F-16 aircraft benchmark based on ground vibration test data

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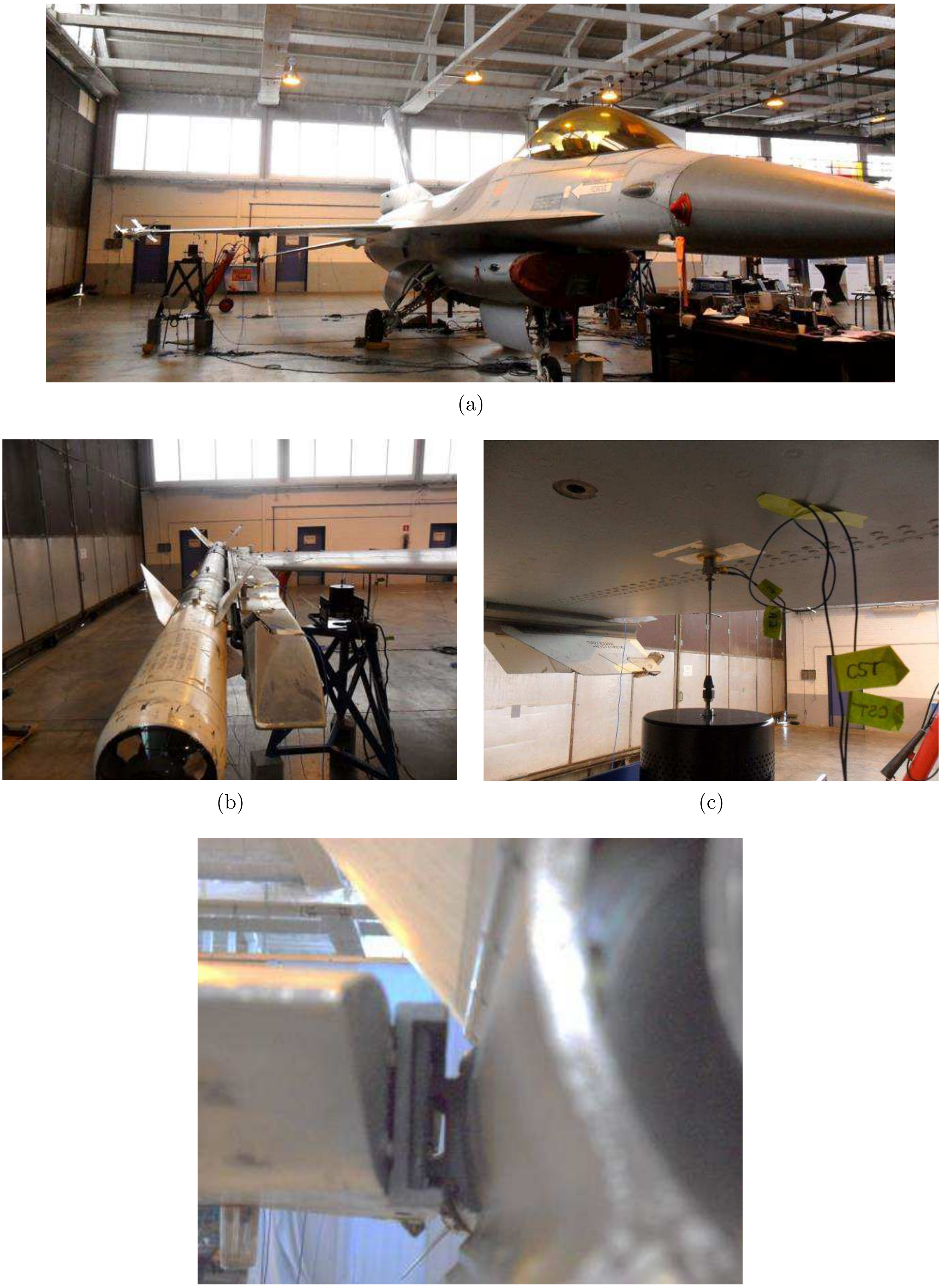
1 Introduction and F-16 instrumentation

The experimental data made available to the Workshop participants were acquired on a full-scale F-16 aircraft (see Fig. 1 (a)) on the occasion of the Siemens LMS Ground Vibration Testing Master Class, held in September 2014 at the Saffraanberg military basis, Sint-Truiden, Belgium.

During the test campaign, two dummy payloads were mounted at the wing tips to simulate the mass and inertia properties of real devices typically equipping an F-16 in flight (see Fig. 1 (b)). The aircraft structure was instrumented by means of 145 acceleration sensors. One shaker was attached underneath the right wing to apply input signals (see Fig. 1 (c)). The dominant source of nonlinearity in the structural dynamics was expected to originate from the mounting interfaces of the two payloads. These interfaces consist of T-shaped connecting elements on the payload side, slid through a rail attached to the wing side (see Fig. 1 (d)). A preliminary investigation showed that the back connection of the right-wing-to-payload interface was the predominant source of nonlinear distortions in the aircraft dynamics, and is therefore the focus of this benchmark study.

Measurements were acquired at a sampling frequency of 400 Hz. Two distinct input signals are made available: (1) the voltage measured at the output of the signal generator amplifier, acting as a reference input, and (2) the actual force provided by the shaker and measured by a impedance head at the excitation location. Three acceleration signals are



(a)

(b)

(c)

(d)

Figure 1: F-16 instrumentation. (a) Complete aircraft structure; (b) dummy payload mounted at the right wing tip; (c) shaker attached underneath the right wing; (d) back connection of the right-wing-to-payload mounting interface.

provided as output quantities. They were measured (1) at the excitation location, (2) on the right wing next to the nonlinear interface of interest, and (3) on the payload next to the same interface. Outputs are listed in this order in the matrices of data.

2 Description of the measured data sets

2.1 Sine-sweep excitation with a linear, negative rate

Sine-sweep excitations with a linear, negative rate of 0.05 Hz/s (sweep down) were applied (data files named F16Data_SineSw_Level#.mat). The covered input frequency range was $15 - 2$ Hz. Seven different levels of excitation are provided as benchmark data. The lowest level at 4.8 N input amplitude can be considered as a linear data set. Three higher excitation levels are given to function as estimation data in nonlinear regimes of vibration, namely data sets number 3, 5, 7 corresponding to 28.8, 67.0 and 95.6 N, respectively. Data sets number 2, 4 and 6 at 19.2, 57.6 and 86.0 N, respectively, are to be used for testing the models estimated using the data sets 3, 5 and 7, respectively.

2.2 Multisine excitation with a full frequency grid

Data recorded under multisine excitations with a full frequency grid from 2 to 15 Hz are provided (data files named F16Data_FullMSine_Level#.mat). At each force level, 9 periods were acquired considering a single realization of the input signal. The number of points per period is 8192. Note that transients are present in the first period of measurement. Similarly to the sine-sweep case, seven excitation levels are considered, starting from linear data at 12.4 N RMS (data set 1). In addition, three nonlinear estimation data sets (number 3, 5 and 7 at 36.8, 73.6 and 97.8 N RMS, respectively) are accompanied by their corresponding test sets (numbers 2, 4 and 6 at 24.6, 61.4 and 85.7 N RMS, respectively).

2.3 Multisine excitation with a random frequency grid

Multisines were also applied considering only odd frequencies excited. Moreover, within each group of 4 successive excited odd lines, 1 frequency line was randomly rejected to act as a detection line for odd nonlinearities (data files named F16Data_SpecialOddMSine_Level#.mat). In this setting, the frequency band from 1 to 60 Hz was excited. 3 periods per level were recorded, considering 10 input realizations per level. The number of points per period is 16384. Note that only the last 2 periods of each realization are in steady state. The data sets were originally sampled at 200 Hz. They were upsampled to 400 Hz in the frequency domain, processing period per period, and assuming the data is periodic and in steady state.

Because of the multiple realizations, the number of tested excitation levels was reduced to 3, namely 12.2, 49.0 and 97.1 N RMS. These 3 levels entail nonlinear oscillations. It is suggested to use, at each level, 9 realizations for estimation and to consider a final realization as test data.

3 Goal of the identification

Identifying a full nonlinear model of the F-16 dynamics represents a great challenge. The goal of this system identification benchmark should therefore be understood in a broader sense, and participants are encouraged to explore other paths for analysis, including:

- general nonparametric analysis of the data.
- linearized modeling.
- linear parameter-varying modeling to track the evolution of the aircraft natural frequencies and damping ratios versus the excitation level.
- nonlinear modeling around a single mode (*i.e.* a single resonance) of the structure (see Section 5 below).

4 Figure of merit

When a parametric model is estimated, we expect the participants to report the following figure of merit using an appropriate test data set to allow for a fair comparison between different methods:

$$\boldsymbol{e_{RMSt}} = \sqrt{1/N_v \sum_{t=1}^{N_t} (y_{mod}(t) - y_t(t))^2}, \tag{1}$$

where y_{mod} is the modeled output, y_t is the output provided in the test data set, N_t is the total number of points in y_t. This error measure can be evaluated considering a single or multiple outputs.

Also mention whether the modeled output y_{mod} is obtained using **simulation** (only the validation input u_t is used to obtain the modeled output $y_{mod}(t) = F(u_t(1), \ldots, u_t(t))$) or **prediction** (both the validation input u_t and the past validation output y_t are used to obtain the modeled output $y_{mod}(t) = F(u_t(1), \ldots, u_t(t), y_t(1), \ldots, y_t(t-1))$). Provide both figures of merit (simulation and prediction) if the identified model allows for it.

5 Nonlinear system identification challenges

We anticipate the F-16 benchmark to be associated with 3 major nonlinear system identification challenges:

- the order of the system is reasonably high. In the $2 - 15$ Hz band, the F-16 possesses about 10 resonance modes. The first few modes below 5 Hz correspond to rigid-body motions of the structure. The first flexible mode around 5.2 Hz corresponds to wing bending deformations. The mode involving the most substantial nonlinear distortions is the wing torsion mode located around 7.3 Hz. Participants wishing to limit the order of their model should focus on this latter mode.
- the mounting interface of interest is expected to feature nonlinearities in stiffness and damping, due to clearance and friction, respectively.
- clearance and friction may lead to hard nonlinearities, and hence may not be appropriately modeled using smooth basis functions.

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