Synchronized Wireless Sensor Network for Landing Gear Loads Monitoring

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ABSTRACT

The objective of this effort was to develop a time-synchronized system of wireless integrated shear pins (WISPs) for landing gear structural loads monitoring applications and to demonstrate the performance of these pins under realistic loading conditions, using the V-22 nose gear trunnion pins as a test platform.

Each V-22 trunnion pin was instrumented with two full strain gauge bridges and SG-Link-MIL™ (MicroStrain, Inc.) to transmit both drag and vertical shear loads. A wireless sensor data aggregator (WSDA, MicroStrain, Inc.) sent periodic beacons to synchronize each WISP to +/- 32 microseconds. Synching nose and main gear WISPs enables gross weight and center of gravity calculations.

Static and dynamic loads simulated V-22 nose gear load conditions. Static calibration was performed at loads from 0-43KN, and repeated at angles of 0, 15, 30, 45, 60, 75, and 90 degrees to the vertical. These data were used to populate look-up tables for increased accuracy. Repeatability was determined by loading to 4.4KN for 10 seconds, ramping to 43KN over 2 seconds, then holding at 43KN for 10 seconds. Hysteresis was determined using sine wave loading from 18KN-26KN at frequencies of 3 and 20 Hz.

Repeatability was measured at 0.3% of full scale (FS) and hysteresis was negligible. A system demonstration was performed at Boeing's V-22 full-scale landing gear test facility at known loads of 133KN (vertical), +/-36KN (drag), 31KN (side) and +/-2.8KNm (torsion). WISPs were found to operate reliably under these loading conditions, and their calibrated output loads were within 5.3% of the actual vertical loads and within 6.4% of the actual drag loads during full-scale landing gear tests.

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INTRODUCTION

Structural health monitoring of fixed wing and rotary wing aircraft is of critical importance to fleet operators. As the fleet ages, structural fatigue becomes a greater concern, and limited financial resources push operators to keep aircraft flying, because new aircraft replacement costs are so high. One critical area of concern includes the landing gear components, which are subject to repeated, variable ground loading.

For the structural health monitoring of aircraft landing gear, it is important to be able to detect the magnitude of load events as well as know the fatigue state of the gear at any point in its life cycle. The overarching vision is to deploy integrated, wireless sensors capable of accurately detecting and tracking dynamic load events. Multi-directional load monitoring capabilities combined with time-synchronized autonomous sensors could provide a wealth of usage information about landing gear systems to enable next generation structural health monitoring.

Current methods for fatigue monitoring of aircraft landing gear relies on assumed load spectra based on counting the number of landings and the estimated aircraft weight. This method does not account for the variable nature of aircraft landings, including weight distribution, vehicle orientation, and force of impact. This leads to conservative remaining life estimation, with greater operator reliance on labor-intensive maintenance practices. The actual fatigue life of landing gear is significantly affected by operational usage. But the challenges associated with this application have made it difficult to incorporate in-service sensors capable of remaining on the aircraft for an indeterminate amount of time.

One approach is to instrument the landing gear shear pins. Shear pins, capable of measuring strains in multiple orientations have been described.[1] Such systems can directly measure ground-to-tire loads in order to generate time histories. Yet, the acceptance of such systems continues to be prevented by several factors.

Conventional instrumented pins continue to rely on cumbersome wiring to effectively link communication between sensors and data loggers. Messier-Dowty used environmentally hardened data loggers placed near instrumented pins, but still depended on cabling.[2] Connectors and cables add installation, maintenance and material costs to load monitoring systems and can decrease their reliability. Wireless shear pins can overcome these limitations through integration of sensing, data acquisition, and communications – all within the pin (Figure 1).

Figure 1. Wireless Shear pin.

Other proposed load measurement solutions are limited by their ability to monitor multi-directional events. Pressure and motion sensors mounted in relation to each of the landing gear struts have been used to measure and record the impact and sink rates as the landing gear initially contacts the ground.[3] Strut pressure sensing techniques, while capable of estimating the vertical loads, cannot measure spin-up/spring-back loads (drag loads) experienced during landing. Drag load levels can be on the same order as vertical loads. The strut pressure technique’s inability to capture the complete dynamic load picture is a severe deficiency for a fatigue tracking system.

Additionally, strut-pressure detection systems rely on conventional, hard-wired communications. Wires and connectors mounted externally on the landing gear are prone to damage and breakage.

Another approach to monitoring landing gear load cycles involves embedding fiber optic sensors within the wheel components. Fiber bragg grating (FBG) systems have been tried for monitoring landing gear strain events by measuring load deflection experienced across the wheel axle[4]. Integrated axle sensors were supported by reinforced connection cables to transfer data to a remote interrogator unit, typically mounted within a protected position inside the aircraft fuselage. Fiber optic strain measurement systems have been shown to successfully monitor landing events, such as hard landings, but the nature of their design suggests multiple weaknesses in their practical application over time. FBG systems rely on tethered communications, which are subject to damage and which may require revisions to existing landing gear designs. Clamping methods used to install such systems promote the ability to remove and replace their components. However, clamping has not been shown to effectively keep the strain sensing fibers in position over long periods of use.

OBJECTIVES

The objective of this effort was to develop a time-synchronized system of wireless integrated shear pins (WISPs) for V-22 nose landing gear and to demonstrate performance under realistic loading conditions. Our technique for wireless network time synchronization, which uses beaconing combined with precision timekeepers on each wireless node in the network, have been described previously[5,6,7]. These techniques achieve +/- 32 microseconds time synchronization and were included in the system of WISPs used in this study. Figure 2 provides potential locations of WISP sensors within the V-22 gear. This study was focused on the trunnion pins within the nose gear.

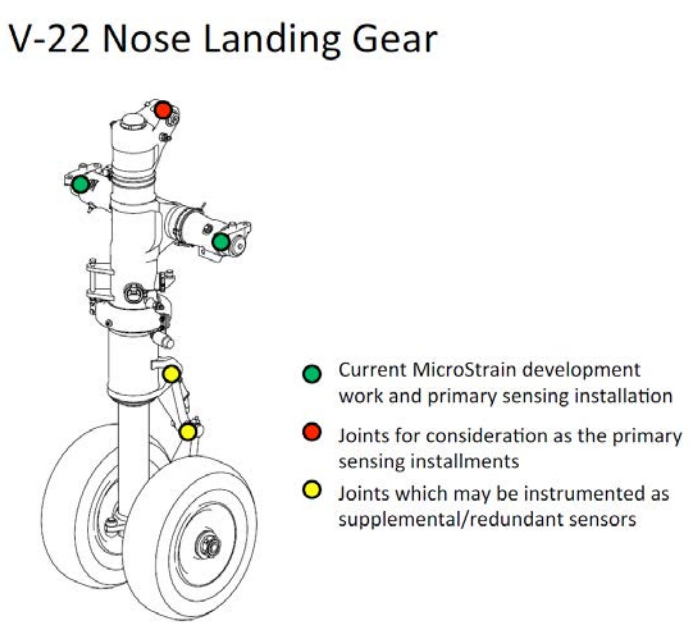

Figure 2. Representative drawing of V-22 nose gear with locations for time-synchronized wireless integrated shear pins (WISPs). Primary measurement points are shown in green and red, and secondary (redundant) points are in yellow. In the present work, the green locations were instrumented.

METHODS

Microelectronics Design

The microelectronics supported two distinct full bridge Wheatstone bridge circuits within each of the two instrumented trunnion pins; each of the two bridges within each pin were arranged at 90 degree angles to enable the measurement of shear loads in both vertical and horizontal directions. The strain gauges within each bridge were also arranged to amplify shear load while cancelling out thermal effects, torsion, bending, and axially directed loads.

The electronics module (SG-Link-MIL, MicroStrain, Inc., Williston, VT, USA) featured an embedded microprocessor, 16 bit analog to digital (A/D) converter, 2 Mbytes non-volatile memory, precision timekeeper, programmable 2.4 GHz IEEE 802.15.4 frequency agile spread spectrum radio, and embedded power management capabilities. An on-board temperature sensor was included to facilitate temperature compensation during planned flight tests, as well a triaxial accelerometer (Analog Devices, Norwood, MA, USA), which was included to support "shake and wake" capability as well as to enable measurement of pin orientation with respect to the gravity vector. The triaxial accelerometer could also serve to collect vibration data during planned flight tests in order to facilitate development of a dedicated vibration energy harvester for this application.

Figure 3 provides a block diagram of the microelectronics module and external base station (WSDA-MIL, MicroStrain, Inc., Williston, VT, USA). The diagram indicates elements for energy harvesting and inductive recharging, however, for the purposes of this study, the WISP was powered with an embedded battery.

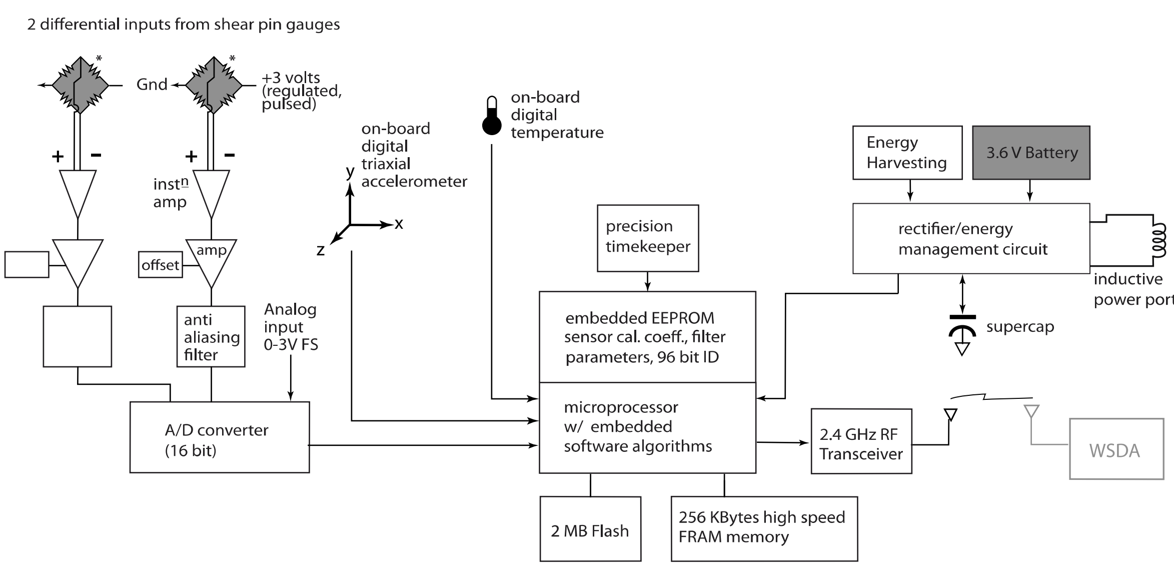

Figure 3. Block diagram of WISP microelectronics (SG-Link-MIL) and base station (WSDA-MIL). Two full bridge channels were monitored from each side of the V-22 nose gear trunnion to provide four channels of shear pin loads data.

The microelectronics module was tested to MIL-STD-810F and passed evaluation tests for thermal shock, thermal soak, high humidity, vibration, and high-G (centrifuge) tests. These modules feature wireless strain gauge offset/gain adjust, wireless control of sample rates to 2 KHz, wireless shunt calibration, and low temperature coefficients (offset: -.007%, span: .015%). The +3 V DC regulated bridge excitation is multiplexed & pulsed to conserve energy. In our experience, the resolution of our wireless strain gauge bridge installations has been observed to be +/- 3 bits, with a strain sensitivity of ~0.3 microstrain per bit.

Data Aggregation

A wireless sensor data aggregator (Figure 4, WSDA-MIL, MicroStrain, Inc., Williston, VT USA) was used for data collection and timing management within the wireless sensor network. The WSDA-MIL features a GPS receiver, timing engine, microprocessor core running Linux 2.6, Ethernet interface, and wireless controller. It provides large on board data storage, and uses the Ethernet interface (or optional cell phone link) to automatically direct aggregated data to an online database.

Figure 4. Wireless Sensor Data Aggregator.

Laboratory Calibration

Calibration data were obtained in the laboratory by loading the pins in a custom test fixture within a hydraulic testing machine (Instron). Static calibration was performed at loads from 0-9750 lbs (43KN), and repeated at angles of 0, 15, 30, 45, 60, 75, and 90 degrees to the vertical. Data were recorded from the vertical and horizontal (drag) output channels and used to populate look-up tables of WISP outputs at each angle to the vertical. Repeatability was determined by loading to 1000 lbs (4.4KN) for 10 seconds, ramping to 9750 lbs (43KN) over 2 seconds, then holding at 9750 lbs (43KN) for 10 seconds. Hysteresis was determined using sine wave loading from 4000-5800 lbs (18KN-26KN) at frequencies of 3 and 20 Hz.

Full Scale V-22 Nose Landing Gear Testing

Production trunnion pins were removed from Boeing's V-22 flight test load calibration test fixture and replaced with the WISP prototypes. A photo of the nose landing gear (NLG) WISP installation is provided in Figure 5. The instrumented load link and load cells were calibrated and certified in accordance with MIL-STD-45662A. Test loads consisted of vertical, drag, side and torsion loads applied individually and in combinations. Due to page limitations, we provide output plots for vertical load of 133 KN with a combined horizontal (drag) load of 17 KN. Plots of un-scaled WISP outputs (i.e., the data are provided in bits) for the entire range of loading conditions tested in the V-22 NLG full scale tests are provided in reference 8. All V-22 full-scale NLG tests were performed at room temperature.

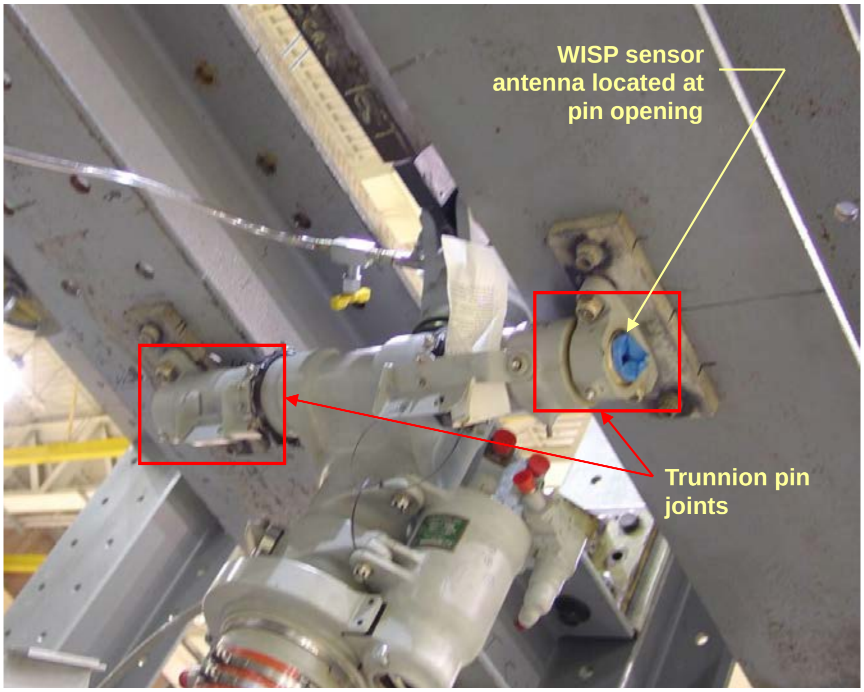

Figure 5. WISP trunnion pin installed in V-22 full scale testing rig.

RESULTS

Calibration Test Results

Repeatability was measured at 0.3% of full scale (FS), and hysteresis was negligible. Crosstalk - drag channel outputs induced by vertical shear loads - of 7%, 8%, and 16% of full scale were measured at applied loading angles of 0, 90, and 45 degrees. Correction using the look-up table approach reduced these crosstalk errors to 2%, 1% and 2% FS at applied loading angles of 0, 90, and 45 degrees.

Full Scale V-22 Nose Landing Gear Test Results

Testing of the WISP trunnion pins within Boeing's V-22 full-scale rig was completed without incident. The sensors exhibited linear relationships over most of the applied load ranges, although non-linearity was evident for most of the combined loading conditions. Hysteresis was most pronounced for torsion loading which may be the result of the relatively large number of non-linear contact pinned joints in that load path[8].

Figure 6 plots the WISP output in physical units as function of applied load for the vertical load condition at 7 inches displacement. This tested our ability to calibrate WISPs in the laboratory (at relatively low calibration loads of 43 KN) and then apply those laboratory calibration factors to WISP raw data obtained during full-scale V-22 NLG tests. Nonlinearity was 5.3% max over the entire range of vertical test loads of 0-133 KN. A known horizontal (drag) load was simultaneously generated due to the geometry of the V-22 nose gear; nonlinearity was 6.4% max over the range of full scale V-22 NLG drag test loads.

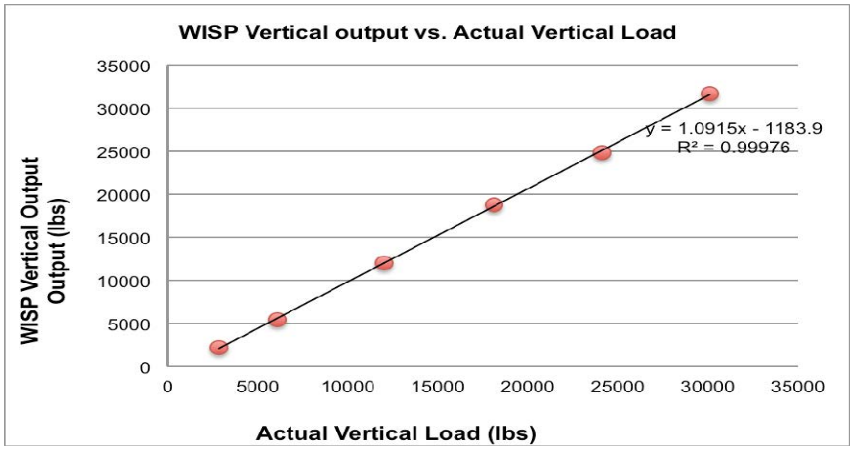

Figure 6. WISP output load using laboratory calibration data as a function of actual vertical loads applied to the V-22 nose landing gear in Boeing's full-scale test rig.

CONCLUSIONS

This work has demonstrated, on a large aircraft (V-22) landing gear system, that a time-synchronized network of wireless, pre-calibrated shear load sensors can directly measure landing gear loads without requiring an *in situ* recalibration. We're currently working to improve sensor accuracy by capturing wireless shear pin multi-channel data over operational loads, loading angles, and temperatures.

ACKNOWLEDGEMENTS

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