An Inertially Referenced Noncontact Sensor for Ground Vibration Tests

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Down times during modal testing can prove very costly. Ground vibration tests at the Air Force Flight Test Center are one example where schedule drives cost. After structural modifications, ground vibration tests verify that aircraft are not at risk for flutter. Ground vibration tests require large channel counts and extensive setup operations with the aircraft unavailable for other uses during this time.

This article introduces a noncontact sensor that simplifies operations for ground vibration tests (GVTs) and reduces the time during which the aircraft is committed. The device, called a noncontact inertia reference velocity (NIRV) sensor, enables noncontact measurement of response degrees-of-freedom in modal analyses. Sensors are mounted to an inexpensive stand. If dimensions of the test article are available, the stand may be assembled and sensor checkouts completed before the article is committed to test. Data acquisition can then start shortly after committing a test article, requiring only shaker mounting and final stand positioning.

NIRV sensors and acquisition methods were demonstrated with a GVT on an aircraft at Edwards Air Force Base (Figure 1). Assembly processes are discussed, test results are compared to those from conventional accelerometers, and differences in data acquisition and reduction methods are examined.

Figure 1. Ground vibration test (GVT) on an aircraft at Edwards Air Force Base.

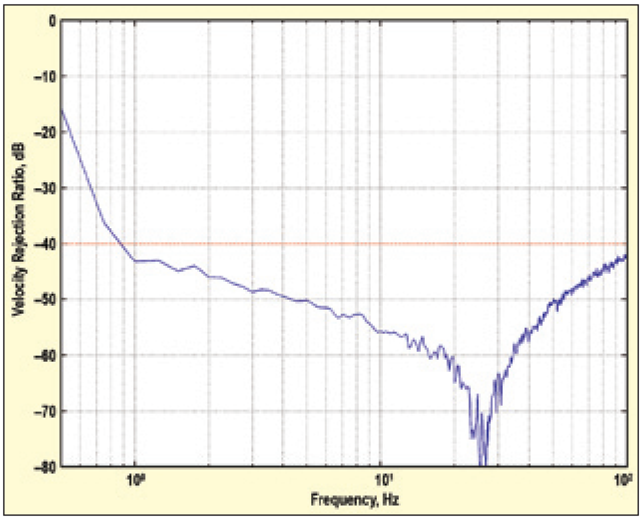

Figure 2. Rejection ratio measurement from typical NIRV sensor.

NIRV Sensor

The NIRV sensor (patent pending) produces an inertially referenced velocity signal using a combination of signals from two conventional sensors and a special combining circuit. An accelerometer is co-located with a noncontact laser displacement sensor and is used to correct for motion of the laser assembly.

The laser sensor demonstrated in this article is a Keyence LK-G displacement sensor. It measures displacement using laser and triangulation principles. It has excellent dynamic range, a relatively long stand-off distance, superior calibration stability with time, and is insensitive to changes in color and texture of targets because of an adaptive circuit that increases the laser intensity on surfaces yielding low light return.

Like any displacement sensor, the LK-G measures relative position between itself and a target, and its output depends on sensor motion as well as target motion. This becomes important in aircraft GVTs where test article size requires the noncontacting sensors to be mounted on large, rather flexible stands. The NIRV sensor solves this problem by using an accelerometer with its inherent inertia reference to remove the effect of stand motion from the displacement signal. Both acceleration and displacement signals are converted to velocity signals that are then differenced to obtain an inertially referenced velocity.

During a GVT, frequency response functions (FRFs) are acquired in terms of velocity per unit force, commonly called "mobility." Data reduction with mobility functions is straightforward. for example, both LMS and I-Deas software have the capability to define the input data type as velocity, maintaining full acquisition and reduction capabilities. Upon channel setup, NIRV sensors are calibrated in velocity. Data reduction from FRFs to mode parameters and shapes are unchanged for typical operations in a GVT. In a GVT master class, LMS demonstrated sine sweep, step sine, and sine dwell acquisition using NIRV sensors for feedback to the acquisition system without any changes in software or operations.

Upon calibration, each sensor is tested for its ability to reject stand motion using a test configuration that shakes the sensor as the laser sights on a stationary object. The correction for stand motion is quantified in terms of a function of frequency, called rejection

Figure 3. View of stand showing suggested construction practices.

ratio. Typical measured rejection ratio of a NIRV sensor is shown in Figure 2. Stand motion rejection is greater than 40 dB, from 1 to 100 Hz, which says that stand motions are rejected by greater than 100 to 1 in amplitude. The dotted red line indicates this level.

Application of NIRV Sensors in an Aircraft GVT

The GVT examined the modal parameters of an aircraft with

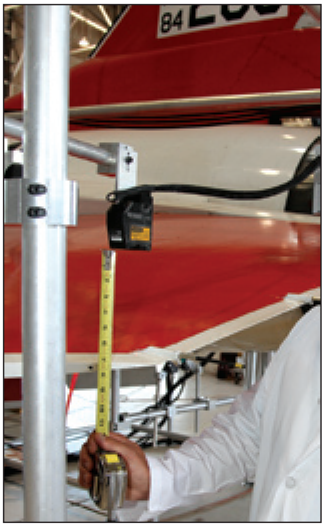

Figure 4. Close-up view of NIRV sensor sighting on aircraft structure.

Figure 5. Modal excitation shaker positioned on aircraft structure.

both NIRV sensors and accelerometers. The latter were mounted to the aircraft in the conventional manner. All response degrees-of-freedom (DOFs) were instrumented with NIRV sensors, and the left wing was also instrumented with accelerometers at identical locations. NIRV sensors were pulled from a stock of 80 that are owned by the Edwards Flight Test Center. Two full-scale ranges were available:

- NIRV 157 sensors have a stand-off distance of 5.9 inches and a peak-to-peak stroke range of 3.2 inches.
- NIRV 87 sensors have a stand-off of 3.2 inches and operate across a range of 1.2 inches.

Accelerometer data presented in this article are from PCB Type 333B32 units.

Building a stand to support NIRV sensors for a GVT is straightforward, since there are few requirements. Sensor sway must not exceed the full-scale range of the displacement sensors but is otherwise unrestricted. Lessons from stand-building have indicated that adjustability speeds modifications. Stands were manufactured with aluminum tubing and custom pinch clamps. Tubing runs extended past the uprights at the end of the horizontal tail in Figure 3, accommodating length extensions without additional tubing cuts. Both coarse elevation and length changes on the horizontal tail stand require only repositioning of pinch clamps. Sensor mounts provide the flexibility to readily locate and orient sensors with only two hex key wrenches. Typical sensor and modal excitation shaker setups are shown in Figures 4 and 5.

High winds typical of the Mojave area were the greatest challenge when hanger doors were open in the afternoon. Deflections were sometimes large enough to over-range NIRV sensors at the top of the vertical tail.

Frequency response functions (FRFs) generated with NIRV sensors are in the form of mobility. Inertance is readily calculated from mobility with a rotation of $j\omega$ in the complex plane. Comparing data from an accelerometer and collocated NIRV sensor is shown in Figure 6. A NIRV 157 generated the data. Functions from the two sensors are virtually indistinguishable, except below 1 Hz where signal/noise ratio from the accelerometer is poor. The modal properties extracted by either of these two functions will generate identical results regardless of whether curve-fitting is performed in this form or as mobility.

The wireframe model associated with this test included 68 response DOFs. The undeformed shape is shown aside the aircraft in Figure 7. Fuselage measurements were bi-axial. In cases where fuselage contour didn't support direct measurements from the aircraft's surface, simple aluminum angles were hot-glued to the aircraft. Figure 8 shows examples on the aircraft belly.

Deformation shapes were determined for six of the lowest-frequency, flexible-body modes of the aircraft. Some of the mode shapes are shown in Figure 9. Deformed shapes are overlayed with the undeformed in different colors for clear viewing. Mode

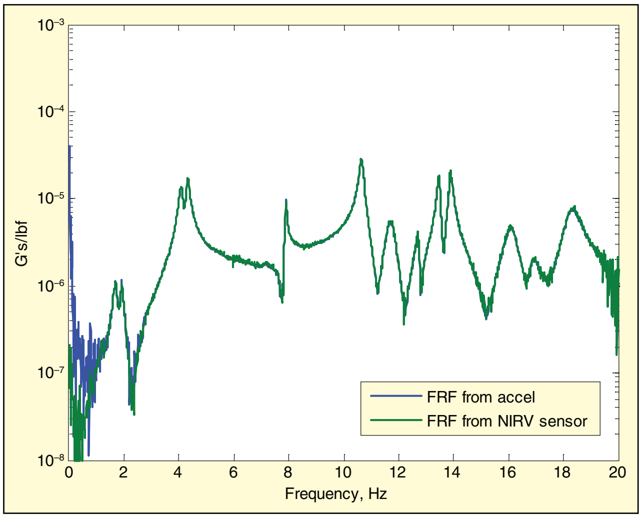

Figure 6. Overlay of inertance frequency response functions generated by accelerometer and collocated NIRV sensor.

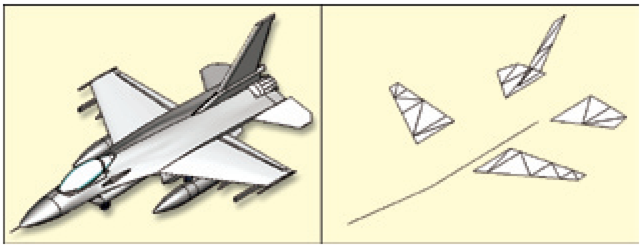

Figure 7. View of aircraft side by side with wireframe.

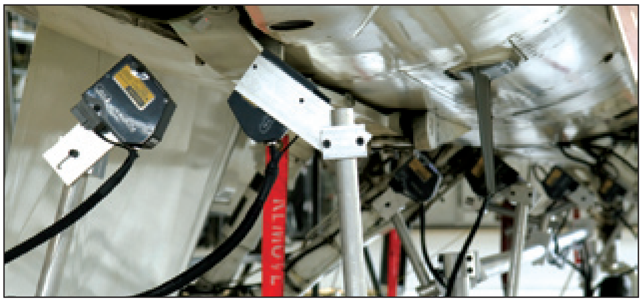

Figure 8. Biaxial DOFs on aircraft belly.

shapes and parameters are as expected for an aircraft of this size and structure. Lowest-order, elastic-body modes are wing bending, followed by first bending of fuselage, and then more complex shapes, including variations on previously seen shapes.

Modal parameters are shown in Table 1. The aircraft was tested with nominally half the operating pressure in the tires. Several of the lowest frequency modes have strain energy in both the aircraft body and in the tires and suspension. They were omitted. Results are typical for an aircraft of this form.

Conclusions

Results demonstrate the function and practical application of a new sensor that can measure the inertia-referenced velocity of a structure without contact. Measurements demonstrate sensor function on the broad variety of surfaces typical of an aircraft ground

Table 1. Table of mode parameters from aircraft.

Mode	Frequency, Hz	Damping, %	Description
1	7.886	0.4	Wing bending, symmetric
2	10.65	0.7	Wing bending, antisymmetric
3	11.709	1.3	Fuselage bending
4	12.716	0.5	Empennage mode
5	13.467	0.4	Wing torsion, symmetric
6	13.885	0.5	Wing torsion, antisymmetric

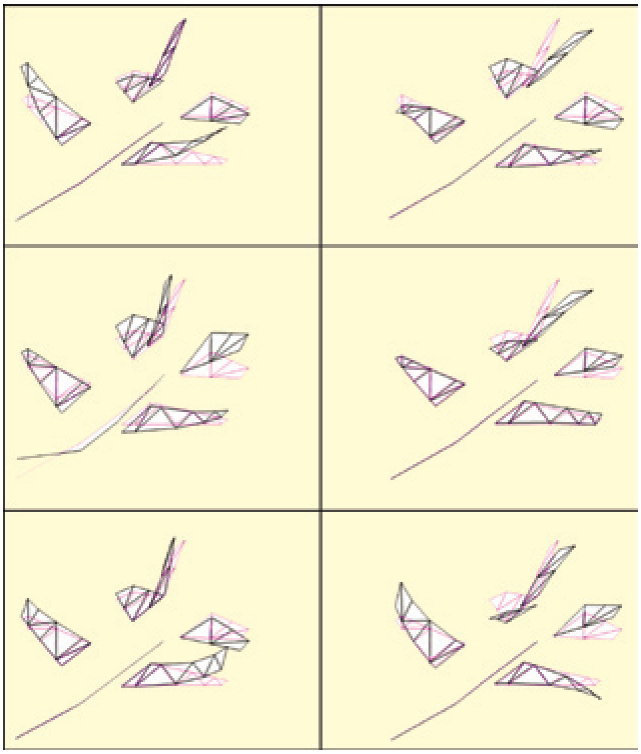

Figure 9. Six mode shapes of the aircraft.

vibration test and show that offset gap and signal-to-noise ratio of the NIRV sensors are practical.

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