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COMPUTATIONAL ANALYSIS OF WEAPON SHOOTING ACCURACY UNDER VIBRATIONS

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Abstract. In several situations involving defense or public safety actions, shooters must operate weapons while boarded in moving vehicles, subject to mechanical vibrations. This is the case, for example, of operations carried out from helicopters. Under these conditions, shooting accuracy tends to be compromised by vibrations transmitted from the vehicle to the armament, through the shooter's body and/or support devices. To minimize this transmission of vibrations, specialized troops use elastic ropes to support the weapons when shooting. In this context, the present study deals with the effectiveness and performance of these elastic ropes to prevent aircraft vibration from compromising the dispersion of shots fired from a light weapon, of the rifle type. The procedure involves two main stages, namely: a) the dynamic modeling of the mechanical system comprising part of the helicopter fuselage, the shooter's body, the rifle and the rope used as supported to this later. This model allows obtaining the three-dimensional vibration history of the gun barrel end, in terms of its orientation, position and velocity; b) the modeling of the exterior ballistics, which allows the determination of the trajectory of the projectile, based on the initial conditions obtained in step a). The study begins with the description of the modeling procedures, followed by the definition of a case study typically found in situations of practical interest. Next, results of numerical simulations are presented, in which the influence of several parameters, such as frequency and amplitude of vibrations, and the flexibility of the weapon supports, on the shooting accuracy is evaluated. The study carried out provides means for evaluating the shooting accuracy and make it possible to devise strategies for improvement of such accuracy.

Keywords: Helicopter vibration, shooting accuracy, external ballistics.

1. INTRODUCTION

The use of helicopters in military operations allows the transport of troops and logistical support in an agile way due to the vertical landing and takeoff capability. This mobility favors combat power in the conflict environments. Especially in Guarantee of Law and Order (GLO) operations, the use of helicopters acquires additional relevance, in view of reconnaissance, intelligence and air support missions (CARVALHO, 2019).

The reconnaissance and intelligence missions are carried out using high-resolution cameras connected to stabilization systems, which allows to obtain images with great clarity. Typically, these images are transmitted to an integrated command and control center, and serve as support for decisions of the operation command.

Lastly, air support missions in GLO operations are intended to provide air support to surface troops. In this case, an aircraft, located at a distance of 500 to 600 meters, manages to provide good visibility of the operation scenario and remains safe against enemy actions (BRASIL, 1998).

It is noteworthy that, in this scenario, the aircraft needs to be far enough from the point of action on the objective for the organic safety of the crew, but it also needs to ensure precision in fire support. For this situation, the use of elite snipers on board helicopters (Fig. 1) is a viable solution, as these snipers can neutralize compensating targets in an objective and rational way, without compromising the safety of people outside the conflict.

An elite shooter needs a stable and ergonomic position to perform an assertive shot. A stable position can be achieved with a hovering helicopter, but the intrinsic aircraft vibration needs to be reduced as, in general, an aircraft in hovering develops high levels of vibration. To improve stability of the armament and minimize the vibration caused by the aircraft, specialized troops use elastic cables (means of fortune) to support the armament, seeking a supported firing position. The elastic ropes or alternative support devices can be designed to improve ergonomics and the stability of the armament and minimize the transmission of vibrations from the aircraft to the armament.

In this context, it is necessary to investigate how the vibrations of an aircraft can compromise the firing accuracy of a light rifle shot. Such an investigation is reported in the present work. The AS365K2 helicopter model is used as the study aircraft, which is the model adopted by the Brazilian Army for this type of operation. This aircraft has two 1000 HP engines, a 4-blade main rotor and a 10-blade fenestron tail rotor. In addition, the Barrett M107 precision rifle with a caliber of 12.7 mm or 0.50 inches was chosen as the study weapon.

(a)   (b)

Figure 1. Snipers into helicopter training precision shooter.

(Source: (a) U.S. Army Video by Spc. Froylan Grimaldo, 7th Mobile Public Affairs Detachment; (b) 2 B Av Ex)

2. VIBRATIONS OF HELICOPTERS

Rotary wing aircraft typically have harmonic and random vibrations. Harmonic vibrations are characterized by components in a wide frequency band. This is due to the fact that a helicopter has several rotating components, such as shafts, bearings and gears, which operate at different rotations (VISWAMURTHY *et al.*, 2016).

Figure 2 illustrates the main rotating components of a generic helicopter. The AS365 K2 model has two Arriel 2C2 GC engines, each with 1000HP of power. These engines operate at a nominal speed of 52,000 RPM on the compressor shaft, but the speed on the main rotor is reduced to 365 RPM.   In this reduction, the power package elevates the torque to drive the main rotor blades. This reduction is carried out by gears of different numbers of teeth.
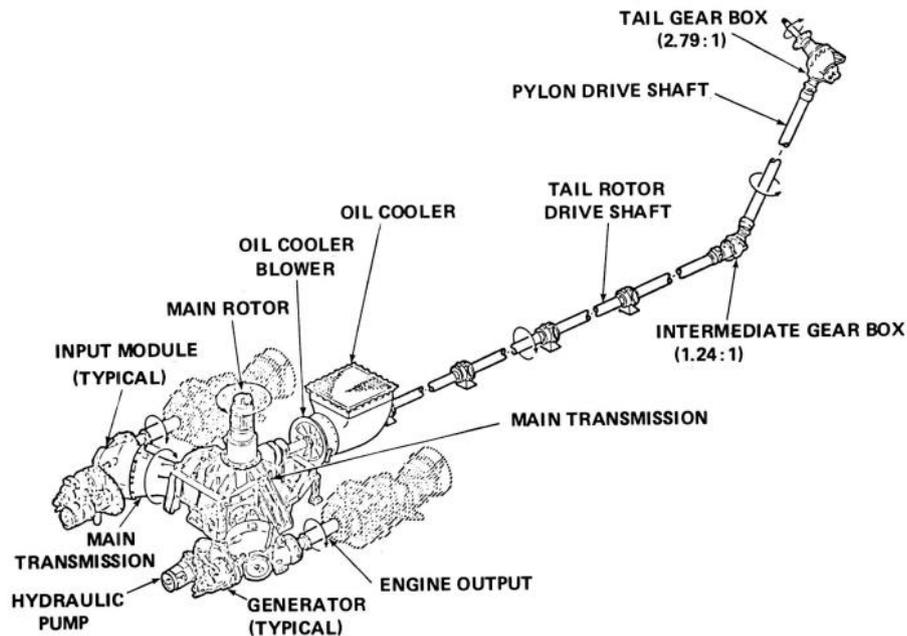

Figure 2. Black Hawk drive train schematic (MANCINI, 1983).

On the other hand, random vibrations come from the contact of the air flow with the blades and fuselage of the aircraft, as illustrated in Fig. 3.
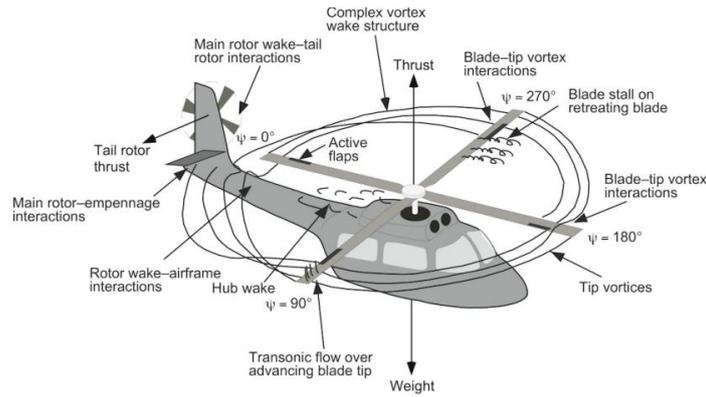
Figure 3.Aerodynamic effects on a helicopter rotor (KARATSIVOULIS, 2020)

3. VIBRATION TESTS IN A HELICOPTER

As a preliminary stage of the present study, vibration data were collected during a flight of an AS365K2 aircraft, using four accelerometers, two of which were fixed to the floor, and two others on the door column (in the longitudinal and lateral directions), as shown in Fig.4. Fig. 5 and Fig. 6 illustrate the acquired signals, in the time and frequency domains, respectively. The acquisition sampling frequency was 1600 Hz.

(a)   (b)   (c)
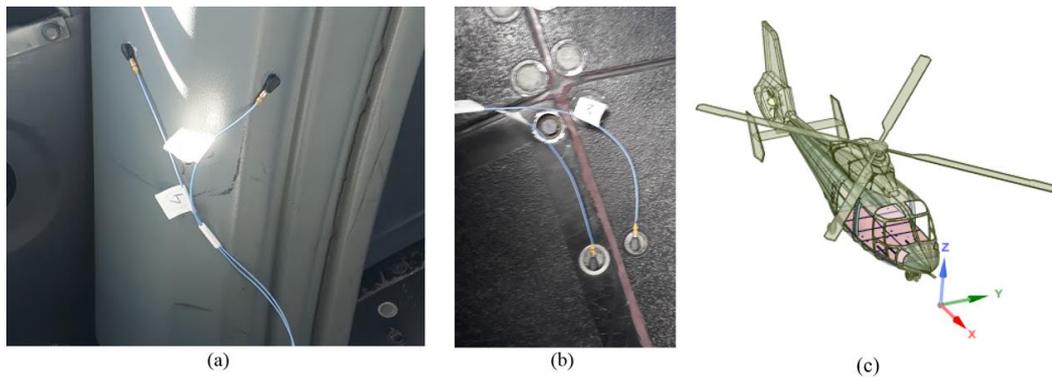
Figure 4. Points of the helicopter where the acceleration was measured.
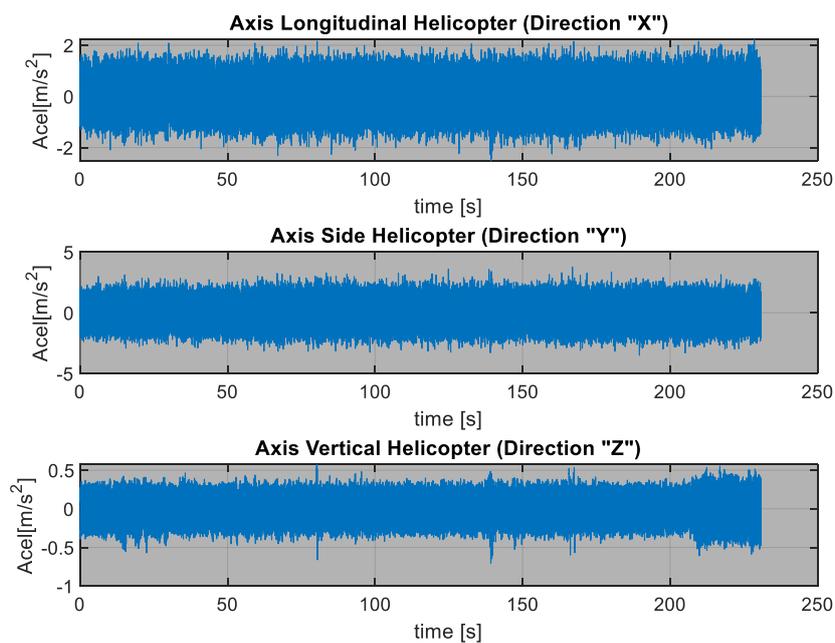
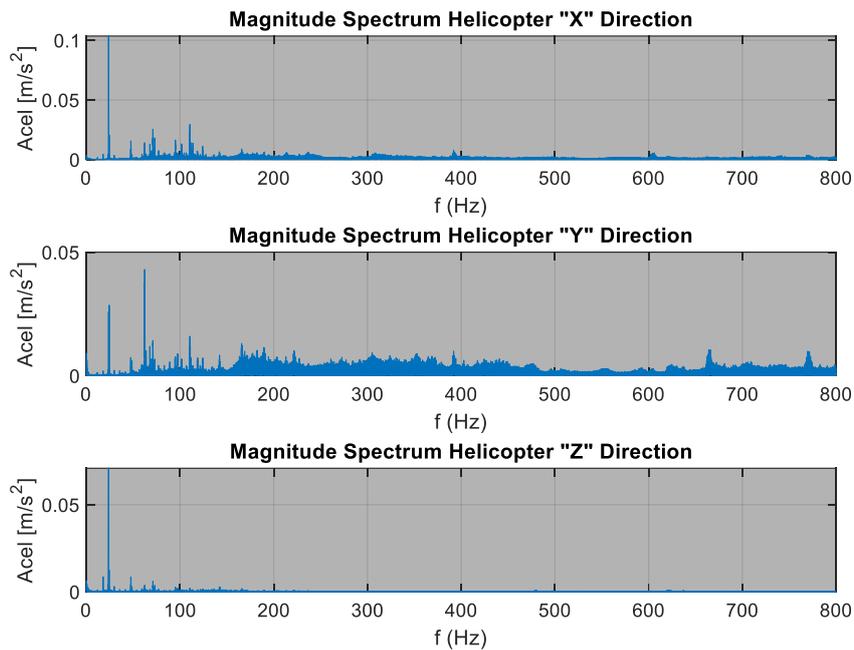Figure 5.Vibration signals in the time domain.

Figure 6.Vibration signals in the frequency domain.

4. FLIGHT TEST ON A PRECISION RIFLE

The next stage of the present study was the collection of vibration data during a hovering flight of an AS365 K2 model aircraft, using four accelerometers of two of which were fixed to the muzzle of the rifle barrel (in the longitudinal direction and in the lateral direction) and two on the butt resting on the shooter's shoulder (in the longitudinal direction and lateral direction), as shown in Figs. 7. Figures 8 and 9 illustrate the acquired signals, in the time and frequency domains, respectively.

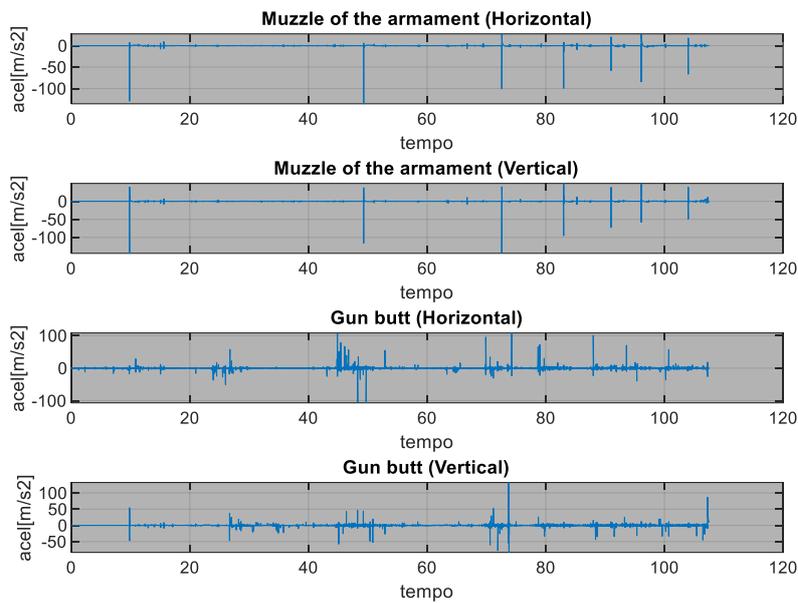Figure 7. Points of the weapon where the acceleration was measured.

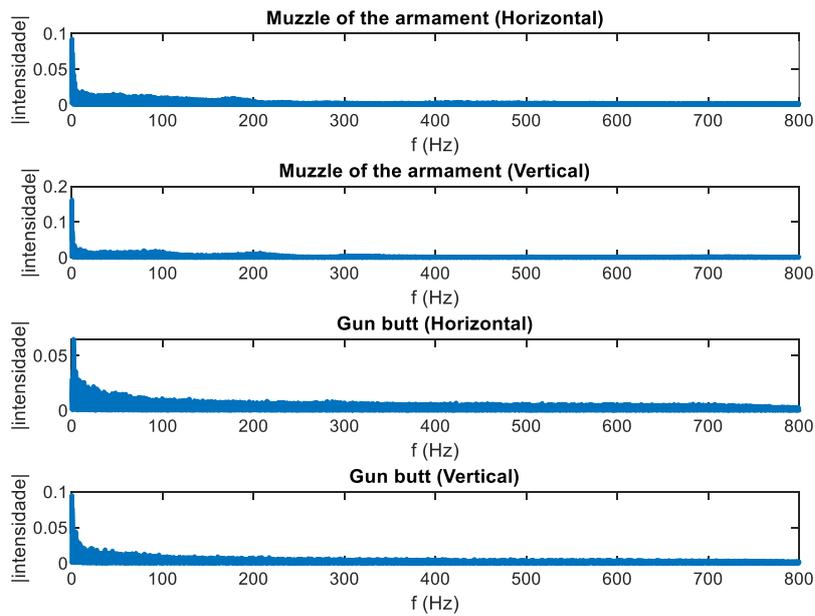Figure 8. Vibration signals in the time domain of weapon.

Figure 9. Vibration signals in the frequency domain of weapon.

The qualitative observation of the results of Figs. 8 and 9 shows that the harmonic components that are present in the structure of the aircraft are not significantly transmitted to the rifle. That said, it shows that both the elastic rope and the shooter's body (shooter) filter or attenuate the harmonic frequencies coming from the aircraft structure. This observation motivated the development of a numerical model to better understand the dynamic effects involved.

5. DEVELOPMENT OF A FINITE ELEMENT MODEL

A finite element model was built, using ANSYS® software, including the armament, the shooter's body, the aircraft floor and a base plate, and columns to which the ropes are attached (Fig. 10). For the simulations, 19 harmonic displacements were prescribed as excitations transmitted through the aircraft structure. The elastic rope was modeled by springs, to which stiffness and damping coefficients are assigned. The elastic rope was modeled using spring and viscous

damping elements with values k = 50000 N/m, c = 10.N.m. These values were chosen because they are compatible with a rope for rappelling, which is commonly used by specialized troops.

The simulation was carried out in transient regime, with the objective of obtaining the motion of the rifle barrel under the influence of the vibrations, in terms of position, velocity and space orientation.

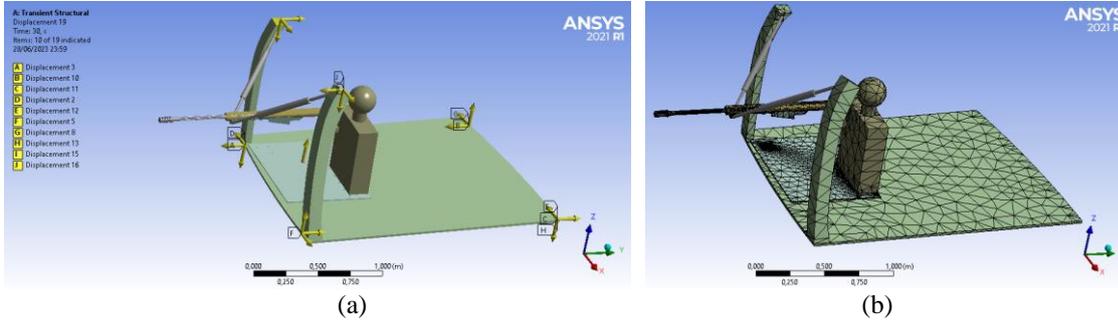| (a) | (b) |

Figure 10. Illustrations of the finite element model.

The model for the shooter's body was adapted from the model proposed by Wei and Griffin (1998). Nine springs were introduced in the model to account for the contact of the human body with the support plate (Fig.11(a)). Furthermore, the interaction of the weapon stock with the shooter's shoulder was modeled with 15 springs (3 in the vertical direction, 6 in the longitudinal direction and 6 in the lateral direction), as shown in Fig. 11 (b)).
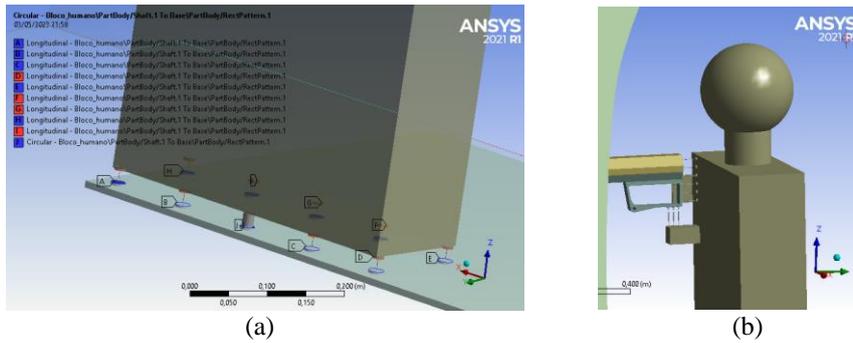

| (a) | (b) |

Figure 11. Details of the springs use to represent contact between the components of the model.

The simulations were performed with different harmonic excitation frequencies. Each frequency was simulated in the transient regime for 30 seconds and a step of 0.1 second, totaling 300 time points. Out of these 300 points, 30 points were randomly selected to be used in the ballistic simulation, which is described next.

6. EXTERNAL BALLISTIC MODEL

The ballistic model used in this work is restricted to external ballistics, considering a model in which the projectile is a material point, disregarding the Magnus Effect and the Coriolis force. This model is detailed by Klimi (2016). This model has the following formulation:

$$\frac{dV_x}{dt} = -J^{-1}.c.h(y).G_D(v).\frac{v_x}{v} \quad , \tag{1}$$

$$\frac{dp}{dt} = -\frac{g}{v_x}, \tag{2}$$

$$\frac{dx}{dt} = v_x, \tag{3}$$

$$\frac{dy}{dt} = v_y, \tag{4}$$

$$p = tan(\alpha) = \frac{dy}{dx}, \tag{5}$$

$$c = \frac{i.d^2}{m}, \tag{6}$$

$$G_D = 3.927.10^{-4}\rho\, v^2\, C_d\left(\frac{v}{\alpha_{0N}}\right), \tag{7}$$

$$h(y) = \left(\frac{\tau_0 - 0,006328y}{\tau_0}\right)^{44},$$

(8)

$$J^{-1} = \left(\frac{P_0}{P_{0N}} \sqrt{\frac{\tau_{0N}}{\tau_0}}\right),$$

(9)

where:
- $g = 9,80665 \ m/s^2$;
- $\rho = 1,225 \ kg/m^3$;
- i is the shape coefficient;
- c is the ballistic coefficient (BC);
- d e m are the diameter and mass of projectile;
- y is height of the shot;
- α is the launch angle;
- τ_{0N}, P_{0N} are respectively the temperature and pressure of air in standard atmosphere.
- τ_0, P_0 are the temperature and the pressure at the shooting site.

The lateral projection is modeled considering the particularity of the tense shot. Therefore, there is the lateral deviation of the impact of the shot on the target is given as:

$$Offset_{Lateral} = distance_{Target} . tan(angle_{Lateral})$$

(10)

As $angle_{Lateral}$ is small the following approximation can be made:

$$Offset_{Lateral} = distance_{Target} . angle_{Lateral}$$

(11)

The intrinsic dispersion (PERKINS,1988) of ammunition and weapon, which is a random error, is included in the model, based on information provided by the manufacturer (Tab. 1)

Table 1. Characteristics of intrinsic dispertion

Item	Accuracy (minute of angle)	Deviation at 1000 m (m)
Ammunition (CBC)	1	0.15
Rifle (Barrett M107)	1.5 to 2	0.22 to 0.30

7. SIMULATION RESULTS

The finite element model simulations provided the position and orientation of the armament barrel. These data were introduced in the external ballistic model implemented in a Matlab® code, which provided the predicted impact position of the projectile in a target at 1000m. The simulation was done with the following values of the excitation frequencies: 6, 15 Hz, 24 Hz, 37 Hz, 45 Hz, 55 Hz, 65 Hz, 75 Hz and 85 Hz. The results are presented in Figs. 12 to 20.

The statistics of the results, in terms of mean distance from the target center, as respective standard deviations, are given in Tab. 2. It can be seen that, for all the excitation frequencies considered, the positions of the impact points are uniformly distributed around the target center, having little dispersion. This indicates that the elastic rope is capable of providing attenuation of the influence of vibrations on the shooting accuracy.

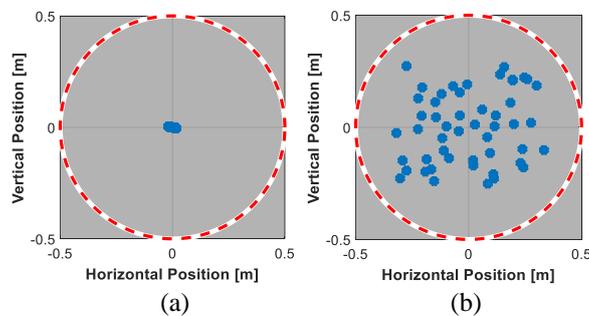(a)   (b)

Figure 12 - Simulation results for harmonic excitation with a frequency of 6 Hz. (a) projectile impact points considering only the dispersion resulting from harmonic vibration; (b) projectile impact points considering the intrinsic dispersion of the weapon and ammunition.
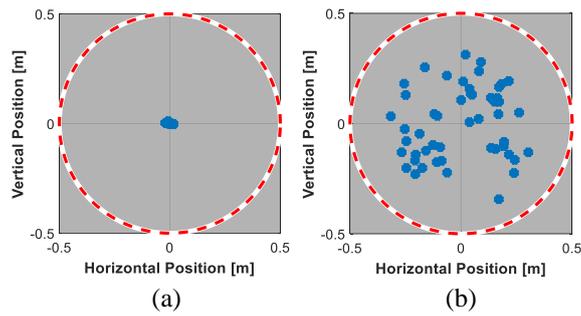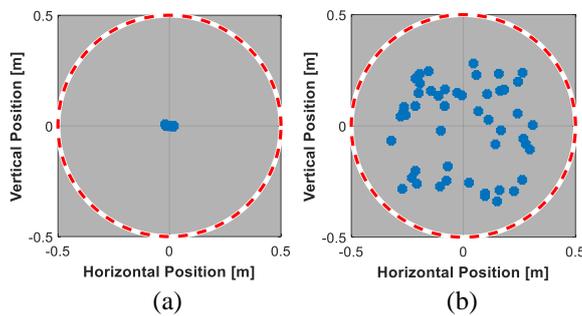
Figure 13 - Simulation results for harmonic excitation with a frequency of 15 Hz. (a) projectile impact points considering only the dispersion resulting from harmonic vibration; (b) projectile impact points considering the intrinsic dispersion of the weapon and ammunition.
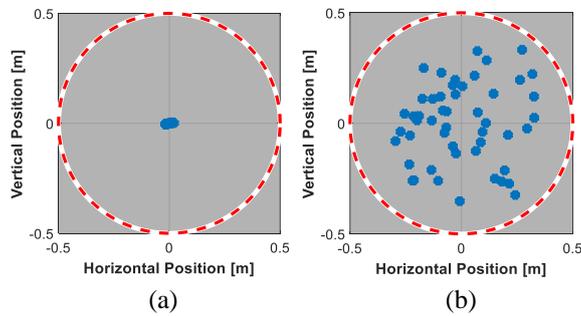

Figure 14 - Simulation results for harmonic excitation with a frequency of 24 Hz. (a) projectile impact points considering only the dispersion resulting from harmonic vibration; (b) projectile impact points considering the intrinsic dispersion of the weapon and ammunition.

Figure 15 - Simulation results for harmonic excitation with a frequency of 37 Hz. (a) projectile impact points considering only the dispersion resulting from harmonic vibration; (b) projectile impact points considering the intrinsic dispersion of the weapon and ammunition.
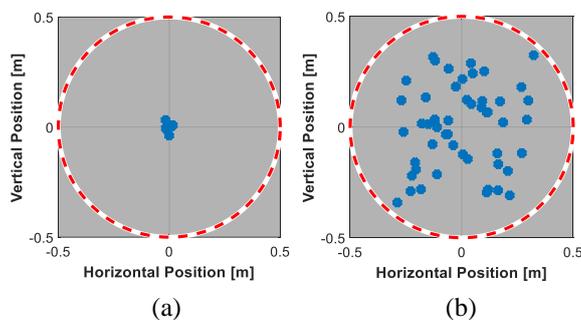

Figure 16 - Simulation results for harmonic excitation with a frequency of 45 Hz. (a) projectile impact points considering only the dispersion resulting from harmonic vibration; (b) projectile impact points considering the intrinsic dispersion of the weapon and ammunition.
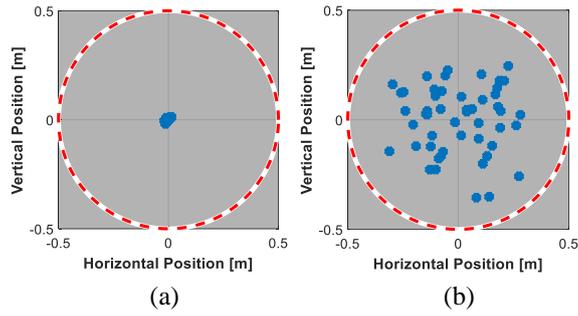
Figure 17 - Simulation results for harmonic excitation with a frequency of 55 Hz. (a) projectile impact points considering only the dispersion resulting from harmonic vibration; (b) projectile impact points considering the intrinsic dispersion of the weapon and ammunition.
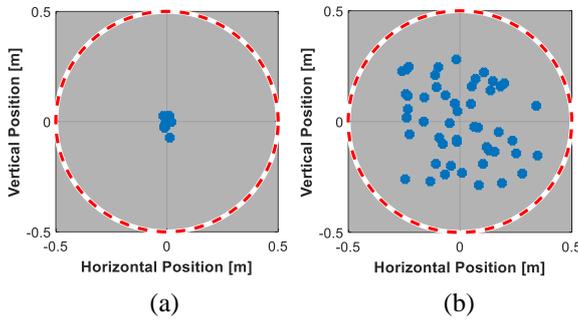

Figure 18 - Simulation results for harmonic excitation with a frequency of 65 Hz. (a) projectile impact points considering only the dispersion resulting from harmonic vibration; (b) projectile impact points considering the intrinsic dispersion of the weapon and ammunition.
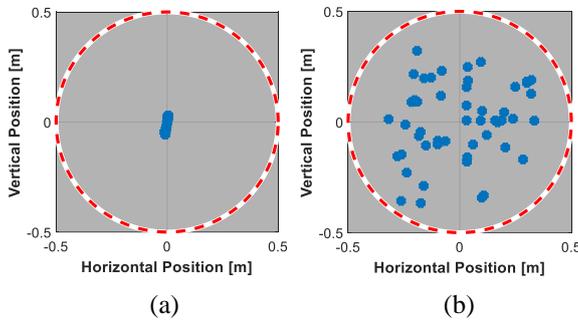

Figure 19 - Simulation results for harmonic excitation with a frequency of 75 Hz. (a) projectile impact points considering only the dispersion resulting from harmonic vibration; (b) projectile impact points considering the intrinsic dispersion of the weapon and ammunition.
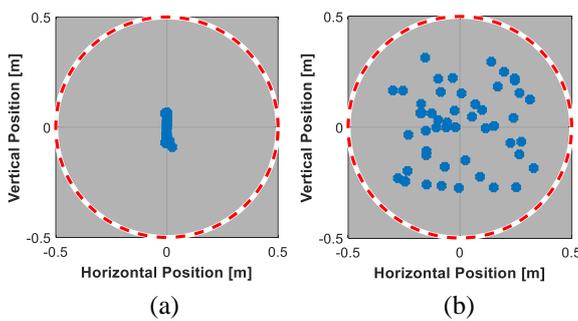

Figure 20- Simulation results for harmonic excitation with a frequency of 85 Hz. (a) projectile impact points considering only the dispersion resulting from harmonic vibration; (b) projectile impact points considering the intrinsic dispersion of the weapon and ammunition.

Table 2. Statistics of shooting simulations.

Frequency (Hz)	Considering the Intrinsic Dispersion of the Weapon and Ammunition	
	Mean Distance [cm]	Standard Deviation [cm]
6	21.431	8.604
15	23.727	8.800
24	22.691	8.527
37	22.345	8.737
45	23.265	9.090
55	23.341	8.444
65	23.617	9.057
75	24.172	9.063
85	22.788	9.240

8. CONCLUSIONS AND PERSPECTIVES

It has been verified that the modeling procedured developed was effective in providing predictions of the shooting accuracy under fairly realistic conditions. From the results obtained from the specific conditions considered in this paper, is can be concluded that the vibration of the helicopter does not compromise the accuracy of the impact on the target, since the weapon resting on the bungee cord and on the shooter's body is satisfactorily isolated from the aircraft vibrations.

Furthermore, in the simulations carried out, the activation of any natural mode of vibration of the weapon was not observed, which shows that the firing of the weapon in this configuration is not disturbed to the point of having one of its natural modes of vibration activated.

It was also found that the intrinsic dispersion of weapons and ammunition has a greater impact on impairing the accuracy of fire.

9. ACKNOWLEDGEMENTS

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