# The Use Of Dynamic Strain Sensors And Measurements On The Ground Vibration Testing Of An F-16 Aircraft

Fábio L. M. dos Santos, Bart Peeters, Jan Debille, Carmine Salzano,
Luiz Carlos S. Góes and Wim Desmet

# THE USE OF DYNAMIC STRAIN SENSORS AND MEASUREMENTS ON THE GROUND VIBRATION TESTING OF AN F-16 AIRCRAFT

**Fábio L. M. dos Santos[1,2,3,*], Bart Peeters[1], Jan Debille[1], Carmine Salzano[4], Luiz Carlos S. Góes[2] and Wim Desmet [3]**

[1]Siemens Industry Software NV
Interleuvenlaan 68, 3001 Leuven, Belgium
fabio.m.santos@siemens.com

[2]Mechanical Engineering Division - Mechatronics Department
Instituto Técnológico de Aeronáutica
Praça Marechal Eduardo Gomes, 50, 12.228-900 - São José dos Campos/SP, Brazil
goes@ita.br

[3]Division PMA
KU Leuven
Celestijnenlaan 300B, 3001 Heverlee, Belgium
wim.desmet@kuleuven.be

[4]PCB Piezotronics Inc.
Depew, USA
csalzano@pcb.com

**Keywords:** strain sensors, strain modal analysis, ground vibration testing

**Abstract:** Ground Vibration Testing (GVT) of aircraft is a measurement campaign performed in the development process of an aircraft, with the objective of obtaining experimental data of the aircraft to validate and update the structural dynamic models, which can in turn be used to predict important behavior, such as flutter. These measurements are usually carried out using standard accelerometers, which lead to the identification of the displacement mode shapes. However, the use of strain sensors in vibration and modal related applications has recently gained popularity, due to some advantages, such as sensor size and the fact that strain relates directly to stress. On the other hand, interpreting the strain mode shapes can sometimes be more complex, so the use of both strain and acceleration sensors can lead to a more complete and understandable dataset.

In this paper, the main results of a GVT campaign on an F-16 aircraft will be shown, where the full aircraft was instrumented with accelerometers and one of the wings was also fully instrumented with dynamic strain sensors. The main results of the test campaign will be shown, where both strain sensor and accelerometer measurements are processed simultaneously, resulting in the strain and displacement mode shapes, respectively, and some characteristics and advantages of carrying out the tests this way will be presented.

## 1 INTRODUCTION

The ground vibration testing of aircraft is often considered a very important step in the aircraft design, being most useful to identify the structural dynamics of the aircraft [1, 2], which in turn are used for to correlate and update numerical models. This in turn leads to better are more accurate models of the aircraft, improving the design efficiency and reducing the overall design cycle time.

This sort of testing has evolved from lengthy tests, such as the normal modes testing, to more efficient (but still accurate) methodologies, using broadband excitation signals and controlled multiple-input multiple-output (MIMO) excitation methods [3]. Nonetheless, various types of improvements are still being sought by the aircraft industry, both in the reduction of testing time, but also on enhanced quality and interpretation of the data, that is, to obtain more relevant results from the same test.

One way to achieve this is to use different types of sensors that can yield information that could not be obtained before. In this sense, even though modal testing has been for a long time associated with the use of accelerometers, the use strain sensors in modal analysis [4, 5] has had increased interest from both industry and academia [6, 7]. They can be used not only to assess structural integrity on prototype stages, but can also give a better insight to where there are higher levels of stress within a complicated structure.

Another application of dynamic strain measurements is related to the strain-displacement relations [8], or more specifically load prediction using strain measurements. In many aerospace applications, where size and weight are very restricted, and any sensor placed on the outside of an aircraft should affect its aerodynamic properties as little as possible, strain gauges make for an attractive solution for in-flight measurements.

In this paper, the use of dynamic strain sensors on a GVT test campaign will be shown. The test campaign was part of the GVT Master Class, where the full testing was carried out on an F-16 aircraft. For this purpose, in addition to the traditional accelerometers, 17 piezo strain sensors [9] were instrumented on the left wing of the aircraft, and the test procedure was carried out using the standard MIMO excitation methods.

## 2 STRAIN MODAL ANALYSIS

The use of strain sensors in modal analysis follows the typical modal formulation - it is similar to the classical modal analysis form, but with some differences. The modal superposition can be applied to strain modal analysis, and it leads to the following formulation:

$$\varepsilon(t, p) = \sum_{r=1}^{n} \psi_r(p) q_r(t) \tag{1}$$

where $\psi_r$ is the $r^{th}$ strain mode at point p, $q_r(t)$ the generalized modal coordinate and $\varepsilon(t, p)$ being the strain at time t and at point p .

Given the theory of elasticity, the strain in a general direction is equal to the gradient of the vector component in that same direction. That is, for the displacement in the general direction u, the strain will be:

$$\varepsilon(t, p) = \nabla u(t, p) \tag{2}$$

with $\varepsilon(t, p)$ being the strain at time t and at point p, and $\nabla$ is the linear spatial differential operator.

The relation between a force input and a strain output, in terms of displacement and strain modes is then represented as:

$$\boldsymbol{\varepsilon} = \sum_{r=1}^{n} \psi_r \Lambda_r^{-1} \phi_r \mathbf{F} \tag{3}$$

where **F** is the time dependent force vector. Finally, the strain frequency response function (SFRF) can be obtained, in matrix form:

$$\mathbf{H}^{\varepsilon} = \sum_{r=1}^{n} \Lambda_r^{-1} \{\psi_r\} \{\phi_r\} = [\psi_r] [\Lambda_r]^{-1} [\phi_r]^T \tag{4}$$

The expansion of (4) is:

$$\begin{bmatrix} H^{\varepsilon}_{11} & H^{\varepsilon}_{12} & \cdots & H^{\varepsilon}_{1N_q} \\ H^{\varepsilon}_{21} & H^{\varepsilon}_{22} & \cdots & H^{\varepsilon}_{2N_q} \\ \vdots & \vdots & \vdots & \vdots \\ H^{\varepsilon}_{N_p1} & H^{\varepsilon}_{N_p2} & \cdots & H^{\varepsilon}_{N_pN_q} \end{bmatrix} = \sum_{r=1}^{n} \Lambda_r^{-1} \cdot \begin{bmatrix} \psi_{1r}\phi_{1r} & \psi_{1r}\phi_{2r} & \cdots & \psi_{1r}\phi_{N_qr} \\ \psi_{2r}\phi_{1r} & \psi_{2r}\phi_{2r} & \cdots & \psi_{2r}\phi_{N_qr} \\ \vdots & \vdots & \vdots & \vdots \\ \psi_{N_pr}\phi_{1r} & \psi_{N_pr}\phi_{2r} & \cdots & \psi_{N_pr}\phi_{N_qr} \end{bmatrix}_{N_p \times N_q} \tag{5}$$

where $N_p$ represents the number of strain gauge measurement stations (or the number of output measurements) and $N_q$ represents the number of excitation points (or the number of inputs).

Strain modal analysis and the use of strain gauges in modal testing can be referred to as a means of using solely strain gauges as the output sensors in modal analysis. However, there can be many benefits in combining strain gauge and accelerometer measurements [10]. On one hand, strain modes can be very hard to interpret, since by themselves they do not directly show how the structure is being displaced. If the structure being analyzed is very complicated in shape and structure (as is the case with an aircraft) then the task of interpreting the strain mode shapes becomes very complex [11]. On the other hand, the strain modes can provide valuable information that otherwise is not available by solely using accelerometers [12, 13].

Being able to visualize where strain (and therefore stress) occurs, as well as find out how the vibration modes contribute to this effect, is very valuable. Therefore, by combining strain gauge and accelerometer measurements, one can be able to combine the ease of interpretation that comes from displacement mode shapes, to the additional strain concentration information provided by the strain modes.

For the mixed strain and displacement modal analysis, the modal superposition formulation has the same format, but is composed of the displacement and strain parts [14, 15].

## 3 PIEZO STRAIN SENSORS

To carry out dynamic strain measurements, many types of sensors can be used, each one with their advantages and drawbacks. For the strain measurements in the GVT measurement campaign, piezo strain sensors were chosen (PCB 740B02). This type of reusable sensor, suitable for dynamic measurements, is is structured with a quartz sensing element and microelectronics circuitry. It can only be used to measure unidirectional strain and has a grid length of 15mm.

The advantage of this type of sensor, in comparison with the resistive strain gauges, comes from its better signal-to-noise-ratio, due to the piezoelectric sensing element. It employs the commonly used ICP® (IEPE) amplifier, a real charge amplifier which converts the original signal (electric charge) of the quartz, in voltage proportional to the measured strain, with their nominal sensitivity being around 50mV/$\mu\varepsilon$, with a frequency range similar to that of piezo accelerometers, varying from 0.5 Hz to 100KHz (not usable to measure static loads). The sensing element of each sensor is protected by a titanium housing which is hermetically sealed, and its stiffness does not allow the use of the sensor of curved surfaces.

These sensors, differently from the resistive strain gauges, can be mounted using a quick-bonding cyanoacrylate gel, which makes the bonding procedure much faster, and more compatible with the instrumentation timings and efforts required for a GVT test campaign. Nonetheless, proper mounting is critical to good sensor performance, as with the traditional strain gauges - all surfaces must be clean, dry, and free of oils before applying adhesive. However, the sensor can be reused and re-applied in case it might be necessary. The calibration of theses sensors is not done on site, and is instead carried out in a controlled environment, where the sensors are dynamically calibrated using a steel cantilever beam.

The 740A02 strain sensor combines a quartz sensing element and microelectronic signal conditioning within a titanium housing of outer dimensions 0.2 x 0.6 x 0.07 inches [5,1 x 15,2 x 1,8 mm]. The sensor measures in- plane normal strain along the length of the sensor (Figure 1). The sensor is designed for minimum sensitivity to transverse strain. Because the sensing element is quartz, it is inherently insensitive to pyroelectric (thermal) disturbances. The sensor

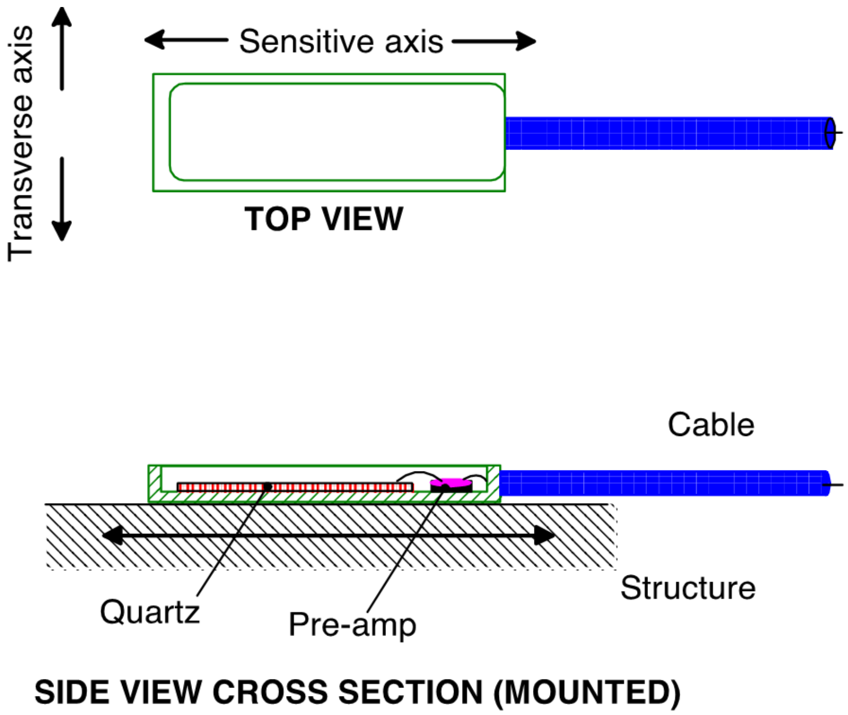



Figure 1: 740A02 strain Sensor construction. Sensitive and transverse axis indicated in top view . Cross section shows mounting to structure

is mounted to the structure under test via an adhesive bond. For accurate measurements and good strain transfer into sensor, the mounting surface must be clean and flat and the adhesive layer must be thin and of high stiffness

The strain sensor sensitivity is calibrated by the method of a steel cantilever beam. When the stiffness modulus of the structure under test is less then the modulus of steel, the actual sensitivity is less than the calibrated sensitivity.

The upper limit to the frequency response is determined either by cable drive consideration or by wavelength of dynamic strain. Long cables capacitively load the frequency output and with long cables measurement of high frequency may require the use of a higher current power supply. Measurements are accurate when the wavelength is large compared to the length of the sensor. The wavelength $\lambda$ can be determined from the following formula [16]:

$$\lambda = c/f \tag{6}$$

where c is the speed of sound and and f is the frequency. A good rule of thumb is that the wavelength can be determined from the following equation:

$$f_u = 0.1 \cdot c/L \quad (7)$$

where L is the length of the sensor.

Low inherent transverse sensitivity is one reason that a quartz sensing element, rather than piezoceramic, is used in the 740A02 strain sensor. Based on the cut of quartz, the inherent transverse sensitivity of the 740A02 sensor is equal to -1.9%. This means that if the sensitivity is 50 mV/$\mu\varepsilon$ along the sensing axis, the sensitivity transverse to this axis will be -0.95 mV/$\mu\varepsilon$. By design, the sensitivity to in-plane shear strain is zero. The following acceptance test, using the calibration beam shown in Figures 2 and 3, can determine the transverse sensitivity to an accuracy of 5% (a more accurate method is being developed which will determine transverse strain to an uncertainty of $\pm$0.5%).

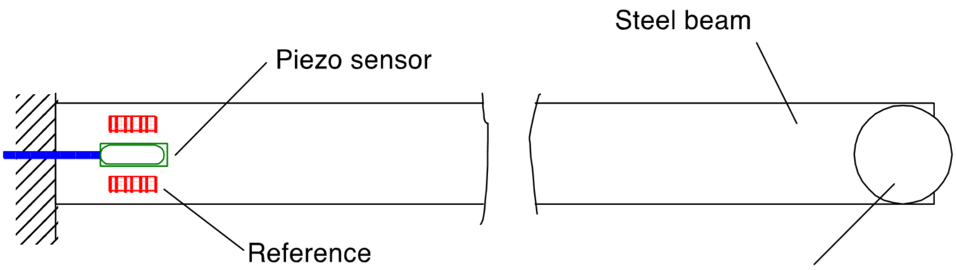



Figure 2. Cantilever beam for determination of sensitivity. (26 x 2 x 0.25 inches steel beam)

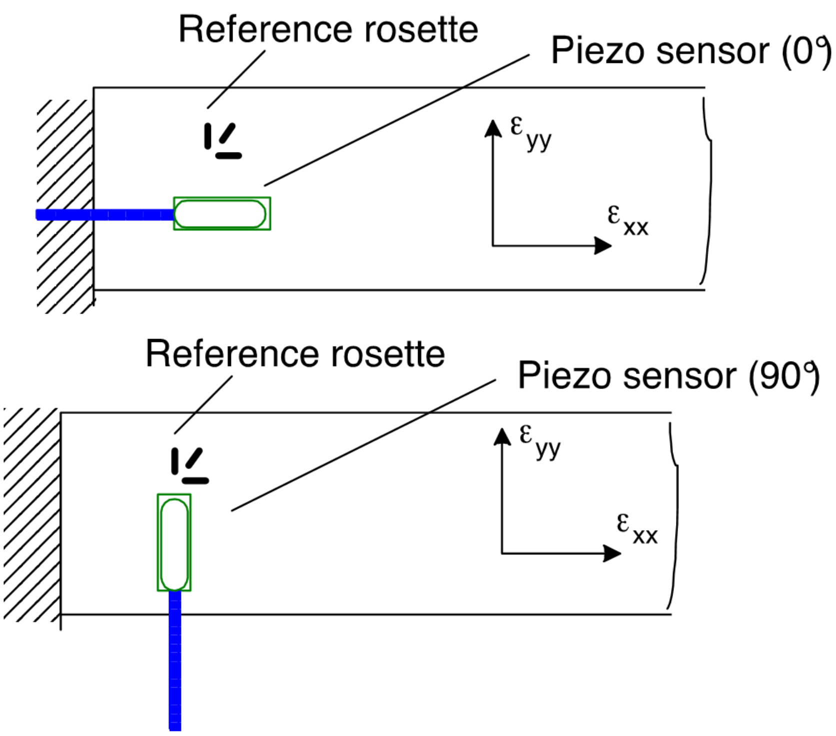



Figure 3. Determination of transverse sensitivity. Piezo sensor mounted at 0 and 90 degrees

The piezoelectric sensor is mounted at 0 and 90 degrees and output recorded. The measured strain field is also recorded:

$$\varepsilon = \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} \\ \varepsilon_{yx} & \varepsilon_{yy} \end{bmatrix} = \begin{bmatrix} \varepsilon_{xx} & 0 \\ 0 & \varepsilon_{yy} \end{bmatrix} = \begin{bmatrix} \varepsilon_{xx} & 0 \\ 0 & -\mu\varepsilon_{xx} \end{bmatrix} \quad (8)$$

As expected, the measured in-plane shear is equal to zero and $\varepsilon_{yy}$ arises because of Poisson's effect (the cantilever beam is uniaxial stress, but biaxial strain!). The output voltage is related to the strain field through:

$$V_0^0 = S\varepsilon_{xx}^0 + S_t\varepsilon_{xx}^0 \quad (9)$$

$$V_0^{90} = S_t\varepsilon_{xx}^{90} + S\varepsilon_{yy}^{90} \quad (10)$$

The superscripts 0 and 90 indicate measurements at $0^o$ and $90^o$ respectively. The above equations can be solved for the main axis and transverse sensitivities, S and $S_t$.

## 4 STRAIN MODAL ANALYSIS APPLIED ON THE GROUND VIBRATION TESTING OF AN F-16

The ground vibration test campaign was carried out using the traditional instrumentation plus the piezo strain sensors described on the previous section. This test campaign was part of the LMS GVT Master Class [17, 18]. In total, 136 measurements were obtained from the instrumentation in the whole aircraft - of these, 17 were strain sensors instrumented on the left wing, 2 force cells and the rest were from accelerometers. On the left wing, 8 tri-axial accelerometers were placed collocated with the strain sensors. Figure 4 shows the sensor geometry on the aircraft. An LMS SCADAS Lab and a SCADAS mobile were used for the data acquisition, and 2

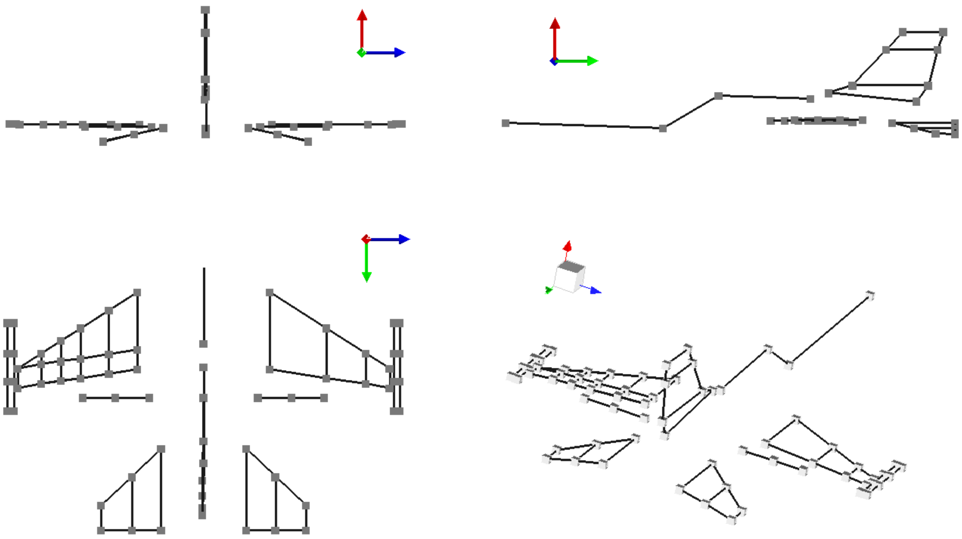
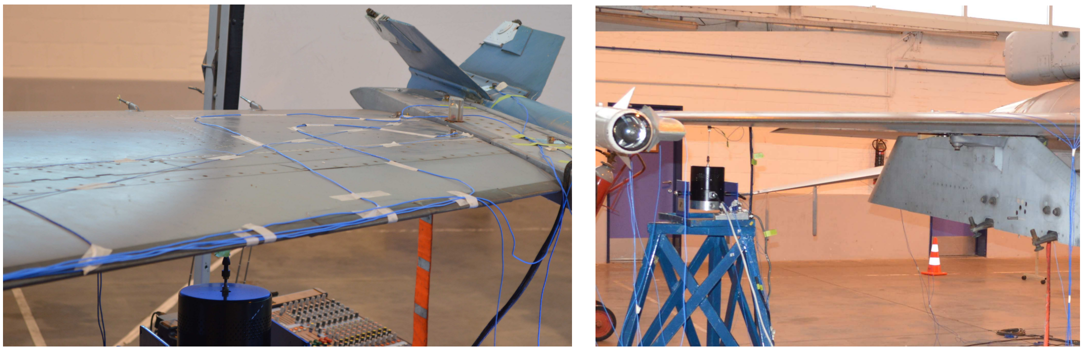


Figure 4. F-16 test sensor locations

shakers were used to excite the structure, near the tip of each wing. Figure 7 shows the full test set-up, with the shakers and the data acquisition systems. To obtain a boundary condition close to free-free, the landing gear tires were slightly deflated, to decrease their stiffness.

Figure 6 shows the shakers on both sides of the aircraft, indicating the position where they were attached, and Figure 6(b) also shows the support used for the shaker. The left wing was

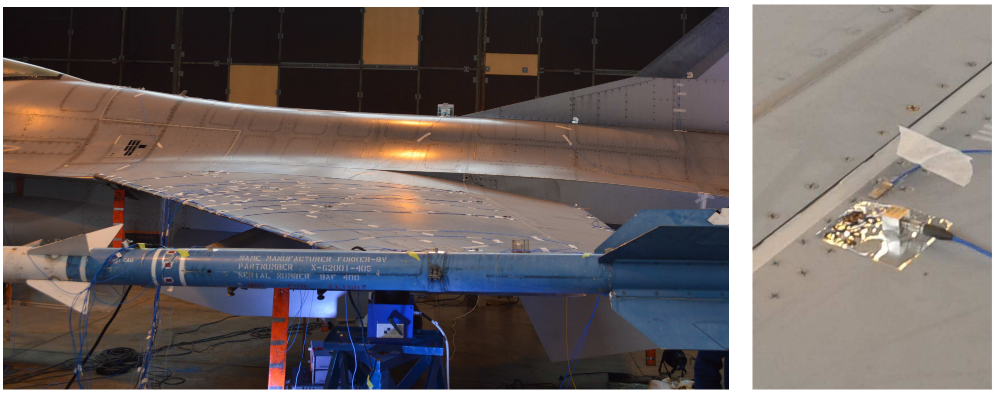
Figure 5. F-16 Test set-up



(a) Shaker on left wing

(b) Shaker on right wing

Figure 6. Shaker locations

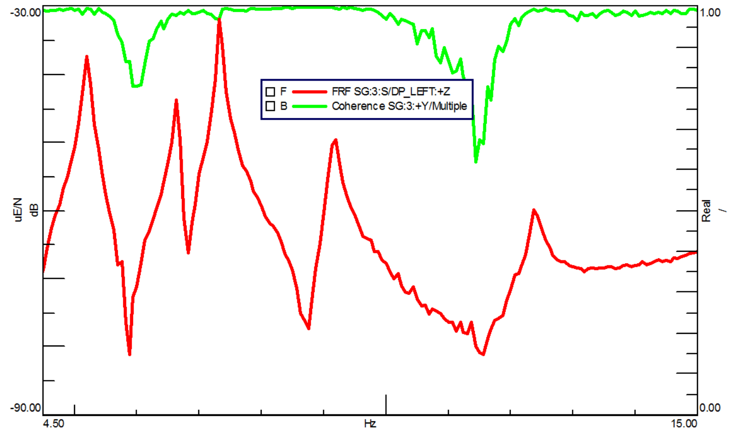


(a) F-16 Left wing set-up

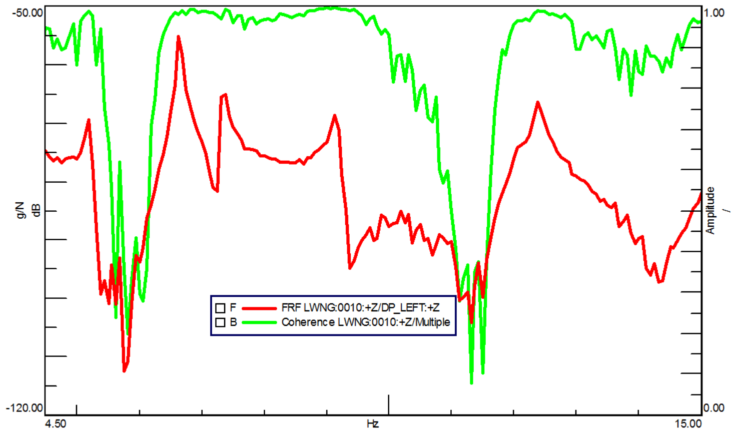
(b) F-16 left wing - collocated strain sensor and accelerometer

Figure 7. F-16 Test set-up and close-up on left wing with strain sensor and accelerometer

instrumented with the strain sensors, and is shown in Figure 7(a), while a close up on one of the (nearly) collocated sensor pair is shown in Figure 7(b). The aircraft was excited the standard types of excitation signals, such as burst random, pseudo random, sine sweep and stepped sine. These different types of signals can be used to achieve different identification objectives, for example, to identify non-linearities. In the case of the tests using the strain sensors, the main objective was to visualize the strain and displacement modes on the left wing, and better understand their behavior. For this purpose, the burst random excitation was adequate and could provide good input for the modal identification procedure. The full bandwidth of the excitation signal ranged from 1 to 64Hz, but a smaller range was used for the identification - there were enough modes present from 4.5 to 15 Hz. Figure 8 shows the strain frequency response function (SFRF) and the frequency response function (FRF), as well as their respective coherence function, from and arbitrary point on the left wing where a collocated pair of sensors was present.




(a) Strain FRF and coherence from an arbitrary point

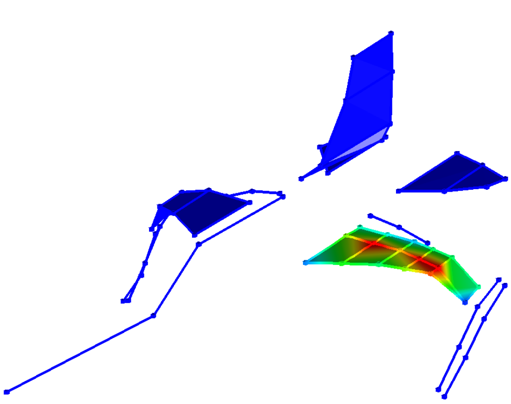



(b) FRF and coherence from and arbitrary point

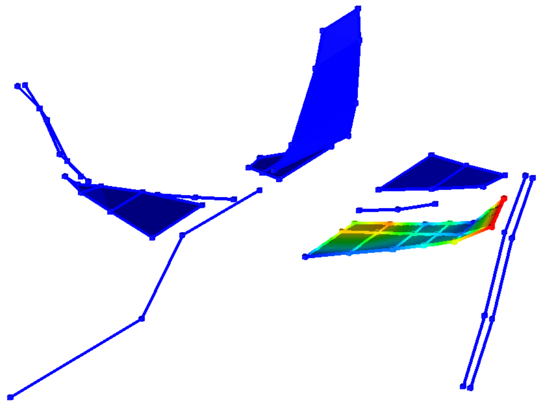
Figure 8. SFRF, FRF and coherence functions from a collocated sensor pair on the left wing

A noticeable characteristic from the piezo strain sensors is their signal-to-noise ratio. As seen from Figure 8(a), the quality of the SFRF is very good, and the signal looks less noisy than the accelerometer.

The next step is to carry out the modal identification procedure. The vibration modes were estimated using the PolyMAX polyreference least-squares complex frequency-domain method [19]. By simultaneously using the accelerometers and strain sensors on the identification procedure, it is possible visualize both displacement and strain components of the mode, where the strain can be displayed with coloring, while the displacement mode is represented by the actual displacement on the geometry. The first mode of the aircraft is a symmetric wing bending mode, followed by an anti-symmetric torsional mode of the wings, then a symmetric torsional mode and finally an anti-symmetric bending of the wings. The last two identified modes are the in-plane mode on the wings and the second symmetric bending of the wing. All these modes are shown in Figures 9 through 11.

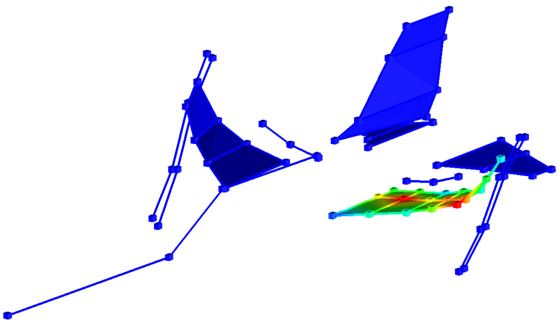


(a) F-16 first wing symmetric bending mode at 5.19 Hz

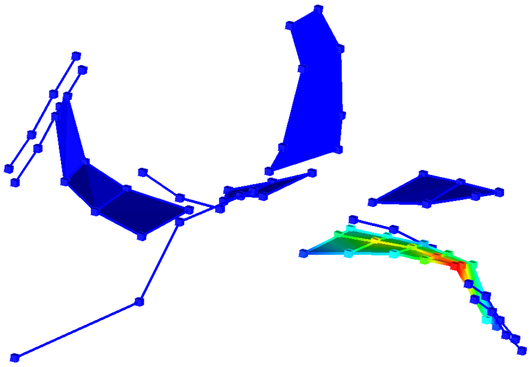


(b) F-16 first wing anti-symmetric torsion mode at 6.63 Hz

Figure 9. F-16 displacement and strain modes on left wing

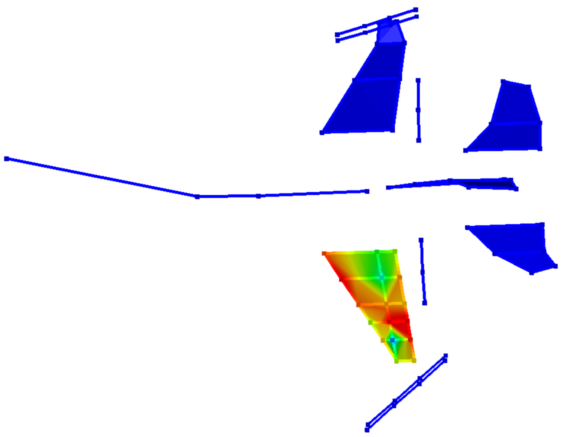


(a) F-16 first wing symmetric torsion mode at 7.29 Hz

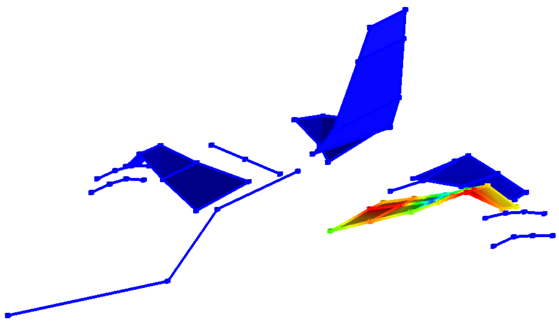


(b) F-16 first wing anti-symmetric bending mode at 9.14 Hz

Figure 10. F-16 displacement and strain modes on left wing



(a) F-16 first wing in-plane mode at 16.43 Hz



(b) F-16 second wing symmetric bending mode at 16.86 Hz

Figure 11. F-16 displacement and strain modes on left wing

The modes show that the strain pattern from the wing cannot always be directly inferred or understood from the displacement modes. In the first case (Figure 10(a)), for the wing bending, there is a high concentration of strain in the middle of the wing, possibly because of the complex internal structure of the wing. In the second case (Figure 10(b)), the strain measurements clearly help visualizing the high amount of stress incurred on the tip of the wing, where the attachment to the bomb is. For the in-plane mode of the wings (Figure 11(a)), it is clear that there is strain on the leading and trailing edges of the wing, meaning that the strain sensors are effective in capturing strain not only in the bending direction.

## 5 CONCLUSIONS

In this paper, the use of dynamic strain sensors for the ground vibration testing (GVT) of an F-16 aircraft was shown. Initially, the theory for strain modal analysis was presented, putting into evidence the differences and similarities between the accelerometer based and strain gauge based modal analysis. Then, the characteristics of the dynamic strain sensors were presented, also providing information on its sensitivity and how it is calibrated.

The set-up for the GVT was introduced, along with the measurement locations for the accelerometers and strain sensors used, as well as the shaker attachment locations. The initial strain FRFs showed very good quality with respect to the signal-to-noise ratio, and the modal identification was carried out using those measurements. As a result, mixed strain and displacement mode shapes were shown, where it is possible to see the strain pattern on the left wing of the aircraft with respect to its motion.

With the results, it is possible to conclude that the strain measurements can be used in a GVT campaign, and that the additional information provided by them is useful for further interpretation of the mode shapes, especially with a complex structure.

## ACKNOWLEDGEMENTS

This research was carried out in the framework of the projects “IMESCON” (FP7-PEOPLE-2010-ITN GA Nr. 264672) and “WiBRATE” (FP7-ICT-2011-7, GA 289041). Fábio Luis Marques dos Santos, first author of this paper, was hosted by LMS International (now Siemens Industry Software NV) as an Early Stage Researcher in the “IMESCON” project. The authors of this work gratefully acknowledge the European Commission for the support.

## REFERENCES

[1] R.J. Dieckelman, A.J. Hauenstein, and R.P. Ritzel. The ground vibration test - a boeing ids perspective. In *Proceedings of IMAC-XXIII International Modal Analysis Conference*, 2005.

[2] Dennis Gge, Marc Bswald, Ulrich Fllekrug, and Pascal Lubrina. Ground vibration testing of large aircraft  state-of-the-art and future perspectives. 2007.

[3] C.R. Pickrel, G.C. Foss, A.W. Phillips, R.J. Allemang, and D.L. Brown. New concepts gvt. In *IMAC XXIV International Modal Analysis Conference*, 2006.

[4] O. Bernasconi and D. J. Ewins. Application of strain modal testing to real structures. In *Proceedings of the 7th International Modal Analysis Conference*, volume 2, pages 1453–1464, 1989.

[5] L. M. Vári and P. S. Heyns. Using strain modal testing. In *Proceedings of the 12th International Conference on Modal Analysis*, volume 2251, page 1264, 1994.

[6] M. Luczak, A. Vecchio, B. Peeters, L. Gielen, and H. Van der Auweraer. Uncertain parameter numerical model updating according to variable modal test data in application of large composite fuselage panel. *Shock and Vibration*, 17(4-5):445–459, 2010.

[7] T. Kranjc, J. Slavič, and M. Boltežar. The mass normalization of the displacement and strain mode shapes in a strain experimental modal analysis using the mass-change strategy. *Journal of Sound and Vibration*, 332(26):6968–6981, 2013.

[8] A. C. Pisoni, C. Santolini, D. E Hauf, and S. Dubowsky. Displacements in a vibrating body by strain gage measurements. In *Proceedings of the 13th International Conference on Modal Analysis*, 1995.

[9] Calabro A.M. and Salzano C. Take the strain: short paper on light flight - new technologies for dynamic strain measurement sensors. *Aerospace Testing International*, pages 128–129, October 2007.

[10] Simone Manzato, Fabio Santos, Bart Peeters, Bruce LeBlanc, and Jonathan R White. Combined accelerometers-strain gauges operational modal analysis and application to wind turbine data.

[11] Matthew Whelan and Kerop Janoyan. Design of a robust, high-rate wireless sensor network for static and dynamic structural monitoring. *Journal of Intelligent Material Systems and Structures*, 2008.

[12] H Xia, Guido De Roeck, N Zhang, and Johan Maeck. Experimental analysis of a high-speed railway bridge under thalys trains. *Journal of Sound and Vibration*, 268(1):103–113, 2003.

[13] Fábio Luis Marques dos Santos, Bart Peeters, Raphaël Van der Vorst, Wim Desmet, Luiz Carlos, and Sandoval Góes. The use of strain and mixed strain/acceleration measurements for modal analysis.

[14] H Lie and KE Kaasen. Modal analysis of measurements from a large-scale viv model test of a riser in linearly sheared flow. *Journal of fluids and structures*, 22(4):557–575, 2006.

[15] AD Trim, H Braaten, H Lie, and MA Tognarelli. Experimental investigation of vortex-induced vibration of long marine risers. *Journal of fluids and structures*, 21(3):335–361, 2005.

[16] Jeffrey J. Dosch. Piezoelectric strain sensor. In *Proceedings of IMAC XVII International Modal Analysis Conference*, 1999.

[17] Jenny Lau, Bart Peeters, Jan Debille, Quentin Guzek, Willam Flynn, Donald S Lange, and Timo Kahlmann. Ground vibration testing master class: modern testing and analysis concepts applied to an f-16 aircraft. In *Advanced Aerospace Applications, Volume 1*, pages 221–228. Springer, 2011.

[18] Bart Peeters, Alex Carrella, Jenny Lau, Mauro Gatto, and Giuliano Coppotelli. Advanced shaker excitation signals for aerospace testing. In *Advanced Aerospace Applications, Volume 1*, pages 229–241. Springer, 2011.

[19] B. Peeters, H. Van der Auweraer, P. Guillaume, and J. Leuridan. The polymax frequency-domain method: a new standard for modal parameter estimation? *Shock and Vibration*, 11:395–409, 2004.

## 6 COPYRIGHT STATEMENT

## What are divisions of PCB Piezotronics?

PCB Piezotronics, a member of the PCB Group families of companies, has five major divisions, all of which offer targeted sensor technologies. These divisions are supported by an active outside direct sales force of Field Application Engineers, as well as international direct sales offices throughout the world. Individual PCB Piezotronics divisions, locations and their primary product specialties include:

PCB PIEZOTRONICS INC.

**Depew, NY, USA** - www.pcb.com – Piezoelectric, ICP®, piezoresistive & capacitive pressure, acoustic, force, torque, load, strain, shock & vibration sensors.

AEROSPACE & DEFENSE
A PCB PIEZOTRONICS DIV.

**Depew, NY, USA** - www.pcb.com/aerospace – Sensors & Instrumentation for aerospace & defense applications, including air and spacecraft testing.

AUTOMOTIVE SENSORS
A PCB PIEZOTRONICS DIV.

**Novi, MI, USA** - www.pcb.com/auto – Sensors & Instrumentation for automotive testing, including modal analysis; NVH; component durability; powertrain testing; vehicle dynamics; safety and regulatory testing.

IMI SENSORS
A PCB PIEZOTRONICS DIV.

**Depew, NY, USA** - www.imi-sensors.com – Industrial vibration sensors, bearing fault detectors, mechanical vibration switches, panel meters, cables & accessories for predictive maintenance and equipment protection.

LARSON DAVIS
A PCB PIEZOTRONICS DIV.

**Depew, NY & Provo, UT, USA** www.larsondavis.com – Precision microphones, sound level meters, noise dosimeters, audiometric calibration systems.

PCB PIEZOTRONICS INC.
MEMS ADVANCED DESIGN CENTER

**San Clemente, CA, USA** - www.pcb.com – Research & development engineering center for special technologies.

**Seattle, WA, USA** - www.pcb.com – Process development and fabrication of MEMS sensors.

PCB LOAD & TORQUE
A PCB PIEZOTRONICS DIV.

**Farmington Hills, MI, USA** - www.pcb.com/LoadAndTorque – Designs and manufactures high quality, precision load cells, wheel force transducers, torque transducers, telemetry systems, and fastener torque-tension test systems.

**PCB® Group Companies:**

TMS DYNAMIC METROLOGY
A PCB GROUP COMPANY

**Cincinnati, OH, USA** - www.modalshop.com – Global leader in dynamic calibration offering a complete line of automated calibration systems and recalibration services to support dynamic vibration, pressure and force sensors in applications such as: national standards, commercial labs, government/military research, consultancies, and industrial/plant floor operations.

sti technologies
turning experience into value

**Rochester, NY, USA** - www.sti-tech.com – Mechanical engineering consulting firm specializing infinite element analysis, advance analytical techniques, experimentation, technology development, &design optimization for turbo machinery, industrial machine systems & mechanical structures.