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Vibrational analysis of Mini – Unmanned Aerial Vehicles Due to Gun Recoil

N. Rino Nelson[a] * and P.M. Siva[b]

Department of Mechanical Engineering, Indian Institute of Information Technology Design and Manufacturing Kancheepuram, Chennai, 600127, India

[a]rino@iiitdm.ac.in, [b]mds20m007@iiitdm.ac.in,

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Abstract. In 21st century, battlefields are being occupied by Artificial Intelligence (AI) controlled machines and one of its kind is mini-unmanned aerial vehicles. Upon arming the mini-UAVs, the load distribution and characterizing the vibrational behavior are important for its safe operation. Usually, the gun recoil force gets transferred to the platform of the mini-UAV, leading to instability or failure of the platform along with the gun. Mini-UAVs being too small don't have the space to set the conventional recoil reduction mechanism. So, it is important to design a mechanism or alternative propellant for achieving the equivalent explosive force instead of TNT. Also, the influence of explosion on the vibration characteristics of the mini-UAV is studied. The high-pressure gas is found as the best alternative to TNT material, for reducing the deflection produced. This work primarily concentrates on determining the deflection and frequency induced in mini-UAVs. By using a pressure canister arrangement, the vibration characteristics under recoil can be improved.

Introduction

Nowadays in battlefields, aircraft is being replaced by unmanned aerial vehicles (UAV) for dog fight, reconnaissance and air-superiority. Even though, the UAVs have the capability to carry large range of ammunition, mini-UAVs were developed for specific operations to make them economically viable. But, its capability of ammunition needs to be improved in mini-UAVs. Upon ammunition, the rearward (recoil) force from the machine gun will be high, which can lead to destruction or failure of the entire unit. The recoil force of the gun gets transferred to the base platform of the UAV, which leads to instability or failure of base platform along with the gun [1]. Usually, UAVs have special recoil reduction mechanism to keep the platform in stable position. To avoid failure, dashpot-spring mechanism is commonly used to absorb the recoil force and bring the cartridge to its original position to fire the next bullet. Here, the recoil frequency depends on the damping coefficient of the dashpot, which is maintained greater than 0.5 for machine guns. Mini-UAVs being too small don't have the space to set the conventional recoil reduction mechanism, making it difficult for ammunition.

In literature, more importance is given to the structural analysis of mini-UAV. This always leads to finding a suitable material, so that the stress lies within the failure limit [2, 3]. With recent advancement in topology and topography optimization, the frame behavior can be analyzed and cost-effective alternatives are proposed [4]. The position algorithm can be used to find the natural frequency at every nodal point in the frame, which helps to position the sensor locations. Most of the unbalance in the mini-UAV occurs due to the deviation in total weight acting on the center of gravity of the mini-UAV, leading to calibration errors. To reduce this error, weight distribution algorithm employed in aircraft is commonly used.

Now with the advent of swarm drone technology, the need for arming the mini-UAVs is increasing. So, it is important to design a mechanism within the limited space, which transfers less vibration to the base platform. This paper concentrates on determining the vibrational characteristics of mini-UAVs and different methodology of recoil reduction for improving the stability of the base platform. When a gun is attached to the mini-UAV, the recoil force causes extra vibrations [5] and shifts the natural frequency of the mini-UAV. The common approach is to use special dampers like MR dampers [6], but these are suitable only for large caliber guns like Howitzers and Anti-aircraft guns. Small caliber guns can only be used in mini-UAV due to the weight constraint. But, small caliber guns like pistols produce more recoil force and has less space to accommodate any special damper arrangements. The suitable approach to solve this problem is to use rarefaction gun [7] and different propellant. A unique way is to use pressure canister mechanism, which can produce less vibration and recoil force compared to the normal chemical propellant. The internal ballistics of the gun is analyzed using special codes to calculate the peak pressure and muzzle velocity [8]. But with pressure canister mechanism, we can eliminate the use of complex ballistics code and common Navier stokes equations are solved.

Another area which needs more attention is to reduce the transmissibility ratio between gun and mini-UAV, so that the vibrations reaching the frame can be reduced. If the mini-UAVs are directly in contact with the gun, the transmissibility ratio will be close to 1. The researchers have focused more on the effect of structural methods to reduce the vibration, but not much importance has been given to the use of alternative propellants. Once such method is pressure cartridge or canister method in which pressure will be used to propel the projectile. The effect of using pressure canister as an alternate propellant is investigated in this work.

Numerical Analysis

First step in building a numerical model for internal ballistics calculation is determining the dependent and independent parameters, along with the theories linking these parameters. The most important parameters include the muzzle velocity (v_m) and barrel pressure (P_b). There exists a variety of analytical approach to describe the interior ballistic process. They are chemical equilibrium, closed form formulations, zero order analytical method and lumped parameter methods. Among various methods [9, 10], Corner's method and Coppock's method belonging to closed form formulation, yield better results compared to other methods. The main benefits of these approaches include the use of dimensionless ballistic parameters and usefulness in testing the convergence and accuracy of developed numerical model [10]. The results from ANSYS are compared with both the analytical methods. The flowchart describing the methodology used in this work is shown in Fig. 1.

Table 1. Input parameters of the barrel

Input Parameter	Value
Bore Diameter	18.52 mm
Barrel Length	457.2 mm
Projectile mass	0.044 kg
Propellant type	Cylindrical
Propellant diameter	1.575 mm
Adiabatic flame temperature	3390 K
Covolume	0.890 cm^3/g
Chamber volume	983200 mm^3

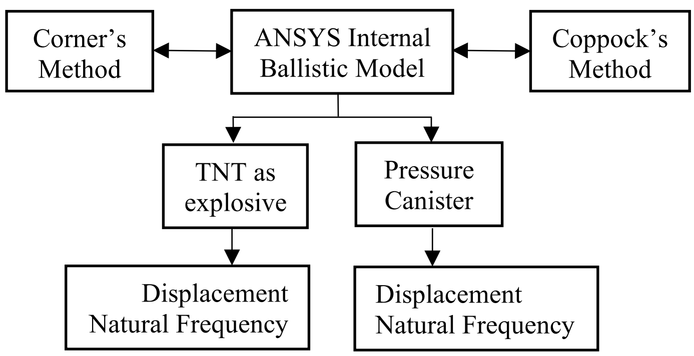

Fig. 1 Flowchart of Methodology

Corner's Method. Corner's method is one of the closed form solutions used for internal ballistics calculation which helps in determining the maximum breach pressure (P_b) and muzzle velocity (v_m). The input parameters needed are projectile diameter, burn rate coefficient, gas co-volume, adiabatic flame temperature, barrel length and diameter. The input parameters for barrel and projectile are listed in Table 1. The first output variable in Corner's method is central ballistics parameter (M), given by Eq. 1. The breach pressure and muzzle velocity are calculated using Eq. 2 and 3.

$$M = \frac{A^2 D^2}{m_p m_c \lambda \beta^2}\left[\frac{\left(1+\frac{m_c}{3m_p}\right)}{\left(1+\frac{m_c}{2m_p}\right)^2}\right] \tag{1}$$

$$P_b = \frac{\lambda m_c}{\left(V_c - \frac{m_c}{\rho}\right)} \frac{\left(1 + \frac{m_c}{2m_p}\right)}{\left(1 + \frac{m_c}{3m_p}\right)} (1 - f) e^{-M(1-f)} \tag{2}$$

$$f = \frac{M + \theta - 1}{M + 2\theta}$$

$$v_m = \sqrt{\frac{m_c \lambda \left\{M + \frac{2}{1-\gamma}\left[\left(\frac{L_B + L_C}{x_C + L_C}\right) - 1\right]\right\}}{m_p + \frac{m_c}{3}}} \tag{3}$$

Coppock's Method. Coppock's method is also a closed form approach. Coppock's method is more accurate than Corner's method. The assumptions made are powder mass burn rate is proportional to the chamber pressure and surface area of the powder. The pressure gradient is assumed as constant for a charge weight and projectile weight ratio. The maximum pressure (P_b) and muzzle velocity (v_m) are given by Eq. 4 and 5.

$$P_b = \frac{m_c \lambda R_{ba} (1 + \theta)^2 (\xi M + \theta)}{A(\xi M + 2\theta)^2 \left(x_m + l_c (1 - \eta\varphi)\right)} \tag{4}$$

$$v_m = \sqrt{\frac{\lambda m_c \left[M + 2Z\left(\frac{1 - r^{1-\gamma}}{\gamma - 1}\right)\right]}{\left(w_1 + \frac{m_c}{3}\right)}} \tag{5}$$

ANSYS Model Setup

Barrel Dimensions and Properties. Gun barrel dimensions have a major contribution towards muzzle velocity [1-3] i.e., longer barrel gives more time for the propellant to expand to its threshold limit which leads to maximum muzzle velocity. But longer barrel causes heaviness and instability making the mini-UAVs to lose control during loitering mode. Therefore, usage of short barrel is recommended in mini-UAVs to fly in stable condition. To analyze the effect of short barrel, a standard length of 116 mm is chosen as shown in Fig. 2.

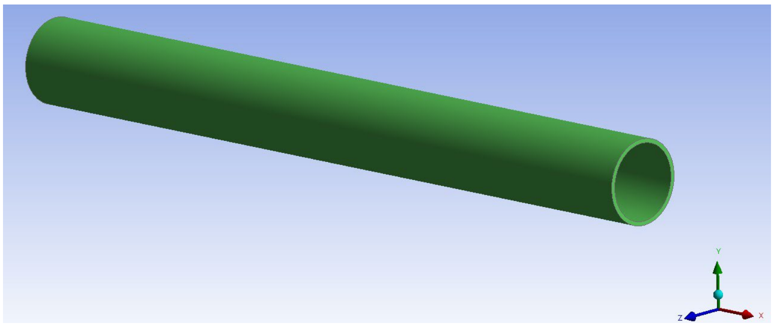

Fig. 2 Barrel model in ANSYS

Projectile Dimensions and Properties. The use of small barrel length leads to more vibrations with propellant expansion. To reduce this vibration, we should choose bullet having small diameter propellant with medium peak pressure. This small diameter also leads to reduction in weight, so more ammo can be carried. Based on the above conditions, a bullet with 9 mm diameter is chosen for analysis (Figs. 3 to 6). To withstand the temperature produced during burning of propellant, the bullet material is chosen as lead. The cartridge material is chosen as copper alloy to have a limited deformation, since the whole explosion needs to be confined to move only in one direction.

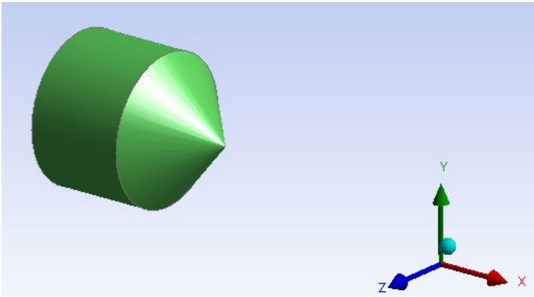

Fig. 3 Bullet model

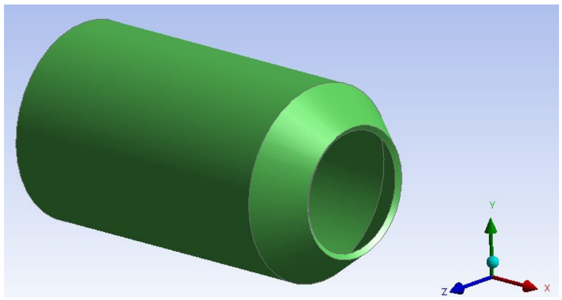

Fig. 4 Cartridge model

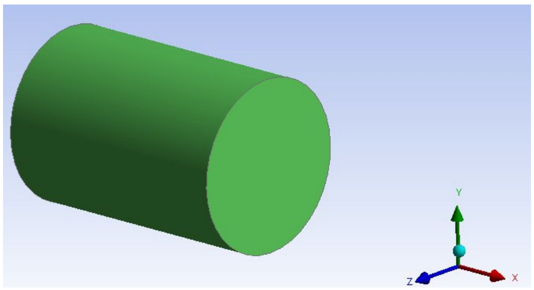

Fig. 5 Explosive model

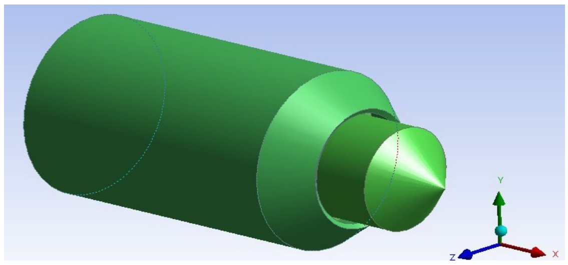

Fig. 6 Full bullet model

Results and Discussion

Analytical vs Numerical. The simulation is performed using ANSYS software. The muzzle velocity and maximum breach pressure values are obtained as output from the simulation. The results obtained from analytical methods (i.e) Corner's and Coppock's methods are compared with values obtained from numerical simulation.

Table 2. Comparison of values from analytical and numerical methods

Method	Muzzle velocity [m/s]	Max breach pressure [MPa]
Corner's Method	815.26	225.38
Coppock's Method	826.75	205.33
ANSYS	800.78	224.37

Deflection comparison. The barrel deflects due to the burst of primer and burning of propellant, which also causes the barrel to vibrate. To reduce the induced vibration, the pressure canister is proposed. This mechanism has no propellant, but the high-pressure air released causes the projectile to move. The deflection of the barrel with pressure canister is comparatively low as shown in Fig. 7. For TNT, the primer burst leads to deflection and thereby causing initial peak in Fig. 7. The second peak corresponds to the propellant burst, causing the expansion of gases and the last peak corresponds to the projectile leaving the barrel. In canister curve, the first peak corresponds to the initial burst of the bubble, which has high pressure air. The second peak corresponds to the projectile leaving the barrel. The curve clearly shows that the canister has reduced the deflection when compared to the use of TNT. Since the deflection is reduced, it will lead to the reduction in vibration along the lateral direction significantly.

TNT vs Pressure Canister. Free vibration analysis helps in determining the natural frequency /resonance frequency of the model. The model is preferred to vibrate with the limit but when it exceeds the limit, the failure happens. In addition, the effect of bullet burst also contributes to vibration causing failure in many cases. To avoid this condition, dampers and vibration absorbers are used suppressing the frequency below the threshold level. With the use of pressure canister, the need of damper is less, since the force imparted is lower than TNT. But, the force is transient and not static in nature. So, the dynamic results of both are compared in the Table 3.

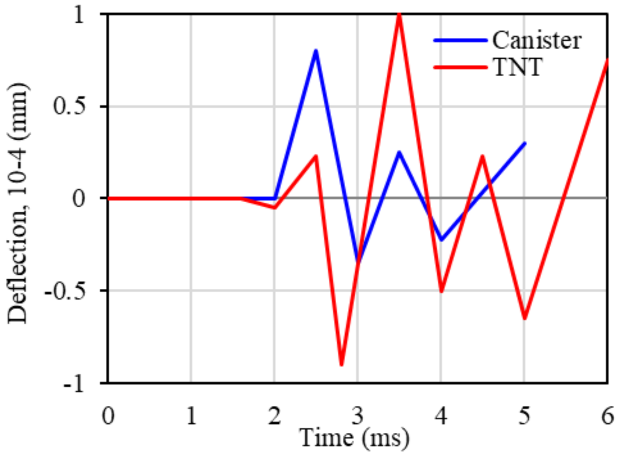

Fig. 7 Comparison of deflection vs time for TNT and Canister

The values show that the vibration due to the pressure canister is lower compared to TNT. The fourth frequency of canister is higher than the TNT, because of the muzzle pressure breaker in TNT and the absence of the same in pressure canister. Overall, the force produced is less for high pressure gas with time. But for TNT, the expansion of the gas increases the force until the projectile moves and then decreases slowly compared to the high-pressure gas stored in the canister.

Table 3. Frequency due to TNT and canister

	Frequency of TNT [Hz]	**Frequency of canister [Hz]**
1	60.25	56.82
2	167.25	158.25
3	304.50	298.60
4	448.25	456.28

Conclusions

Based on the present study, feasibility of using alternate propellant for projectile motion is studied and the following conclusions are derived,

- The results of deflection and vibrational frequency show that the frequency is lower with the use of the high-pressure canister than the TNT material. There are also propellants which have lower blast peak pressure reducing the deflection.
- The frequency of vibrations still be same and necessitates the use of damper, which increases the weight.
- Though pressure canister is better from vibration perspective, it has low range of fire and low projectile velocity upon reaching the target.
- To determine a suitable frame for carrying the gun and withstand the vibrations, topology optimization needs to be done. This further helps in making the mini-UAV more stable for the recoil.

Nomenclature

A	Area of bore
D	Web fraction
f	Mass fraction
L_b	Barrel length

L_c	Chamber length
m_p	Projectile mass
m_c	Charge mass
r	Expansion ratio
R_{ba}	Ratio of breach pressure
V_c	Charge volume
w_1	Adjusted projectile mass
x_C	Charge burn-out length
x_m	Fraction of propellant burnt
Z	Form function
β	Burn rate coefficient
λ	Specific force
θ	Shape function
γ	Specific heat ratio
φ	Volume fraction
η	Covolume correction
ρ	Density
ξ	Characteristics length

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