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Dynamic characterization of MEMS-based Inertial Unit under combined vibration stresses

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***Abstract* – MEMS-based Inertial Measurement Units (IMU) are becoming essential components in automotive applications, as well as in many other fields. However, current literature misses to extensively consider dynamic characterization of such devices under the actual operating conditions typical of the field of application. In this work, a specific test plan and a customized experimental setup have been developed in order to characterize the dynamic performances of low-cost IMU enduring a combined vibration stress. More in detail, the specific test plan is composed by two simultaneous stimuli: a standard movement generated by a specific Pan-Tilt unit, and a high-frequency random noise provided by a vibration shaker in order to emulate the real conditions typical of automotive field of application. The analysis of the experimental results emphasized the necessity of corrective actions in case low-cost IMU are used in presence of harsh operating conditions in terms of vibration noise.**

Keywords* – • Diagnostic, Inertial Measurement Unit; Vibration testing; Metrological characterization; Industry, Innovation and Infrastructure.

I. INTRODUCTION

In the context of Industry 4.0 and Internet of Things (IoT), the ability of measuring and recording multiple parameters is becoming more and more essential. Data coming from multiple sensors regarding different parameters are nowadays used for several purposes in every industrial and technological field [1]-[2]. For instance, in automotive applications, multiple sensors are installed in the vehicle for several reasons, such as [3]-[4]:

- Standard driving functionalities;
- Safety instrumented systems for safety regulations;
- Optimization of driving experience;
- Self-driving and semi-self-driving;
- Obstacles and hazards recognition;
- Automatic regulation and control of vehicle's parameters;
- Diagnostic and prognostic purposes;
- Remaining Useful Life estimation and maintenance optimization of critical components and systems.

In this context, Inertial Measurement Units (IMU) play a fundamental role in different types of terrestrial vehicles in order to acquire reliable information regarding the real-time positioning of the vehicle [5]-[7].

Usually, IMU integrates multiple sensors like accelerometers, gyroscopes and magnetometers. Most of the time, three identical sensors are used to acquire information toward the three axes of orientation. After the acquisition, suitable filtering and fusion algorithms are used to convert the triaxial acceleration, triaxial angular rate and triaxial magnetic field into three separated values of positioning, in compliance with Euler angles of the object [8].

To ensure the integration of multiple inertial sensors in the same small low-cost package, Micro Electro Mechanical Systems (MEMS) represent the only valid alternative for automotive applications. As a matter of fact, MEMS-based IMU allows to ensure cost, weight, dimensions, and consumption constraints, as well as guaranteeing suitable performances [9]-[11].

However, the analysis of literature pointed out two major lacks related to the performance characterization of this kind of devices:

- Data sheets provided by manufacturers of low-cost MEMS-based IMU usually include only classical metrological characteristics (i.e., offset and sensitivity) evaluated in standard operating conditions which are not well representative of the actual final installation of the device. See for instance [12].

- Recent literature only marginally deals with the dynamic characterization of MEMS-based IMU considering the real operating conditions that the device will endure after the installation. For instance, in [13] authors discussed about a static and dynamic characterization of low-cost commercial IMU, but they performed the test considering only the standard non-stressing operating conditions. Similarly, Xia et al. [14] investigated IMU misalignment in automotive field neglecting all possible noise vibration sources typical of this application area. Similarly, also [15]-[16] (just to mention a few) miss to consider the real environmental stresses and actual disturbances that characterize installation on road vehicles.

International standards regarding testing of electric/electronic components and IoT devices for automotive applications agree that such items must endure high-frequency vibration stress sources, depending on the type of installation. This high-frequency noise could remarkably affect the performances of low-cost MEMS-based IMU despite most of the times such devices are designed to acquire only ultra-low-frequency movements.

In some previous works we investigated the response of low-cost IMU subjected to the actual operating conditions typical of the automotive installation like motorcycles, cars, trucks, etc. (see for instance [17]-[18]).

However, all previous tests considering the real environmental stresses typical of automotive field have been performed only in static condition. This means that the previous characterizations have been carried out considering a fixed position of the Device Under Test (DUT) and applying the stress related to the application area. In the previous works some important metrics have thus been proposed to study the transfer function, the signal-to-noise ratio, the performances of the internal anti-aliasing low-pass filter, the cross-axis sensitivity and the spurious phenomena of the IMU.

In order to further proceed and improve the previous characterization, this work illustrates a customized test plan and a specific experimental platform to dynamically characterize the performances of low-cost IMU considering two simultaneous input sources to the device: a low-frequency movement that emulates the actual movement of the object that must be monitored, and a high-frequency vibration noise that emulates the real operating conditions in automotive field.

The rest of the paper is organized as follow: section II briefly illustrates the device under test, section III shows the proposed test plan for dynamic characterization, section IV explains the proposed experimental setup and finally section V presents some preliminary results.

II. DEVICE UNDER TEST

In this work, the performances of a MEMS-based 9-Dof (Degrees of freedom) Inertial Measurement Unit have been investigated.

In particular, the device under test is a low-cost platform that integrates a triaxial accelerometer, a triaxial gyroscope and a triaxial magnetometer. For this reason, the device is commonly used to acquire data for the most common filtering and positioning algorithms used to estimate the Euler angle of an item and thus it's actual position.

Furthermore, the device also includes an additional temperature transducer that can be used for temperature compensation when the IMU is used under harsh thermal conditions (see for instance [19]-[20]).

A summary of the major metrological characteristics of the implemented platform is reported in Table 1. It is extremely important to notice that the sensor automatically introduce an anti-aliasing low-pass filter with cut-off frequency of 50 Hz. This is due to the fact that the output data rate is just above 100 Hz.

Table I. Major characteristics of the MEMS-based IMU under test.

	Accelerometer	Gyroscope	Magnetometer	Temperature transducer
Axes	3	3	3	1
Max Full scale	±16g	±2000 dps	±16gauss	+85 °C
Sensitivity	0.732 mg/LSB	70 mdps/LSB	0.58 mgauss/LSB	16 LSB/°C
Output Data Rate	119 Hz			
Anti-Aliasing filter	50 Hz			
Output data	16 bit			

As a consequence, such device can be used to acquire and measure only low-frequency movements, while high-frequency vibrations should be automatically rejected.

III. PROPOSED TEST PLAN

Since the device under test automatically introduce a 50 Hz low-pass filter, it becomes of fundamental importance to study the performances of the IMU when it is subjected to high-frequency random noise, which is typical of several fields of application. As a matter of fact, when the MEMS-based IMU is used in a real case scenario, there could be the presence of non-negligible vibration noise outside the band of the filter.

For instance, according to several international testing standards and procedures, a critical environment by vibration point-of-view is represented by the automotive field. More specifically, electronic and sensing devices used in terrestrial vehicles (such as cars, trucks and motorbikes) must endure random vibration noise from few hundreds of Hz up to approximately 1 kHz. Such random vibration noise could be caused by several sources, such:

- Opening/closing of valves;
- Frictions between gears;
- Proper functioning of the thermal motor;
- Intake air;
- Uneven and rough road;
- Wind gusts.

The exact amount and the precise frequency range of such vibration noise depends on the type and place of installation of the sensor, as well as the type of vehicle and the actual vibration source which is predominant in the analyzed moment. However, several international standards (see for instance [21], [22], [23]) summarize such behavior majorly in the frequency range between 200 Hz and 1 kHz.

For this reason, in this work, a random vibration noise has been applied to the IMU under test in the same frequency range, with a constant Acceleration Spectral Density (ASD) equal to:

$$ASD = 0.01\, g^2/Hz = 1\, m^2/s^3 \quad (1)$$

Along with such random vibration noise, a second stimulus has been applied to the IMU. More specifically, a low-frequency movement (completely within the bandwidth of the IMU) has been considered. A controlled and repeatable low-frequency movement that involves two axes of rotation (i.e., TILT movement and PAN movement) with different aperture angles has been considered as second source of excitation.

Furthermore, three different sets of speed/acceleration have been considered to investigate the effects of the random noise on different movements. More in detail, the considered speed sets are the following:

- V0 which represent the standard speed and standard acceleration;
- V1 which has the same acceleration of V0 while the speed has been doubled;
- V2 which has double speed and double acceleration with respect to the standard V0 condition.

Moreover, for the sake of measurement repeatability, 30 consecutive movement repetitions have been acquired to make the test plan more consistent. Between two consecutive repetitions, a static neutral position should be maintained for 5 s.

The two above-mentioned excitation (i.e., low frequency repeatable movement and high-frequency random noise) are applied simultaneously by a dedicated experimental setup described in the next section.

The entire test has also been repeated three considering three different axes of application of the vibration noise (X, Y, and Z).

A summary of the presented test plan is reported in Table II, including both high-frequency and low-frequency sources of excitation. The acquired data have also been compared with a reference condition in which no noise has been applied to the DUT.

Table II. Summary of the proposed test plan involving two simultaneous excitations for the IMU under test.

SIMULTANEOUS EXCITATIONS			
HIGH-FREQUENCY SOURCE		**LOW-FREQUENCY SOURCE**	
Type	Random vibration	**Type**	Controlled movement
Axes of application	3 axes performed in sequence	**Axes of rotation**	2 simultaneous (PAN and TILT)
Frequency Range	200 Hz ÷ 1 kHz	**Aperture range**	180° on PAN rotation 70° on TILT rotation
Magnitude	0.01 g^2/Hz	**Speed**	3 different speed sets
Time duration	Entire test	**Number of repetitions**	30
Meaning	Emulates real automotive noise	**Meaning**	Emulates actual movement of the vehicle

IV. EXPERIMENTAL SETUP

This section briefly illustrates the experimental setup that has been used to characterize the dynamic performances of the MEMS-based IMU under test considering the proposed test plan illustrated in the previous section. In order to perform two stimuli simultaneously (high-frequency vibration and low-frequency controlled movement) and to acquire the data coming from the MEMS sensors, the following equipment has been used in this work:

- An electrodynamic vibration shaker with a suitable power amplifier, a dedicated controller and an accelerometer-based control feedback loop has been used to generate the high-frequency random noise that emulates the actual operating conditions typical of automotive field of application. A customized fixture has been used in order to safely and stiffly fastened the devices on top of the shaker.
- A PAN-TILT Unit (PTU) has been used to generate the low-frequency repeatable and controllable movement that emulates the actual vehicle movements. The PTU has been programmed via serial interface in order to allow the repetition of 30 identical movement with specified aperture angle and speed set.
- A data acquisition unit and a laptop have been used to initialize the IMU, as well as to acquire and store the measured data.

A picture of the entire experimental setup in case of vibration noise applied toward Z axis is illustrated in Fig. 1. To apply vibration toward X or Y axis, the shaker must be rotated to apply a horizontal excitation.

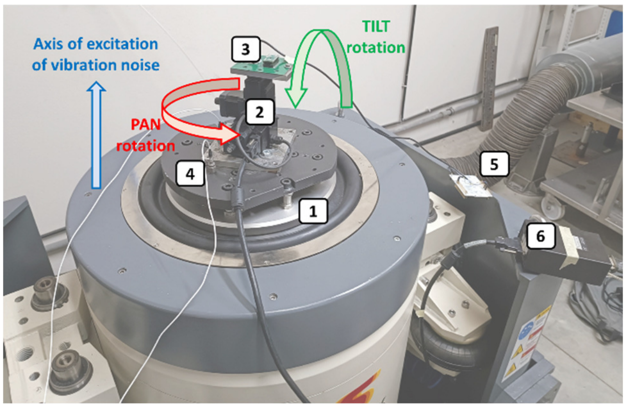

Fig. 1. Picture of the entire experimental setup for dynamic characterization of IMU: 1) shaker, 2) PTU; 3) MEMS-based IMU under test; 4) control accelerometer; 5) acquisition board; 6) PTU controller.

V. RESULTS AND DISCUSSION

In this section, the response of the accelerometer and gyroscope embedded in the IMU under test has been analyzed, comparing two scenarios:

- Application of the random vibration noise that emulates the real conditions typical of automotive field along with the low-frequency movement.
- Acquisition of the low-frequency movement in standard reference conditions, without application of any external vibration noise.

A first qualitative analysis is reported in Fig. 2, where the X-output of the Accelerometer (top subplots) and the X-output of the Gyroscope (bottom subplots) are illustrated comparing the two above-mentioned scenarios.

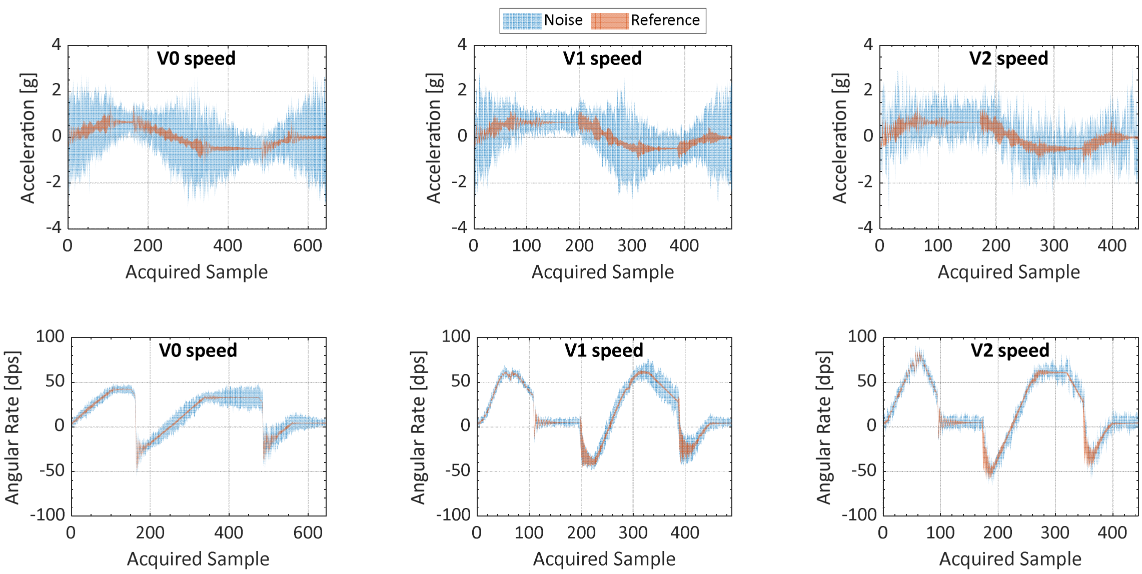

Fig. 2. Comparison between signal acquired in presence of noise (blue area) and without noise (red area). Top subplots refer to accelerometer with different speed sets, bottom subplots refer to gyroscope with different speed sets.

More in detail, Fig. 2 emphasizes the impact that the noise application has on the measured data as a function of the different speed sets. Every signal is illustrated as a bandwidth area centered on the mean value of the 30 acquisitions, with size given by the standard deviation of the same acquisitions. First of all, the figure points out a clear impact that the actual operating conditions typical of the automotive field could have on the performances of the IMU under test. As a matter of fact, the blue area representing the signal in presence of the actual automotive noise is significantly wider than the reference condition (red area), meaning that a non-negligible data dispersion occurs in presence of high-frequency noise.

Furthermore, what stands out from the figure is that the applied noise, which should be rejected by the internal anti-aliasing filter, has a higher impact on the performances of the accelerometer respect to the gyroscope. Instead, the specific speed set seems to have no correlation with the data dispersion.

However, it is also important to note that Fig. 2 represent the worst-case condition. In fact, only the X-output of the sensors have been illustrated, whit high-frequency noise applied toward X direction.

To further investigate this point, Fig. 3 illustrates as filled area the data acquired by the X-output of the accelerometer (top subplots) and the X-output of the gyroscope (bottom subplots) when the noise is applied toward different directions, fixing the V2 speed set.

As a confirmation of then previous analysis, the maximum dispersion of the acquired data in presence of high-frequency noise (grey areas) has been obtained when the noise is in compliance with the output of the sensor (i.e., applied toward X axis).

However, the most striking results to emerge from the figure is that a certain data dispersion is present also in case of noise applied toward Y and Z axes. This is caused by the presence of a cross-axis sensitivity of the IMU's sensors, which is not well described by the manufacturer. However, it is essential to characterize this phenomenon in order to ensure trustworthy results.

V. CONCLUSIONS

This work presents the results of a dynamic characterization carried out on a MEMS-based IMU composed by a triaxial accelerometer and a triaxial gyroscope. A customized test plan and experimental setup have been developed in order to investigate the performances of the IMU considering the actual operating conditions typical of automotive field of application. More in detail, a high-frequency vibration random noise has been superimposed to a low-frequency movement. The former emulates all the actual sources of vibration present in a real car or motorcycle, while the latter stands for the actual movement of the vehicle.

Different test repetitions have been performed in order to study the effects that the axis of application of the noise or the speed of the movement could have on the measured signal. The preliminary time-domain analysis pointed out a significant data dispersion when the high-frequency noise is applied with respect to the reference conditions.

Future development will regard the investigation of the causes of this dispersion, as well as the quantitative analysis required to implement the necessary corrective action to make the device usable in a real scenario.

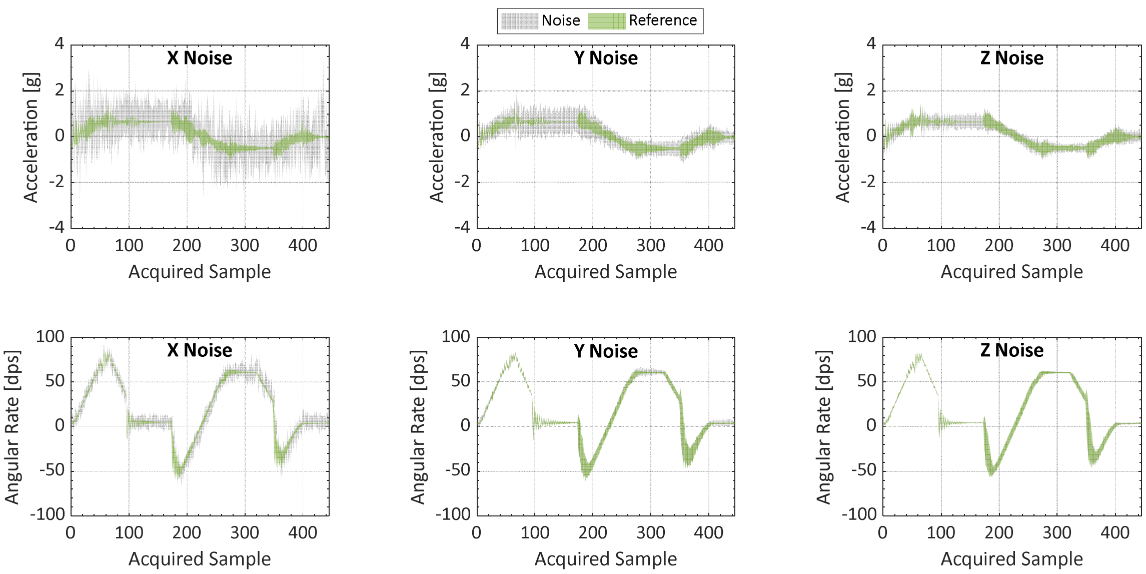

Fig. 3. Comparison between signal acquired in presence of noise (grey area) and without noise (green area), considering noise applied toward different directions.

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