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SMART ISOLATION MOUNT FOR AIRBORNE GUNS

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Structural deformations at the turret interface points in an airborne-helicopter system need improvement. Such deformations occur due to large firing reaction forces. The deformation of the helicopter body and propagation of vibrations result in reduced accuracy and cause reoccurring failure of hydraulics and onboard electronics. Smart Isolation Mount for Airborne Guns addresses the vibration issues in the weapon stabilization and fire control systems. SIMAG™ is composed of the optimum integration of vibration control by confinement and a smart control system. It reconfigures the distribution and propagation of excess vibration energy; and therefore, confines vibrations within its own structural elements. SIMAG™ makes significant progress towards solving the firing control problems with acceptable weight and power penalties by compensating for all errors at the turret-aircraft interface. Concentrated smart damping elements or cancellation techniques effectively dissipate the trapped vibrations. The insertion of SIMAG™ in an onboard gun system reduces the fluctuating loads and deformations by up to 50%.

INTRODUCTION

There exists a need for the development of a low-cost, high-performance weapon stabilization and fire control system for the U.S. Army. These developments may include optimal sensor fusion algorithms and fire control implementation prototypes. Applications consist of platforms such as attack helicopters and ground vehicles.

Currently, there are several major error sources influencing turreted weapon accuracy on a helicopter. Among the major sources of error are non-linearity and uncertainties in hydraulic elevation and azimuth drivers, deformations of the supporting structure in the vicinity of the turret attachment points, turret dynamics excited by firing action, and non-observable motions that include deformations of the gun barrel. For example, helicopter structural deformations, local to the turret interface points, can exceed 15 mrad, depending on the location of the interface point. Such deformations occur due to large firing reaction forces that can be as high as 8000 lbs at 10 Hz. The firing accuracy of the gun is significantly affected by the deformation of the helicopter body (also referred to as body bending) and bending of the gun barrel. Both of these deformations influence the vertical exit angle of the fired round.

The exit angle is one of the most significant parameters affecting the trajectory of the round as demonstrated in the following example. A small vertical displacement, h, will result in a small error at a distant target. On the other hand, a small rotational displacement, θ, may result in a large error at a distant target. For instance, for a shot fired downrange 1500 ft, a

0.25 ft vertical displacement at the barrel tip produces only a 0.25 ft error. An angular deviation of 0.002 radians produces an 8.5 ft error.

Presence and propagation of such relatively large vibration levels not only result in reduced probability of kill but also cause reoccurring failure of hydraulics and onboard electronics (i.e., fuses) in an attack helicopter. The attack helicopter PMO and manufacturers [1] been identified aircraft structural deformation and vibration issues as well documented, long-term, and unresolved problems.

The Advanced Drives and Weapons Stabilization (ADAWS) laboratory in ARDEC has focused on the development of the Advanced Electric Turret (AET) based on a gearless electronic drive, digital control technologies, and smart barrel actuators. The AET program addresses only two of the error sources, non-linearity in hydraulic elevation and azimuth drivers and turret dynamics. Improvement in these two error sources may result only in reduction of operating and support (O&S) cost of hydraulics.

The ***S***mart ***I***solation ***M***ount for ***A***irborne ***G***uns (SIMAG^{TM}) addresses the other two error sources, deformations of the helicopter structure near the turret attachment points and non-observable motions such as deformations of the gun barrel. The main weapon O&S cost drivers for these improvements will be the failure reduction of onboard electronics and enhanced probability of kill. The latter benefit will result in reduction of onboard ammunition and thus, an increase in fuel storage and payload capabilities. Additional benefits of reducing excess vibration propagating to the body of the helicopter include: decreased wear to the helicopter structural components, reduced whole-body vibrations on crew, increased effectiveness of maintenance procedures, enhanced man-machine interface, and reduced crew fatigue.

In this paper, the feasibility of developing the SIMAG system is presented. SIMAG is based on the Vibration Control by Confinement^{TM} (or VCC^{TM}) approach [2,13-16]. It is shown that SIMAG reduces the transmission of excess vibratory loads to the helicopter structure and improves the pointing accuracy of the gun. The former will result in damage reduction in the helicopter structure and onboard electronics.

AN OVERVIEW ON VIBRATION CONTROL BY CONFINEMENT^{TM}

Researchers have explored the applicability of the mode localization phenomenon and vibration energy confinement to engineering problems, such as vibration suppression, isolation, absorption, and control. Recently an overview of these works and the impact they may have on vibration control was presented [2]. One of the main questions raised in these studies was whether passive and/or active vibration control by confinement has the potential to become an alternative or complementary approach to the current noise and vibration control schemes. A review of the current literature [2-16] indicates that the Vibration Control by Confinement approach is an effective means for managing the vibration energy associated with a structure.

The patented VCC approach [13,14] is comprised of four primary steps. First, certain design parameters of the structure are modified within allowable limits to induce a desired vibration energy confinement. This confinement causes a significant portion of the vibration energy to be directed to non-critical sub-structures, thereby isolating and quieting critical areas. Second, should a stronger confinement, and thus greater suppression, be required, specially designed add-on components can be used to strengthen the degree of confinement. Third, passive and/or active damping elements concentrated in the regions of trapped vibration energy are applied to remove the confined energy. Fourth, a set of discrete or distributed feedback forces may be employed to transform the original system-wide vibration response into spatially decaying (regionally confined) or vortex power flow responses. This four-step process results in simultaneous decay of vibrations in the time and spatial domains. Therefore, excess vibration energy may be trapped near its source, dissipated, and prevented from propagating to other parts of a structure.

The energy diversion and confinement features in spatial domain is analogous to the effect that damping has on the vibration response in time domain. Whereas damping decays vibration in the time domain, VCC decays vibration in the spatial domain. Confinement may also be used to control the vibration power flow throughout the structure. VCC also differs fundamentally from conventional controls in that conventional controls are reactive, acting on incoming vibration energy to reduce its levels. VCC is proactive; prohibiting vibration energy from entering selected regions of a system. It is used to tailor the final energy distribution and resultant vibration levels to meet the specified vibration and damage control requirements.

The VCC technique is an integral part of SIMAG concept that has enormous applications in aircraft, spacecraft, ground vehicles, surface ships, submarines, and commercial systems. Our first attempt will be to fulfill the described Army requirements for airborne guns. However, the larger market is in the commercial segments including automotive, manufacturing, and space systems. Other applications will be pursues at the end of this work.

SIMAG CONCEPT

In this work, the issue of controlling the gun-generated vibrations is address by an energy flow control approach. Managing the propagation of vibration and shock energy within a smaller structural space (i.e., SIMAG) that interfaces the gun and an air vehicle (i.e. helicopter) will be an effective technique to protect the onboard electronic and optical systems, and interrupt the random flow of this destructive and often dangerous propagation of energy throughout the airborne vehicle. It is dangerous because not only can it damage interior systems but it also can cause excess vibration and noise that can distract and fatigue the crew. Steering and confining the excess vibration energy to less critical sections or less-radiating modes of the continuous isolation unit allows for the application of concentrated passive or active control efforts. The SIMAG system has both passive and active energy managing elements. The energy-managing approach reduces effectively the propagation of vibration or shock energy to a helicopter shell and frame structures. SIMAG approach is implemented without compromising the performance of the equipment or vehicle while keeping the structural weight and cost of the isolation units at their minimum.

The development of SIMAG whose continuous structural elements can **manage** (i.e., **confine, divert, convert, absorb, steer, and dissipate**) excess vibration and shock energies has a profound impact on the general area of vibration isolation and shock mitigation technologies. In particular, our ultimate isolation system will be a high pay-off product with direct benefits to U.S. Army, other DOD components, and commercial markets.

SIMAG utilizes the isolating capabilities of VCC to suppress vibration levels across the helicopter body by performing five functions. (1) It redirects the vibration energy away from its interface to the helicopter body. (2) It redirects the vibration energy away from its interface to the gun turret. (3) It traps vibration energy within itself at non-interface locations. (4) It converts elastic energy to kinetic, and vice versa. (5) It dissipates the energy before it can propagate to the helicopter shell. The SIMAG insert is shown in Figure 1. First, the helicopter body is separated from the gun turret components. Second, the energy diverting SIMAG insert is positioned between the helicopter body and the turret. Third, the components are reassembled with both the helicopter body and the gun turret interfacing the SIMAG insert. Positioned in this manner, SIMAG is capable of performing its five functions. SIMAG may be used to retrofit the current gun-turret systems or may also be integrated into a new design of turret structures. It is anticipated that when SIMAG is an integral part of a turret, it will have the highest performance and payoff.

SIMAG is composed of optimum integration of two innovative technologies, namely Vibration Control by Confinement and an active control system. In the current project, these two complementary approaches are combined to solve the firing problem at the gun mount and turret interface location. SIMAG is designed to first passively reconfigure the distribution and propagation of excess vibration energy and confine vibrations to certain pre-defined non-critical regions of the helicopter-turret-gun system. Concentrated damping elements (CDE), in passive or active forms, are then applied to effectively dissipate or cancel the trapped vibrations and to prevent an energy build up in the assembly. Should a more robust confinement be required, closed-loop control forces may be applied to further redirect and confine the vibratory energy. The application of SIMAG results in a significant reduction in fluctuating loads and deformations. SIMAG makes significant progress towards solving the firing control problems. It accomplishes these goals with very small weight and power penalties. The application of the SIMAG approach to the gun barrel is also under investigation and will be reported in subsequent papers.

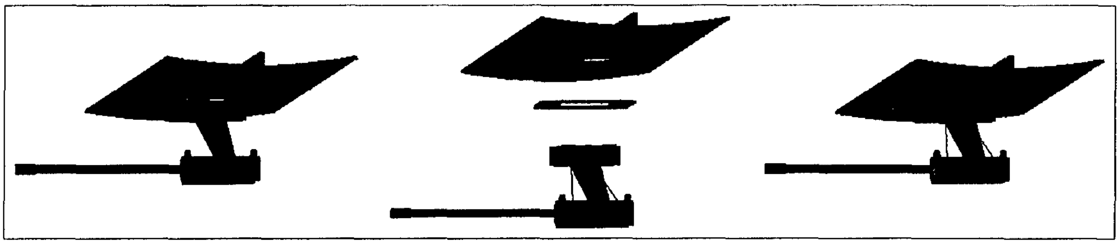

Figure 1 SIMAG system approach (a) baseline system, (b) SIMAG inserted between helicopter body and gun system, (c) SIMAG-inserted system

ANALYSIS AND RESULTS

The free vibration analysis of the baseline helicopter-gun structure and SIMAG-helicopter-gun system were modeled using standard ANSYS-based finite element package. The forced vibration and active control parts of the analysis were conducted using in-house developed software, VECAS (Vibration Energy Confinement Analysis Software), that is based on the commercially available MATLAB package. The baseline model was calibrated against measured vibration characteristics of an attack helicopter in ground and non-operating conditions.

Details significant to the dynamic characteristics of the system components were modeled. The baseline and SIMAG-inserted system models are displayed in Figures 1(a) and 1(c), respectively. The baseline model consists of the following components: the bottom section of a helicopter body, turret, gun-supporting forks and cradle, gun, barrel, and end suppressor. The SIMAG-inserted model consisted of the above gun and helicopter components plus SIMAG inserted between the helicopter body and turret.

For this study, all the components of the models were comprised of steel. Table 1 shows the material properties used in this study.

Table 1 Material properties and geometry of the modeled components

Property		**Value**
Elastic Modulus		30.023x10^{6} psi
Density		7.3463x10^{-2} lb-s^{2}/in^{4}
Poisson Ratio		0.29
Helicopter Shell: Single Curved Plate	Dimensions	240 in. × 48.8 in. × 0.5 in
	Curvature	Radius: 148 in, Arc: 18.9°
	Rectangular Hole	21 in. × 14 in.
Passive SIMAG	Footprint	24 in. × 26 in.
	Center Hole	21 in. × 14 in.
	Weight	61 lb
Finite Element Model	No. of Nodes	1,897
	No. of DoF	11,382
	Active DoF	10,378
	No. of Elements (solid, shell, discrete)	846

The helicopter body was modeled as a singly curved plate with the axis of curvature lying along the length of the plate whose dimensions and curvature are given in the above table. The curvature of the plate was a circular arc having a radius of 148 in. subtending an angle of 18.9°. The actual helicopter body must have the capability to transport ammunition to the gun. The computer model accommodated this need with a hole placed toward the front of the plate. To mimic the dynamic behavior of the actual helicopter body, a stiffening keel was added to the model along the length of the helicopter body. The geometric requirements for SIMAG limited the insert footprint as shown in Table 1. To accommodate the transport of ammunition to the gun, a hole was also required in the SIMAG insert.

In this preliminary study, passive confining elements were employed to induce the required energy distribution within SIMAG. Even though the passive version of SIMAG has limited flexibility, it can be used to demonstrate the effectiveness of the concept. Several configurations of passive energy-diverting components were considered for this study.

Stiffening ribs have been used for decades for static and dynamic strengthening of structures. It has been shown [2-16] that the addition of confining ribs and patches may also be used effectively for energy redistribution and confinement. For example, rib geometry, material properties, and placement may significantly alter, in a predictable manner, the flow of vibration energy within a structure. In the work presented here, component (patch) thickness and location were used to induce confinement. The passive SIMAG insert adopted for this demonstration had a total weight of 61 lb. By retrofitting existing Apache systems with SIMAG, the normal take-off weight of the helicopter is increased by a nominal 0.37%.

The ANSYS-based, SIMAG-inserted model contained 846 solid, shell, and discrete spring elements. The number of nodes, total degrees-of-freedom (DoF), and total active DoF are given in Table 1. The helicopter body was simply supported at its edges. The models were designed to capture the dynamic behavior of a typical helicopter-turret-gun system. Not only the models were developed and correlated with measured vibration characteristics of the helicopter-turret-gun system, but also existing lumped-mass fire-control models [17] of the 30mm gun were used during the calibration process.

The input firing load was simulated using the digitized version of the measured firing force for the 30mm gun. The actual measured and digitized forces are shown in Figures 2(a) and 2(b), respectively. As shown in Figure 3, the input forces (firing loads) were applied at the gun surface interfacing the barrel. Also shown in Figure 3 are the output locations (nodes). Six nodes selected on the helicopter body component and labeled with 500- and 600-series numbers are shown in the figure. These six nodes were used for quantifying the reduction of vibratory energy propagating to the helicopter bottom shell. Also of interest for this study are the interface nodes between the helicopter body and turret (baseline model) or SIMAG insert (SIMAG-inserted model). These nodes are located at the helicopter interface points.

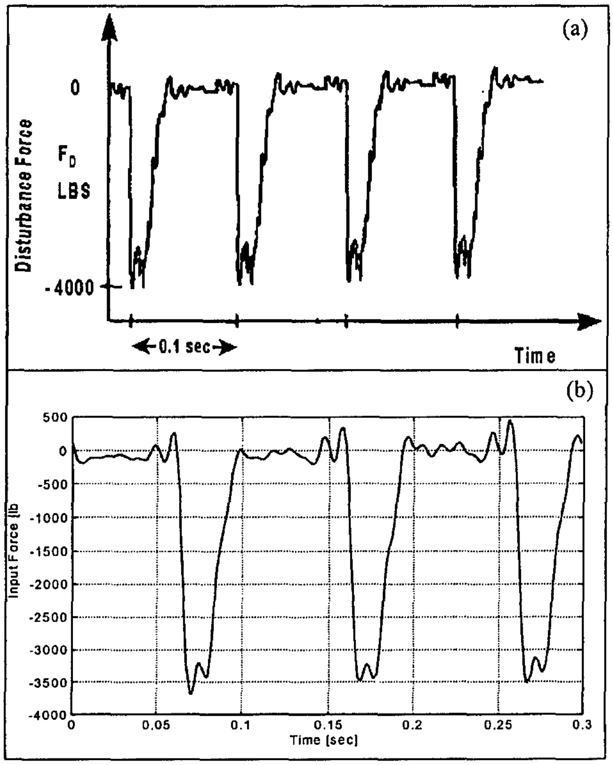

Figure 2 Gun firing force (a) measured, (b) digitized for computer models

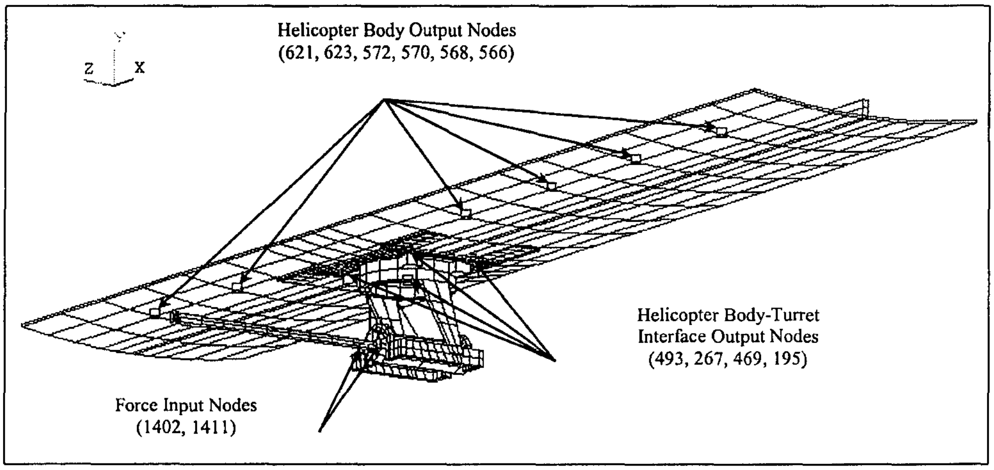

Figure 3 Input and output nodes for baseline and SIMAG-inserted models

The free vibration characteristics of the systems were determined from the FEA model. The vibration characteristics (natural frequencies and mode shapes) were exported to an in-house developed analytical software, namely VECAS (Vibration Energy Confinement Analysis Software). VECAS has the capability to perform forced-response analyses once given a system's vibration characteristics. It also has the capacity to simulate active control loops. The active control strategies investigated in this study include direct velocity feedback control (DVFC) and the implementation of active vibration confinement via the method of Spatial Decay-Causing Actuators (SDCA) [7,9,12]. VECAS has been verified previously for accuracy against accepted closed-form and numerical analysis routines [15]. Sample verification results for this project, however, are shown in Figures 4 and 5. Figures 4(a) and 4(b) show the dynamic response of the models calculated with the ANSYS transient analysis routines and with VECAS, respectively. The output locations for this verification study were the helicopter body nodes shown in Figure 3. Figure 5 shows a similar plot of dynamic response for the helicopter gun-system interface points. It is observed from these figures that the two analysis procedures produce results in acceptable agreement.

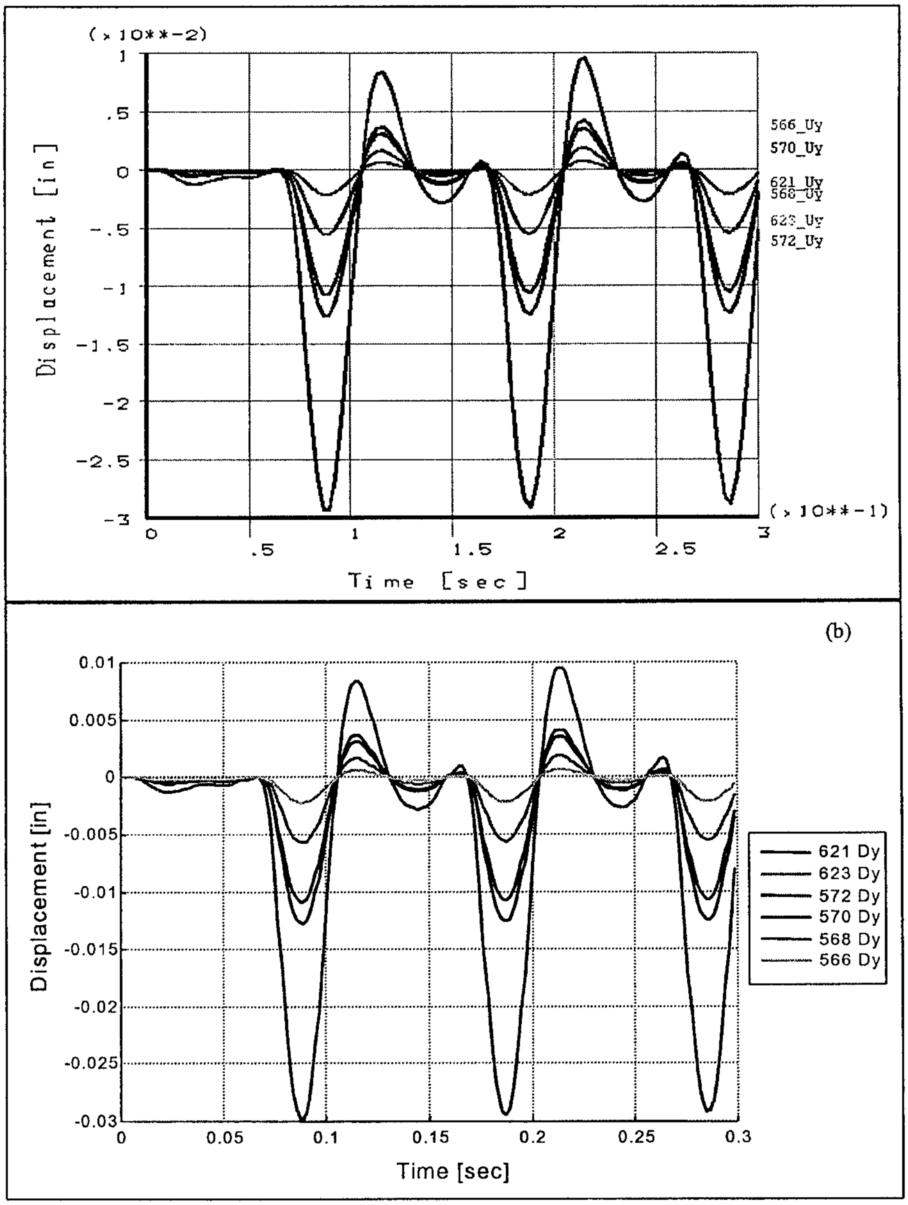

Figure 4 Validation of ***VECAS*** analysis codes for helicopter shell output nodes (a) ANSYS transient response results, (b) ***VECAS*** transient response results

For both the baseline and SIMAG-inserted models, the dynamic response of the system due to the simulated gunfire was calculated. The method of modal superposition was used to calculate the response. Twenty-five modes, covering a frequency range of 15 Hz to 180 Hz were used in the analysis. A constant damping factor of 35% was used for all modes. Time histories for the aforementioned output nodes were stored and plotted. For comparison, the maximum absolute displacement magnitudes were determined for all relevant points on the helicopter model.

Forced response analyses were conducted to demonstrate the effectiveness of several passive confinement configurations for the SIMAG Insert. Results indicate that SIMAG significantly reduces the firing-induced vibratory energy transmitted to the helicopter body.

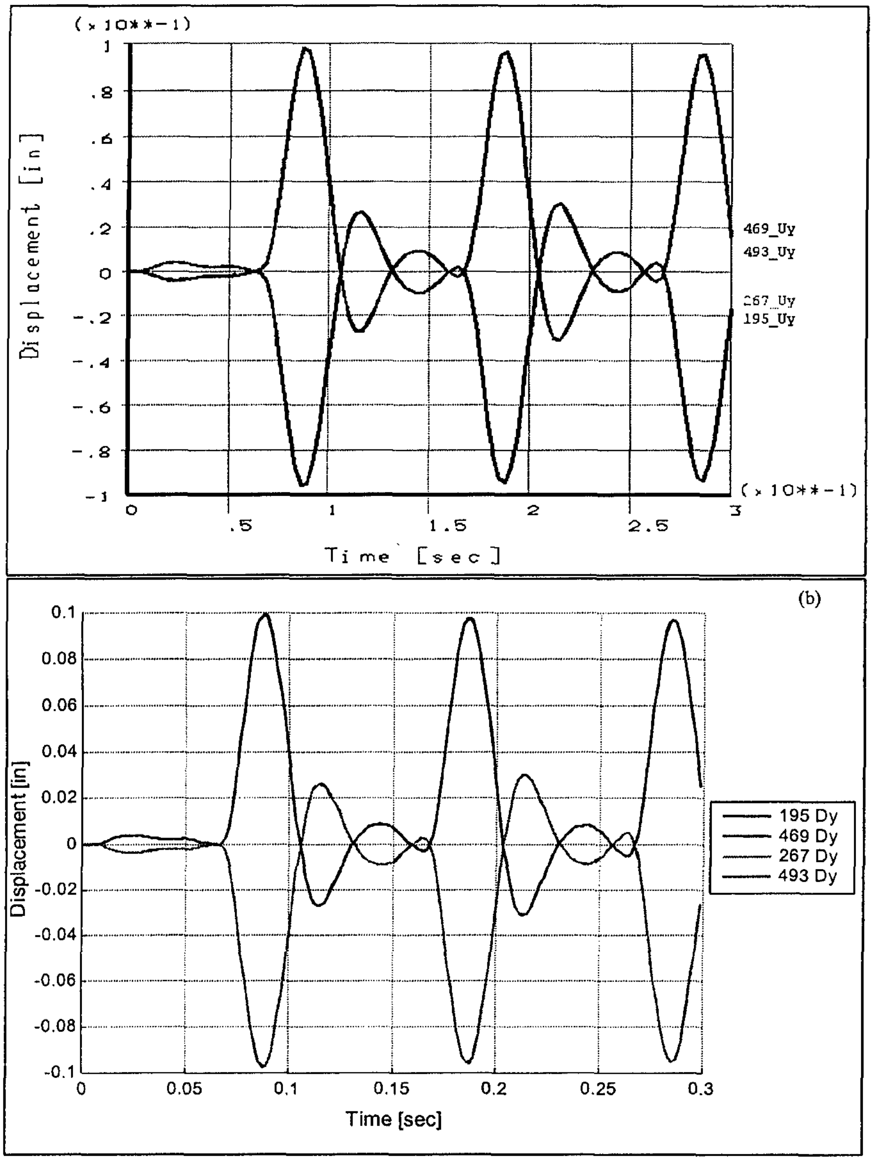

Figure 5 Validation of ***VECAS*** analysis codes for helicopter shell-gun system interface nodes (a) ANSYS transient response results, (b) ***VECAS*** transient response results

Figure 6 shows the results in tabulated; charted; and time history format. Figures 6(a-c) show the influence of the passive SIMAG on reducing the energy transmitted to the helicopter body over its length. Figures 6(d-f) show the similar results as calculated at the helicopter-gun system interface locations. Figures 6(g-i) illustrate the reduction in gross-body rotations of the gun turret once the passive SIMAG insert is in place. As mentioned in the introductory section, the gross rotation of the gun system due to helicopter body bending has a critical impact on the accuracy of gun firing. It may be seen from Figure 6(a) that the maximum absolute transverse displacements of the helicopter body is reduced by as much as 40% at all points along its length. This is an extremely good indication of the effectiveness of the passive SIMAG system.

It is pointed out that SIMAG is most effective at reducing the displacements at nodes 623 and 572, which had the highest baseline displacements. The bar graph in Figure 6(b) shows a comparison of the two systems for displacement reductions at the helicopter body. Figure 6(c) traces the time response of node 572 for both the baseline and SIMAG-inserted systems. Figures 6(a-c) show the passive SIMAG is effective at isolating the helicopter body from the firing-induced disturbances. It is observed that SIMAG does not adversely influence the modal characteristics of the system in that the participating modes, which dominate the transient response of the system, have not changed. The latter may be a requirement when considering the integration of SIMAG, as a retrofit solution, into the current fire-control systems.

Figures 6(d-f) relate the significant reduction in displacements transmitted to the helicopter-turret interfaces. The transverse displacements at these interfaces indicate the effectiveness of the SIMAG system at reducing energy propagation to the helicopter shell. These displacements are also related to the gross rotation of the turret, and subsequently the rotation of the gun-barrel system. Effectively reducing the interface displacements may directly and significantly impact the firing accuracy of the gun system. It may be seen from the table and bar graph that SIMAG operates equally on all interface locations and reduces the transverse displacements by over 50%. Figure 6(f) shows a representative interface time response at node 267. It is observed that SIMAG brings the turret to a near-rest state more quickly than does the baseline system. This is significant for firing accuracy and repeatability, as a more stable gun mount will behave more predictably.

Figures 6(g-i) show that the insertion of SIMAG reduces the gross rotations of the turret. In these figures, the relative displacements at the four interface locations were determined and the maximum angular deviations produced by these displacements were calculated and tabulated in Figure 6(g). The rotations are defined as follows. The x-axis runs along the length of the helicopter, directed from the front to the back. The z-axis runs along the width of the helicopter, directed from the left to right when facing the helicopter.

	Maximum Shell Displacements [in.]		
Node #	Baseline	Passive SIMAG	Percent Change
621	**1.09E-02**	**7.03E-03**	**-35.3%**
623	*2.99E-02*	*1.79E-02*	*-40.2%*
572	*2.98E-02*	*1.78E-02*	*-40.4%*
570	**1.27E-02**	**8.19E-03**	**-35.6%**
568	**5.64E-03**	**3.58E-03**	**-36.4%**
566	**2.17E-03**	**1.34E-03**	**-37.9%**

(a)

	Maximum Turret Displacements [in.]		
Node #	Baseline	Passive SIMAG	Percent Change
195	*9.75E-02*	*4.60E-02*	*-52.8%*
469	*9.92E-02*	*4.69E-02*	*-52.7%*
267	*9.77E-02*	*4.60E-02*	*-52.9%*
493	*9.93E-02*	*4.69E-02*	*-52.8%*

(d)

		Maximum Turret Rotation [rad]		
Rotational Axis	Edge	Baseline	Passive SIMAG	Percent Change
X	*Front*	*1.41E-02*	*6.64E-03*	*-52.8%*
X	*Rear*	*1.41E-02*	*6.64E-03*	*-52.8%*
Z	**Right**	**9.07E-06**	**2.31E-06**	**-74.5%**
Z	**Left**	**1.03E-05**	**2.83E-06**	**-72.6%**

(g)

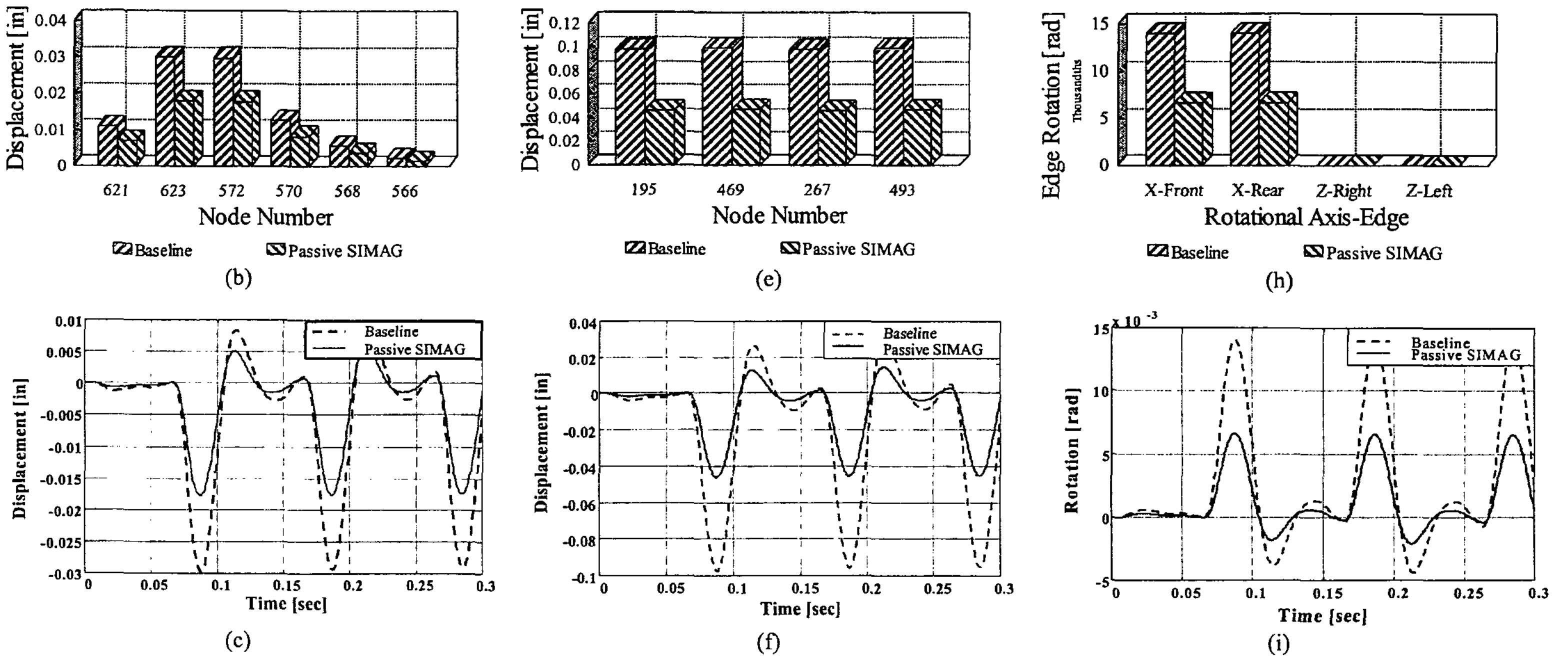

Figure 6 Analytical results for baseline and SIMAG-inserted models (a)-(c) helicopter shell output nodes, (d)-(f) helicopter shell-gun system interface output nodes, (g)-(i) turret gross rotation

Rotations about the x-axis are critical for the pointing accuracy of the side-pointing gun as they affect the vertical displacement of the gun barrel. The less-critical rotations about the z-axis affect gun canting. SIMAG reduces (see Figures 6(g) and 6(h)) the critical x-axis rotations by over 50% along lines connecting both the front interface points and the rear interface points. Figure 6(i) shows the time response of the angular measurement at the turret interface about the critical x-axis at the front of the interface locations. It is observed that SIMAG operates effectively to reduce rotations at both the maximum and minimum values.

CONCLUSIONS

The presented results indicate that the passive SIMAG effectively isolates the helicopter body from the gun firing-induced vibrations. The passive SIMAG reduces the transverse displacements propagating to the helicopter shell by as much as 40% while reducing the displacements at the turret interfaces by over 50%. Therefore, SIMAG is capable of effectively isolating mission-critical electronic components within the helicopter. The latter was accomplished while improving an attack helicopter as a stable platform for mounting the 30-mm gun. The performance of SIMAG was demonstrated through the reduced gross rotations of the gun turret with the passive SIMAG in place. The passive SIMAG approach thus provides an effective and relatively light-weight isolation system, capable of maintaining or improving the gun system objectives and reducing operating and support costs, while providing the additional benefits by reducing exposure to whole-body vibrations and fatigue for the crew. The passive SIMAG used in this work had a total weight of 61 lb that increased the normal take-off weight of the helicopter only by 0.37%. Our goal is to reduce the SIMAG weight by 14% resulting in a 47 lb insert.

SUMMARY AND FUTURE DIRECTIONS

In this paper, two of the opportunities for improving the performance of Army airborne guns were identified and resolved via SIMAG. The positive impacts that *S*mart *I*solation *M*ount for Airborne Guns (SIMAG) may have on the deficiencies of the current system were reviewed. Baseline and SIMAG-inserted finite element models were developed and analyzed. A forced response of the two systems under simulated gun firing loads was analyzed. Numerical simulations indicated that a completely passive SIMAG system has a strong potential for significantly reducing the vibratory energy propagating from the gun system to the helicopter shell. It was demonstrated that SIMAG has the capability to redirect the vibratory energy present in the system away from the interfaces between the helicopter shell and turret. The subsequent reduction in adverse excess energy may have numerous benefits to the operating and support cost for an attack helicopter and its subsystems. Additionally, SIMAG provides these benefits while enhancing the capabilities of attack helicopters as a viable mounting platform for the gun.

In the future phases of this work, conventional closed-loop active control capability will be added to the passive SIMAG system. These active control layers will target the vibratory energy remaining after the insertion of the passive SIMAG layer. Further studies will investigate the effectiveness of an active energy confinement system based on Spatial Decay-Causing Actuators (SDCA). It is anticipated that the addition of the SDCA layer will make SIMAG a smart system. With the realization of the full SIMAG system, the distribution of vibratory energy will be optimized and conventional active controls will be seamlessly incorporated into the control algorithm.

In addition to an attack helicopter, both passive and active versions of SIMAG have strong potentials for other Army systems. The SIMAG technology may be transitioned in ground vehicles such as various HMMWV and the Light Scout Vehicle.

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