



## ✚ Cloverleaf Vibratory Microgyroscope With Integrated Post

Modifications should lead to greater unit-to-unit consistency.

NASA's Jet Propulsion Laboratory, Pasadena, California

A modified design and fabrication sequence has been devised to improve the performance of a cloverleaf vibratory microgyroscope that includes an axial rod or post rigidly attached to the center of the cloverleaf structure. The

basic concepts of cloverleaf vibratory microgyroscopes, without and with rods or posts, were described in two prior articles in *NASA Tech Briefs*, Vol. 21, No. 9 (September 1997): "Micromachined Planar Vibratory Microgyroscopes" (NPO-19713), page 68 and "Planar Vibratory Microgyroscope: Alternative Configuration" (NPO-19714), page 70. As described in more detail in the second-mentioned prior article, the cloverleaf-shaped structure and the rod or post are parts of a vibratory element that senses rotation via the effect of the Coriolis force upon its vibrations.

Heretofore, the posts for devices of this type have been fabricated separately, then assembled manually onto the cloverleaf structures. The resulting imperfections in the assembled units have given rise to asymmetric stresses in the cloverleaf structures and, consequently, to changes in resonant frequencies of vibration and in shapes of vibration modes. These changes, in turn, have caused variations in performance among nominally identical devices.

The modified design provides for the fabrication of the upper half of the post as an integral part of the cloverleaf structure; this is accomplished by reactive-ion etching of a single-piece half-post-and-cloverleaf structure from a wafer of silicon. The lower half of the post and a baseplate are also a single piece made by reactive-ion etching from a wafer of silicon. The two pieces are bonded together (see figure) by a thermal-compression metal-to-metal bonding technique to form a cloverleaf gyroscope with an integrated post structure.

*This work was done by Tony K. Tang, Roman Gutierrez, and Damien Roger of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1).*

*In accordance with Public Law 96-517, the contractor has elected to retain title to this invention. Inquiries concerning rights for its commercial use should be addressed to*

*Intellectual Property group*

*JPL*

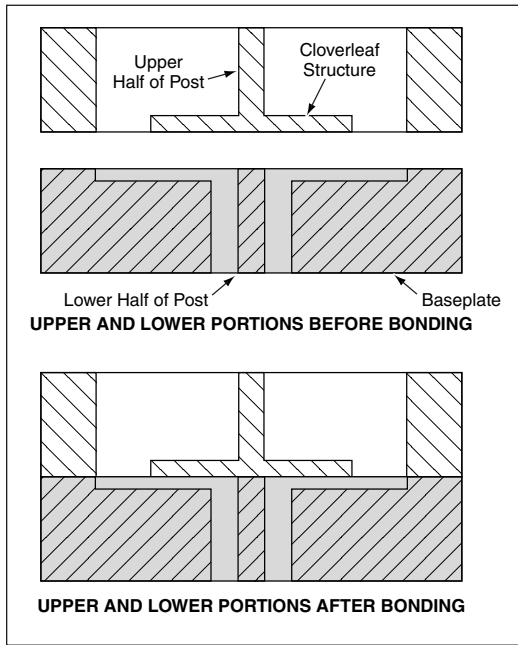
*Mail Stop 202-233*

*4800 Oak Grove Drive*

*Pasadena, CA 91109*

*(818) 354-2240*

*Refer to NPO-20688, volume and number of this NASA Tech Briefs issue, and the page number.*



The Upper and Lower Portions of the Post and Cloverleaf Structure are micromachined from silicon, integral with unitary upper and lower portions of a vibratory microgyroscope. The upper and lower portions are then bonded together.

## ✚ Single-Vector Calibration of Wind-Tunnel Force Balances

Improved data quality with an order of magnitude reduction in cost and calibration cycle time over prior methods.

Langley Research Center, Hampton, Virginia

An improved method of calibrating a wind-tunnel force balance involves the use of a unique load application system integrated with formal experimental design methodology. The Single-Vector Force Balance Calibration System (SVS) overcomes the productivity and accuracy limitations of prior calibration methods.

A force balance is a complex structural spring element instrumented with strain gauges for measuring three or-

thogonal components of aerodynamic force (normal, axial, and side force) and three orthogonal components of aerodynamic torque (rolling, pitching, and yawing moments). Force balances remain as the state-of-the-art instrument that provide these measurements on a scale model of an aircraft during wind tunnel testing. Ideally, each electrical channel of the balance would respond only to its respective component of load,

and it would have no response to other components of load. This is not entirely possible even though balance designs are optimized to minimize these undesirable interaction effects. Ultimately, a calibration experiment is performed to obtain the necessary data to generate a mathematical model and determine the force measurement accuracy.

In order to set the independent variables of applied load for the calibration

experiment, a high-precision mechanical system is required. Manual dead-weight systems have been in use at Langley Research Center (LaRC) since the 1940s. These simple methodologies produce high confidence results, but the process is mechanically complex and labor-intensive, requiring three to four weeks to complete. Over the past decade, automated balance calibration systems have been developed. In general, these systems were designed to automate the tedious manual calibration process resulting in an even more complex system which deteriorates load application quality.

The current calibration approach relies on a one-factor-at-a-time (OFAT) methodology, where each independent variable is incremented individually throughout its full-scale range, while all other variables are held at a constant magnitude. This OFAT approach has been widely accepted because of its inherent simplicity and intuitive appeal to the balance engineer. LaRC has been conducting research in a “modern design of experiments” (MDOE) approach to force balance calibration. Formal experimental design techniques provide an integrated view to the entire calibration process covering all three major aspects of an experiment; the design of the experiment, the execution of the experiment, and the statistical analyses of the data.

In order to overcome the weaknesses in the available mechanical systems and

to apply formal experimental techniques, a new mechanical system was required. The SVS enables the complete calibration of a six-component force balance with a series of single force vectors. This new system improves on the “trusted” aspects of current manual calibration systems. The SVS enables the efficient execution of a formal experimental design, is relatively inexpensive to manufacture, requires minimal time to operate, and provides a high level of accuracy.

The system allows for single vector calibration, meaning that single, calibrated dead-weight loads are applied in the gravitational direction generating six component combinations of load relative to the coordinate system of the balance. By utilizing this single force vector, load application inaccuracies caused by the conventional requirement to generate multiple force vectors are fundamentally reduced. The system features significantly fewer components than the LaRC manual system and therefore fewer sources of systematic error. The primary components include a non-metric positioning system, a multiple-degree-of-freedom load-positioning system, a three-axis orthogonal accelerometer system, and calibrated weights (see figure).

The three balance force components are a function of the applied load and the orientation of the balance in three-dimensional space. To generate a desired combination of the three forces, the balance is manipulated to a prescribed orientation using the non-metric positioning system and precisely measured using the accelerometer system. This accelerometer system provides the components of the gravitational vector projected onto the three axes of the balance coordinate system. Combining the measured gravitational components on the balance axes and the known dead-weight enables the determination of the three force components.

The three balance moment components are a function of the three force vectors and the position of the point of load application in three-dimensional space relative to the balance moment center (BMC). The BMC is a defined location in

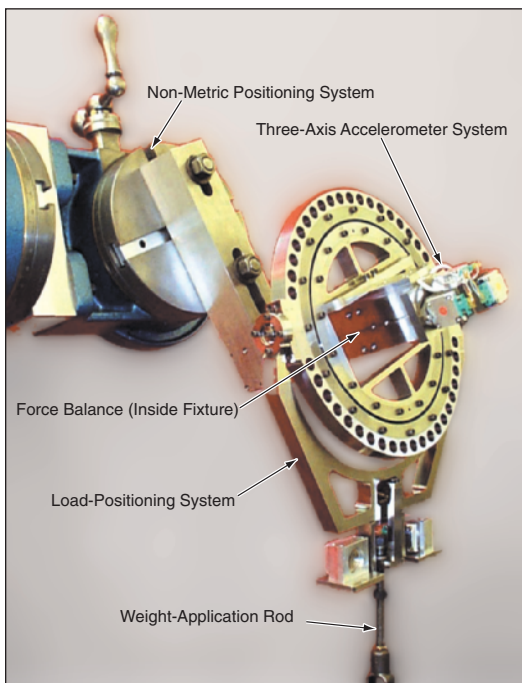
the balance coordinate system that serves as a reference point in which the moment components are described. The point of load application is set using the multiple-degree-of-freedom load-positioning system. This system utilizes a novel system of bearings and knife-edge rocker guides to maintain the load orientation, regardless of the angular orientation of the balance, which makes the point of load application independent of the angular orientation of the balance. Stated another way, when the balance is manipulated in three-dimensional space, the point of load application remains constant.

The SVS performs rapid and accurate setting of the independent variables. Even though this load application system would greatly enhance the execution of the current OFAT design, it is particularly well suited to meet the requirements for the execution of a formal experimental design. The use of a single calibration load reduces the set-up time for the randomized multi-axis load combinations prescribed by a formal experimental design.

The purpose of using an MDOE approach is to efficiently achieve the primary objective of the calibration experiment; namely, the determination of an accurate mathematical model to estimate the aerodynamic loads from measured balance responses. Theoretical and experimental results have shown that MDOE makes it possible to perform a given calibration with an order of magnitude fewer data points than current methods.

The three fundamental MDOE quality-assurance principles are randomization, blocking, and replication. Randomization of data-point ordering ensures that a given balance load combination is just as likely to be applied early in the calibration as it is near the end. If some systematic variation (e.g., instrumentation drift, temperature effects, or operator fatigue) causes earlier measurements to be biased differently from later measurements, then randomization converts such unseen systematic errors to an additional component of simple random error.

Blocking entails organizing an experiment into relatively short blocks of time within which the randomization of point ordering ensures stable sample averages and statistical independence of measurements. While randomization defends against systematic within-block variations, substantial between-block systematic varia-



The **Single-Vector Calibration Apparatus** is mechanically simpler, and hence easier to set up, relative to other apparatuses used to calibrate force balances.

tions are also possible. Blocking makes it possible, during the subsequent analysis of the data, to remove this between-block component of the unexplained variance.

Averaging of genuine replicates causes random errors to cancel. These errors can include what would otherwise be undetectable systematic variations that are converted to random errors by randomizing the loading schedule. Replication also facilitates unbiased estimates of pure error, the component of error attributable to ordinary chance variations in the data. Estimates of pure

error enable an objective assessment of the quality of fit of the mathematical model.

Integration of the single-vector hardware system with MDOE techniques has enabled an order of magnitude reduction in wind-tunnel balance calibration time and cost, while simultaneously increasing the quality of the information obtained from the calibration experiment. The SVS provides the basis for further advancement in force measurement technology in the areas of higher-order mathematical models, implementation of statistical process con-

trol, and an expansion of the calibration mathematical model to include temperature as an independent variable.

*This work was done by P. A. Parker and R. DeLoach of Langley Research Center.*

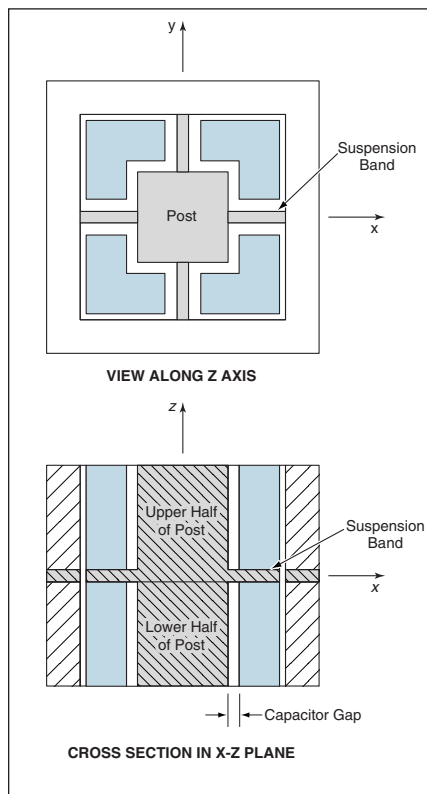
*This invention is in the process of being exclusively licensed. Inquiries concerning technical aspects of the invention may be directed to the inventor, Pete Parker, at (757) 864-4709. Inquiries concerning the licensing and commercialization of the invention may be directed to Barry Gibbens of the NASA LaRC Technology Commercialization Program Office at (757) 864-7141. LAR-16020*

## Microgyroscope With Vibrating Post as Rotation Transducer

Unlike in prior vibratory microgyroscopes, there is no cloverleaf structure.

NASA's Jet Propulsion Laboratory, Pasadena, California

The figure depicts a micromachined silicon vibratory gyroscope that senses rotation about its z axis. The rotation-sensitive vibratory element is a post oriented



The Outer Ends of the Post Oscillate in the x-y plane as the suspension bands flex and bend. The oscillations are affected by rotation of the entire device about the z axis.

(when at equilibrium) along the z axis and suspended at its base by thin, flexible silicon bands oriented along the x and y axes, respectively. Unlike in the vibratory microgyroscopes described in the immediately preceding article ["Cloverleaf Vibratory Microgyroscope With Integrated Post" (NPO-20688)] and other previous articles in *NASA Tech Briefs*, the rotation-sensitive vibratory element does not include a cloverleaf-shaped structure that lies (when at equilibrium) in the x-y plane.

As in the cases of the previously reported vibratory microgyroscopes, vibrations of the rotation-sensitive vibratory element are excited electrostatically, the vibrations are measured by use of capacitive proximity sensors, and the rate of rotation along the axis of sensitivity is deduced from the effect of the Coriolis force upon the vibrations. To create electrodes for electrostatic excitation and capacitive sensing of vibrations, portions of the facing surfaces of the post and of the four stationary members that surround the post are rendered electrically conductive; this can be accomplished by either depositing metal films or else doping the silicon in the affected areas.

In this case, the vibrations in question are those associated with motion of the outer ends of the post in the x-y plane, and the axis of sensitivity is the z axis. The post is initially driven to os-

cillation of its outer (free) ends along, say, the x axis. Under rotation about the z axis, the Coriolis force causes the outer ends of the post to oscillate along the y axis also. The rotation-rate sensitivity of the microgyroscope is proportional to the rate of rotation about the z axis, the drive amplitude, and the resonance quality factor (Q) of the vibratory element.

Like the vibratory microgyroscope described in the immediately preceding article, this one is fabricated as two micromachined silicon components, which are then bonded together. In this case, the four flexible suspension bands and half of the post are made from one silicon wafer, while the other half of the post is made from another silicon wafer.

*This work was done by Tony K. Tang and Roman Gutierrez of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1).*

*In accordance with Public Law 96-517, the contractor has elected to retain title to this invention. Inquiries concerning rights for its commercial use should be addressed to*

*Intellectual Property group*

*JPL*

*Mail Stop 202-233*

*4800 Oak Grove Drive*

*Pasadena, CA 91109*

*(818) 354-2240*

*Refer to NPO-20690, volume and number of this NASA Tech Briefs issue, and the page number.*