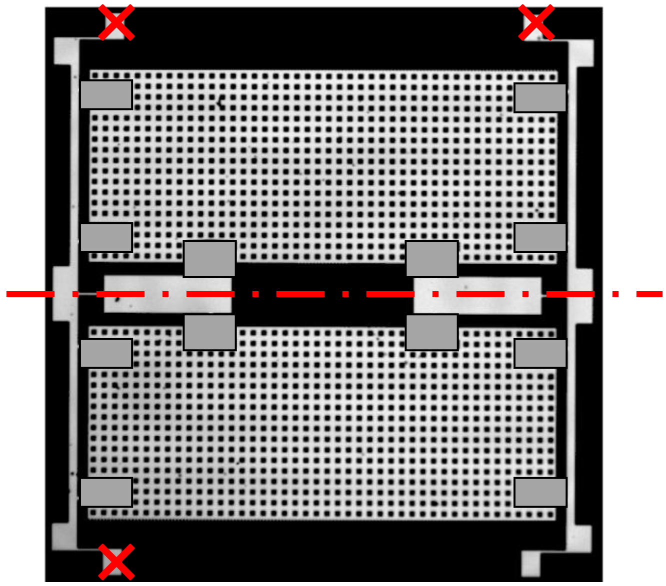

Fig. 2. Modulation map of MEMS surface with identification of leveling points and extracted trace(s).

Initial test measurements were made upon fabrication of the devices. Shape measurements were repeated after 2 and 4 years of storage at ambient laboratory conditions (70ºF, 50% RH). After four years of storage the high G-load testing is performed with additional shape measurements made before and after each stage of loading. Loads initially began at approximately 10,000 G's.

High G-loading was conducted at the University of Alabama in Huntsville's Aerophysics Research Center located on Redstone Arsenal, Alabama. This facility houses and operates three light gas gun ranges for the purpose of performing experiments and supporting analysis for the evaluation/assessment of hypersonic flight and hypervelocity impact phenomenology. High G-testing was conducted within the large impact chamber using a custom fabricated mini powder gun with a 1.2" bore x 3.5" barrel. The test sample was contained within a 2" diameter x 1.25" block located at the muzzle bonded to a 1.2" diameter shaft within the barrel. The high G-loading on the sample was provided by accelerating the shaft within the barrel which transferred the load to the test sample at the muzzle. Varying the powder type and load determined the peak loading on the test sample. Acceleration was determined by measuring the displacement history of the sample package using a Vision Research Phantom V7.0 (phase I) or a Phantom V710 (phase II) high speed video cameras. The positions and times were recorded with the TrackEye Motion Analysis (TEMA) video software. A series of images extracted from a video of a test are shown in Fig. 3, along with a plot of various point velocities as a function of time in Fig. 4. Fig. 3. Representative examples of position measurement using TEMA video software.

The test sample is contained within an aluminum test cylinder. A "soft" recovery system decelerates the aluminum fixture at a rate much slower than the initial acceleration.

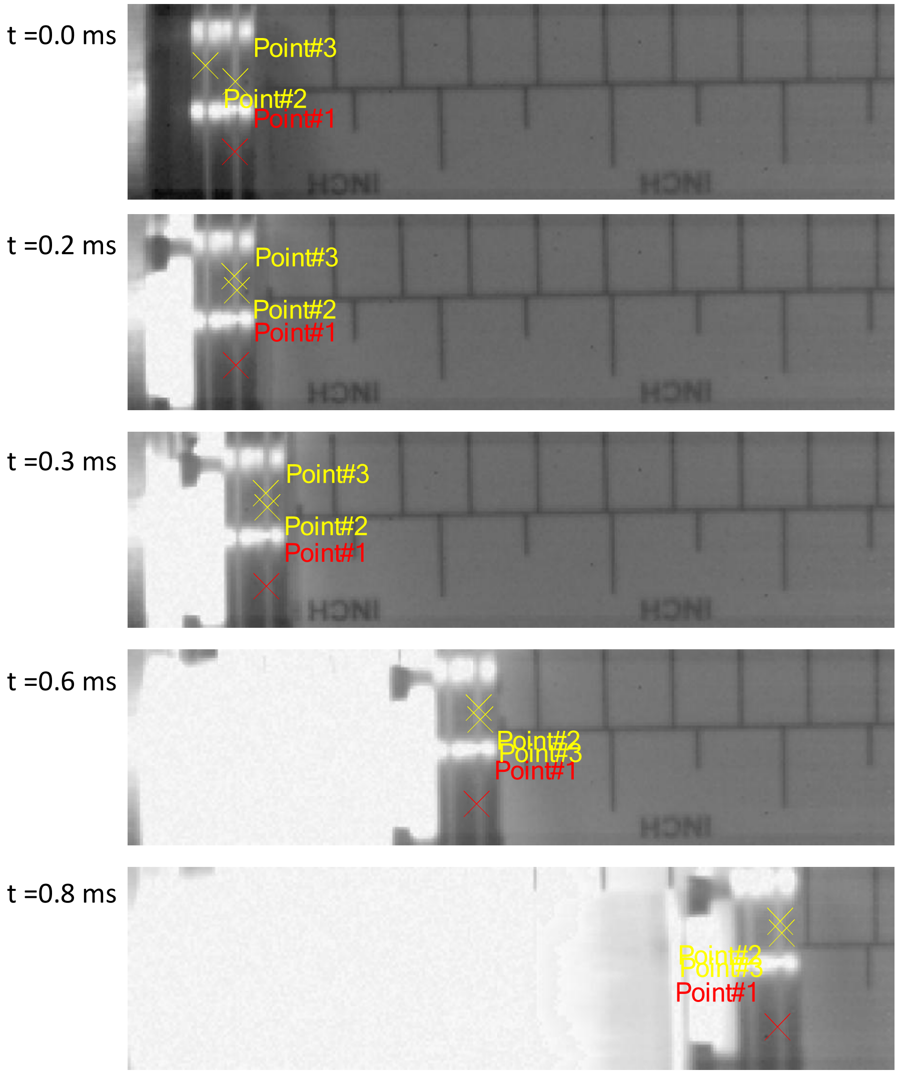

Fig. 3. Representative examples of position measurement using TEMA video software.

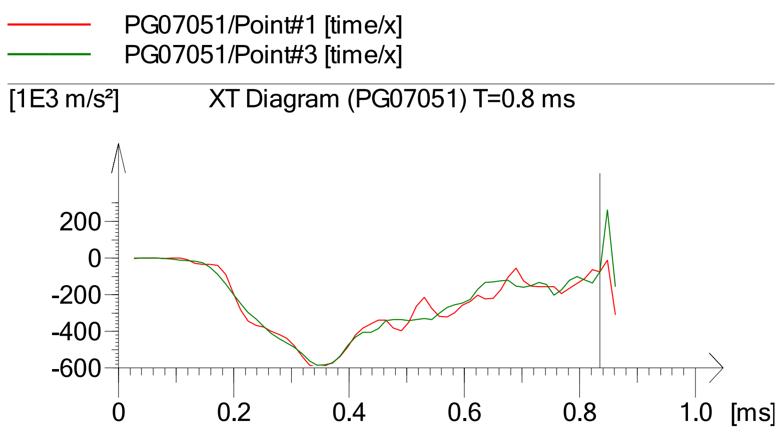

Fig. 4. Velocity as a function of time for images shown in Fig. 3.

A number of tests were conducted to characterize the loading conditions needed to meet the desired test requirements. The position as a function of time is recorded by the high speed camera, allowing for differentiation to determine velocity and acceleration. Loading is performed at 10,000 and 20,000 G's. Only two articles were subjected to the 10,000 G acceleration in the event that this loading would destroy the components, to still maintain two samples. All four samples were subjected to the 20,000 G-load. A summary of the shape measurements made is provided in Table 1.

Table 1. Test matrix for performed measurements.

	g01	**g02**	**g03**	**g04**
2005	4/21/2005 λ = 639.2 nm	4/20/2005 λ = 639.2 nm	3/2/2005 λ = 639.2 nm	4/15/2005 λ = 639.2 nm
2007	8/3/2007 λ = 634.6 nm	8/3/2007 λ = 634.6 nm	8/14/2007 λ = 634.6 nm	8/14/2007 λ = 634.6 nm
2009	4/16/2009 λ = 634.6 nm	4/16/2009 λ = 634.6 nm	4/16/2009 λ = 634.6 nm	4/16/2009 λ = 634.6 nm
10,000 G	--	12/3/2009 λ = 634.6 nm	--	12/3/2009 λ = 634.6 nm
20,000 G	12/8/2009 λ = 634.6 nm	12/8/2009 λ = 634.6 nm	12/8/2009 λ = 634.6 nm	12/8/2009 λ = 634.6 nm

RESULTS

Four components were measured at multiple time intervals as well as after high G-loading. For comparison purposes all test measurement results have been presented per test article. A representative example of the full field of view (FFV) of a TFG and the line traces through the center of the article g01 are shown in Fig. 5.

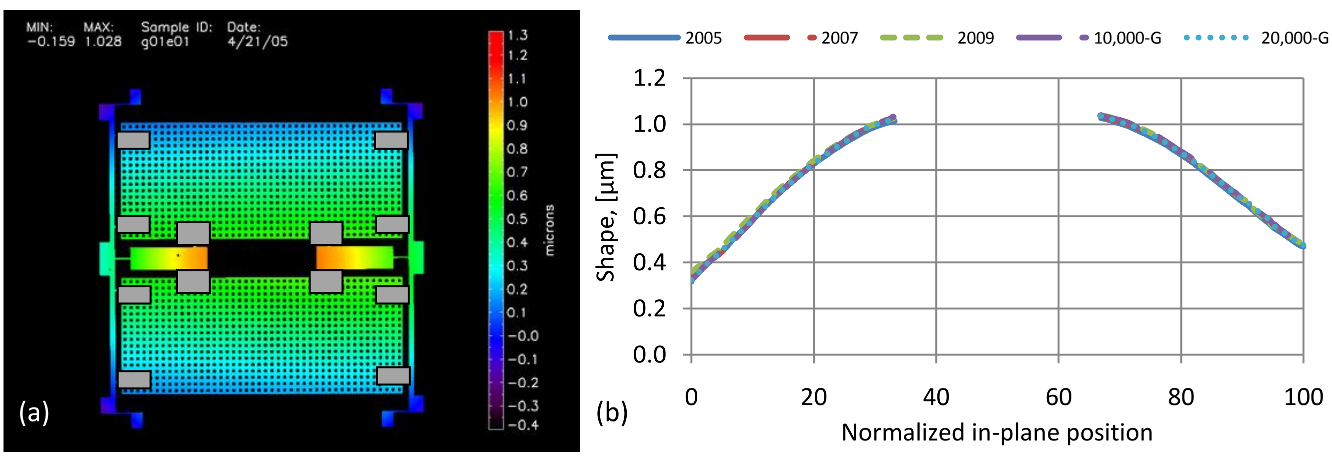

Fig. 5. (a) FFV of g01, 2005, (b) traces of five shape measurements.

Test article g02 was omitted from testing at 10,000 G's. It was observed after the 20,000 G-load that a small crack was developed in the glass cover of the test article, Fig. 6. The crack did not obstruct the imaging of the TFG structure, allowing unobstructed measurements, displayed as a representative surface and line traces in Fig. 7.

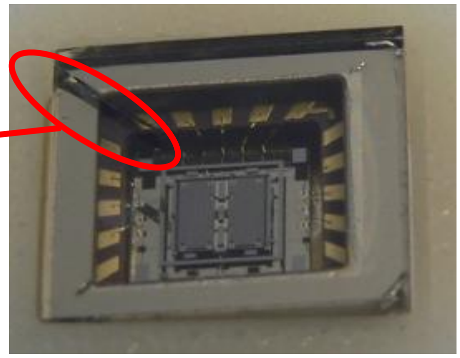

Fig. 6. Crack in lid of test article g02 after 20,000 G-load.

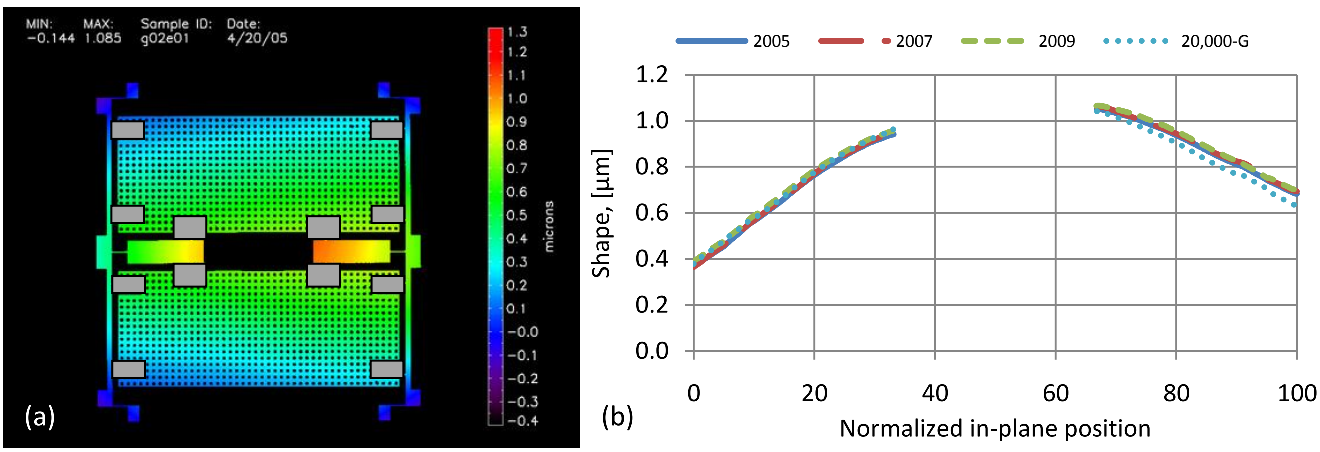

Fig. 7. (a) FFV of g02, 2005, (b) traces of five shape measurements.

Test article g03 was subjected to both G-load tests. A small chip in the corner of the cover glass was observed after the 20,000 G-test, Fig. 8, however it does not appear to compromise the seal integrity. There was no obstruction in the imaging of the TFG surface due to the chip. A representative shape measurement and line traces from all five measurements are shown in Fig. 9.

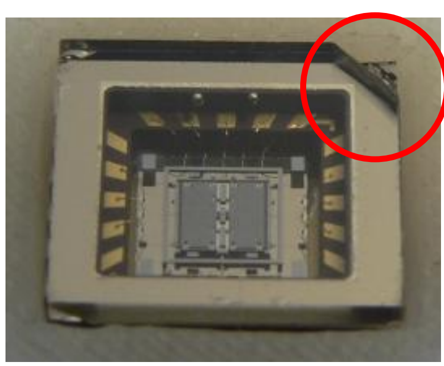

Fig. 8. Chip in corner of g03 after 20,000 G-loading.

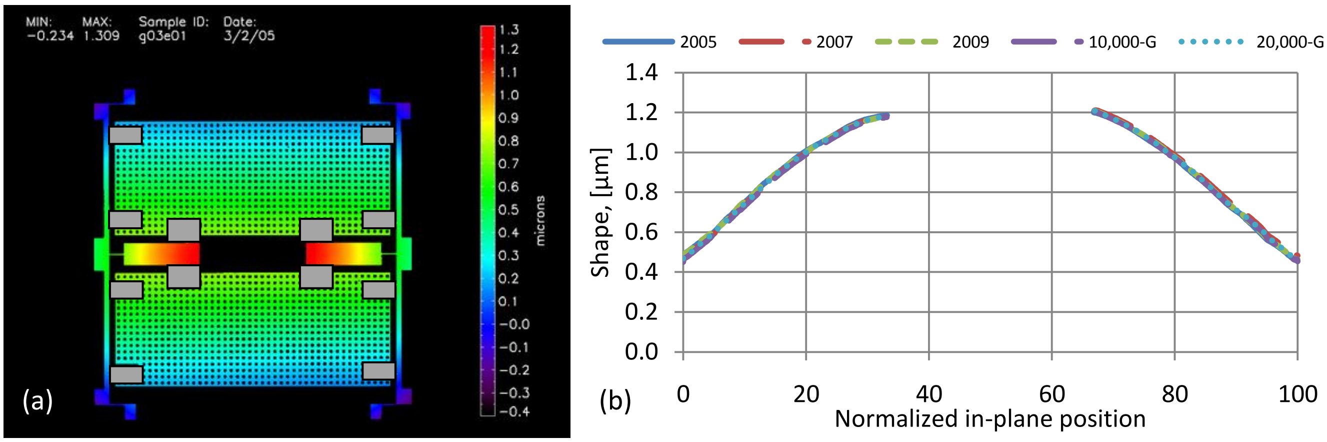

Fig. 9. (a) FFV of g03, 2005, (b) traces of five shape measurements.

Test article g04 was not subjected to the 10,000 G test. Inspection after the 20,000 G-test showed a large crack in the glass surface, Fig. 10. Inspection revealed that although the TGF structure was intact, the substrate was fractured diagonally across approximately half the dimension.

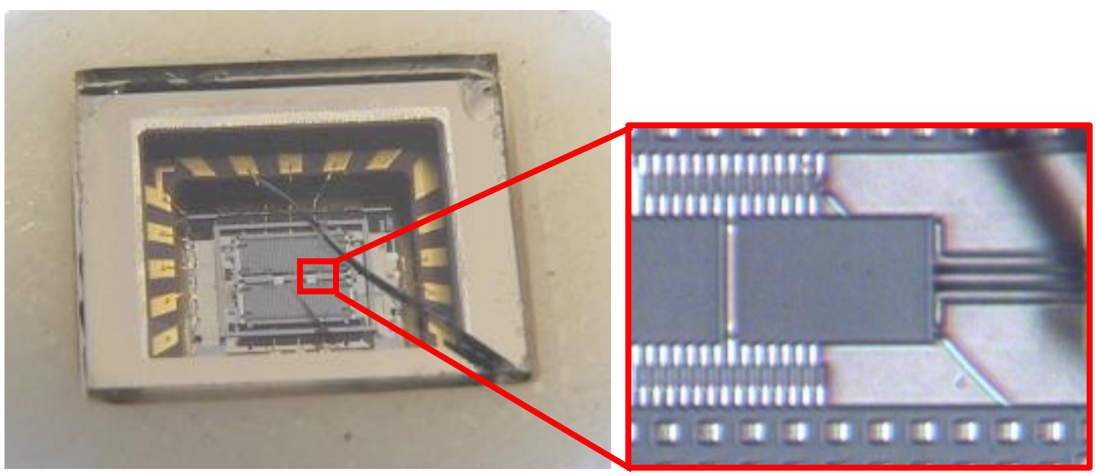

Fig. 10. Test article g04 with crack in cover glass and crack in MEMS substrate.

Although the lid crack obstructed a portion of the TFG surface, measurements are possible on much of area. The line traces will only be missing data in a small the region beneath the crack on the right side island, Fig. 11. The three posts used for leveling are still visible, allowing for similar analysis.

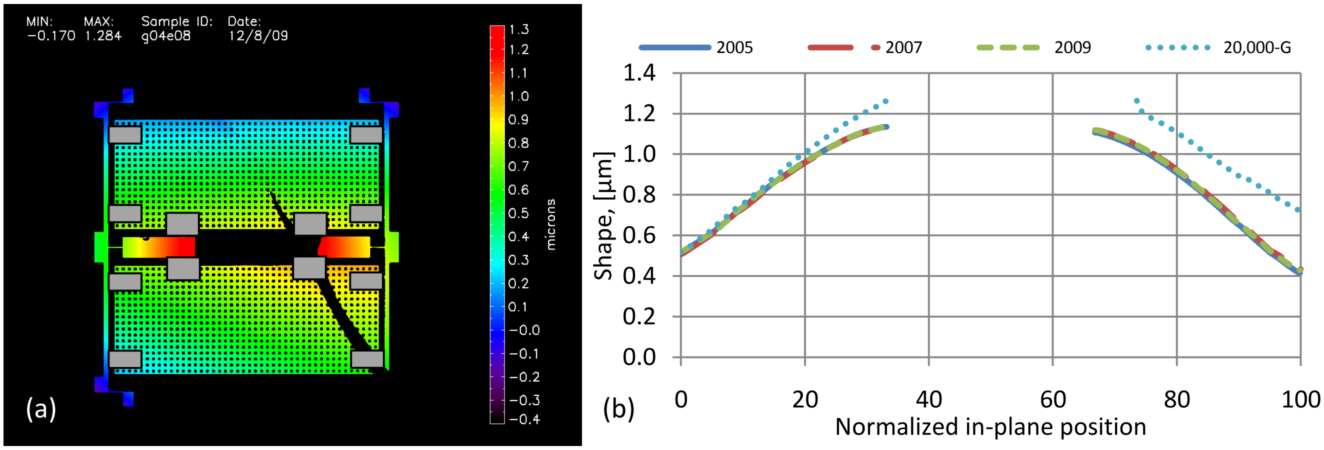

Fig. 11. (a) FFV of g04, 2009, (b) traces of five shape measurements.

DISCUSSION

Four custom test articles with sealed glass lids have been studied as functions of time and high-G inertial loading. In one case, g01, there is no discernable damage caused by the inertial loading. The glass lid has survived loading up to 20,000 G's, while the line traces through the center islands of the test article are nearly indistinguishable.

Sample g03 appears to have been damaged in a cosmetic manner only, by the chip in the corner of the glass lid. This defect does not appear severe enough to compromise the integrity of the hermetic seal.

Sample g02 has been damaged to the point of a breached seal of the glass lid at 20,000 G-loading, yet there is no evidence of an effect on the MEMS component within the package.

Sample g04 has been severely damaged, with a large crack in the glass lid as well as the Hoya glass substrate on which the MEMS has been bonded. Optical inspection of the MEMS component shows little damage as the substrate crack is obscured by the TFG suspended above, however interferometric analysis shows a major change in the shape of the structure. In the event of a more robust metal lid to the package the shock may still be sufficient to fracture the MEMS substrate without compromising the vacuum environment of the package. It is unknown if the gyroscope would function at all, yet the response would be inaccurate if able to drive and respond to rotations.

CONCLUSIONS

Traditionally MEMS response to high G-loading has consisted of electrical characterization after loading. Current study has presented a method for which mechanical damage may be assessed for shock loading by light gas gun up to 20,000 G's. Cover glass reliability is an issue in that a failure of the lid may be observed in this testing that may not occur with a metal lid such as those used in a flight system.

Testing on TFG components shows that prior to fracture failure, as observed in g04, there is little effect on the shape of the MEMS component. This suggests that any deformations during the loading are elastic and the device will remain functional after the load is removed.

The boundary condition of the gyroscope may be a critical design component. All devices in this study have a braze die attachment. Although robust due to the large area of the die bond this technique has recently been surpassed by gold bump die bonding of military grade inertial sensors into packages. The gold bump bond provides less residual stress in the device after cooling from bond temperatures to ambient [7].

REFERENCES

[1] D. Karnick, G. Ballas, L. Koland, M. Secord, T. Braman, and T. Kourepenis, "Honeywell gun-hard inertial measurement unit (IMU) development," *Position Location and Navigation Symposium, PLANS 04*, pp. 49-55, 2004.

[2] T. G. Brown and B. Davis, "Dynamic high-g loading of MEMS sensors: ground and flight testing," *Proc. SPIE 3512*, pp. 228-235,1998.

[3] T. G. Brown, "Harsh military environments and microelectromechanical (MEMS) devices," *Proc. IEEE Sensors*, vol. 2, pp. 753-760, 2003.

[4] T. F. Marinis, J. W. Soucy, J. G. Lawrence, R. T. Marinis, and R. J. Pryputniewicz, "Vacuum sealed MEMS package with an optical window," *IEEE Electronics Components and Technology Conference (ECTC)*, Orlando, FL, pp. 804-810, 2008.

[5] R. T. Marinis, *Development and implementation of automated interferometric microscope for study of MEMS inertial sensors*, PhD Dissertation, Worcester Polytechnic Institute, Worcester, MA, 2009.

[6] R. T. Marinis, A. R. Klempner, S. P. Mizar, P. Hefti, and R. J. Pryputniewicz, "Stroboscopic illumination using LED light source," *Proc. IMAPS New England 32nd Symposium and Exhibition*, Boxboro, MA, May 17, 2005.

[7] T. F. Marinis and J. W. Soucy, "Gold bump attachment of MEM sensor die using thermocompression bonding," *53rd Electronic Components & Technology Conference (ECTC)*, New Orleans, LA, pp. 385-391, 2003.