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FLIGHT DEMONSTRATION OF AN ACTIVE HELICOPTER SEAT SYSTEM FOR AIRCREW WHOLE BODY VIBRATION MITIGATION

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Abstract. Helicopter aircrew are exposed to high levels of Whole-Body Vibration (WBV) in fight operations, which may degrade their ride comfort and performance in the short-term, and contribute to adverse health issues in the long-term. The Active Seat Mount technology, presented in this paper, was developed to reduce the whole-body vibration of the helicopter aircrew through active cancellation of the N/rev vibration peaks related to the helicopter main rotor speed. The latest development of the Active Seat Mount technology including structural redesign for integration into the helicopter rear cabin, extensive tests of human occupants on the shaker table and flight tests on the NRC Bell-412 helicopter are described in detail. The shaker and flight test results demonstrated that the redesigned Active Seat Mount achieved significant reduction of the occupant WBV levels at the bottom seat cushion interface per ISO2631-1 metrics and also reduced the occupant head vibrations simultaneously. The promising results show that the Active Seat Mount is capable of improving the ride quality of the Bell-412 helicopter in representative flight conditions and mitigating adverse long-term health issues of the helicopter pilots.

Key words: helicopter vibration, Active Seat Mount, aircrew whole-body vibration, adaptive vibration control, flight testing, Bell-412 helicopter

1 INTRODUCTION

Although the helicopter is a versatile aerial platform for military and civilian applications, its ride quality is generally poor mainly due to the harsh vibration and noise environment within the cabin. The helicopter fuselage vibration is excited by the rotor aerodynamics and inertia loads at N/rev frequencies of the main rotor speed, where N is the number of main rotor blades [1]. During flight, helicopter floor vibration is transmitted from seat frame through seat cushions to the seated aircrew, exposing the aircrew to an environment known as Whole-Body Vibration (WBV). Exposure to high levels of WBV adversely affects ride comfort, leading to reduced operational performance. Long term exposure to high WBV levels contributes to health issues such as lower back pain and neck strain in the helicopter aircrew community, which in turn results in the aircrew losing their flight status [2, 3].

Most helicopters are designed to operate at relatively low main rotor speeds, typically close to 5 Hz. ISO2631-1 standard indicates that the human body responses significantly to the vibration within the low frequency range, dominantly between 0.5 Hz and 80 Hz [4]. In particular, the frequency range between 0.5 and 12 Hz is the most sensitive regime in the human spine direction that introduces significant vibrational effect on the human body. Therefore, the

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ISO2631-1 standard requires the WBV of a seated human to be measured at the seat cushion interfaces. Moreover, this standard also provides detailed technical guidance on the methodologies for WBV measurement and assessment. Note that since the dominant N/rev peaks of the helicopter vibration are typically below 25 Hz, it is very important to control the amplitudes of these peaks in order to effectively reduce the WBV exposure of the helicopter aircrew during flight operations.

The mitigation of helicopter aircrew WBV typically falls into three categories, namely passive, semi-active and active control [5, 6]. Passive methods such as anti-vibration seat cushions are generally effective in reducing vibrations at high frequencies, but relatively ineffective for low frequency vibrations that are most important for helicopter applications. In addition to compromising seat crashworthiness requirements, the impedance properties of the seat cushions are difficult to optimize for varied aircrew and flight conditions, which can sometimes lead to amplification of low frequency N/rev peaks. Therefore, relying solely on passive methods is not generally sufficient to mitigate the aircrew WBV exposure.

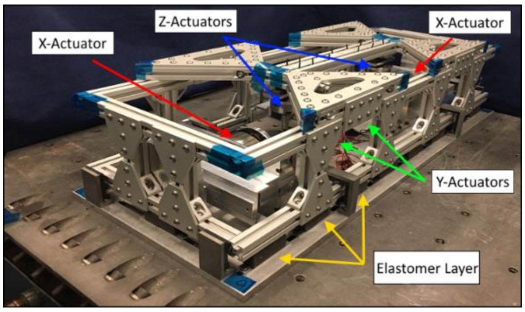
Semi-active methods have also been explored by some researchers for helicopter aircrew vibration mitigation. These techniques rely on functional materials or variable structures whereby the structural stiffness and damping properties can be tuned for more effective energy dissipation. A semi-active helicopter seat suspension design, where magneto-rheological dampers are integrated in the vertical columns of the H-60 pilot seat frame, has demonstrated significant reduction to high frequency vibrations, but the performance in the lower frequency range, specifically the 1 and 2/rev peaks, was degraded [7].

To provide more effective WBV mitigation to the helicopter aircrew, especially for the critical low N/rev frequencies, active control designs for adaptive vibration cancellation have been explored by the National Research Council (NRC) Canada during the past two decades. The active mitigation of helicopter aircrew WBV was explored by Chen et al. [8, 9] using two parallel stacked piezo-stack actuators on a Bell-412 helicopter pilot seat. Under representative Bell-412 vibration profiles, the active seat was able to provide effective vibration reduction at major N/rev peaks except at the 5.4Hz 1/rev. This was mainly due to the fact that the piezo-stack actuators cannot provide sufficient stroke required for reduction of the 1/rev vibration. Further development of the technology using miniature electro-magnetic actuators achieved simultaneous WBV reduction at major N/rev peaks including the 1/rev on the shaker table [10-12]. These studies demonstrated that an active control solution is effective in the mitigation of WBV for helicopter aircrew.

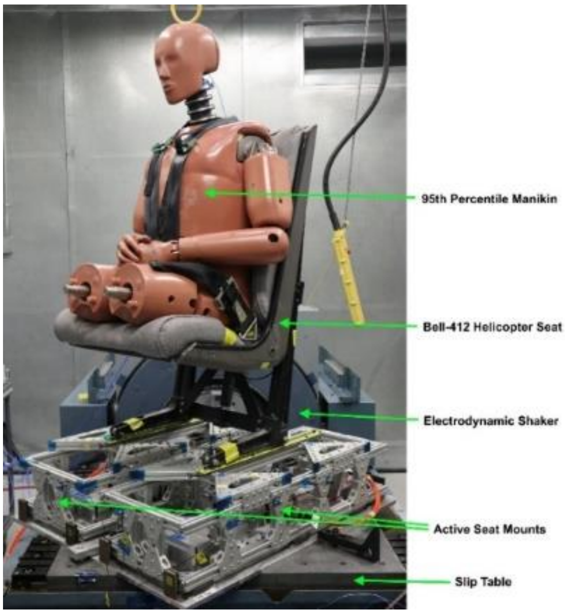
Inspired by these progresses, NRC further improved the Active Seat Mount technology to meet stringent airworthiness requirements for integration into the NRC Bell-412 helicopter. Extensive shaker tests of human subjects using a Bell-412 non-armored pilot seat on a human-rated shaker table were performed, and the system was then tested under four selected flight conditions including rotor ground run at 100% nominal rotator (Nr) speed, low altitude hovering, level flights at 100kts and 120kt. This paper presents the details of the design of the flight worthy Active Seat Mount system integrated into the NRC Bell-412 helicopter. The results from the human-rated shaker tests are also discussed. Furthermore, preliminary flight test results in ground run at 100% Nr and level flight at 100kts are presented. Comprehensive shaker and flight test results have convincingly demonstrated that the Active Seat Mount technology was able to significantly reduce the WBV levels of the helicopter pilots on the Bell-412 non-armored pilot seat in representative flight conditions to enhance the ride quality of the Bell-412 helicopter, and also has the potential to reduce adverse long-term health issues to the aircrew.

2. PROTOTYPE ACTIVE SEAT MOUNT DESIGN AND TESTS

The proof-of-concept multi-axis Active Seat Mount was designed to retrofit the Bell-412 helicopter non-armored pilot seat in initial studies. Since the Bell-412 pilot seat has two short horizontal supports that are locked to the floor rails of the helicopter cockpit, the prototype seat mount design introduced two identical Active Seat Mount assemblies. The Active Seat Mount assemblies were designed for installation between the Bell-412 pilot seat frame and the helicopter floor rails, where each short horizontal support is attached to the upper frame of each seat mount assembly that functioned as a vibration stabilized platform. This arrangement was expected to minimize the impact on the crashworthiness certification of the Bell-412 pilot seat, and also facilitated integration with other existing helicopter seat designs [10, 11]. One of the early prototype assemblies is shown in Figure 1a, along with the installation of a Bell-412 non-armored pilot seat on the prototype active seat system is shown in Figure 1b.



a. Active Seat Mount assembly



b. Active Seat Mount and Bell-412 pilot seat

Figure 1: prototype multi-axis Active Seat Mount

The prototype Active Seat Mount assembly was designed with two parallel load-carrying paths. The upper frame of the Active Seat Mount assembly was attached to the seat mount base frame through two structural elements, and the base frame was fastened directly to the seat rails on the helicopter floor:(1) the upper frame structure was attached to the seat mount base frame through a soft elastomer support which provided the baseline damping and stiffness for passive support of the pilot seat;(2) two miniature actuators were connected between the upper frame and the seat mount base to provide vertical vibration control capability in parallel. Similar arrangements were designed in the X and Y directions.

The proof-of-concept Active Seat Mount has been tested extensively for feasibility and performance assessment. Three Hybrid III mannequins have been tested on the Bell-412 pilot seat using a large Unholtz-Dickie mechanical shaker table with representative Bell-412 floor vibration profiles as the base excitation in the X, Y and Z directions, one direction at a time. A Filtered-x LMS algorithm was used to control the miniature actuators to suppress the vibrations at the Bell-412 pilot seat bottom cushion interface, per metrics of the ISO2631-1 standard. In these cases, an accelerometer attached to the shaker table was used to measure the floor vibration input and used as the reference signal.

Extensive shaker tests of the prototype multi-axis Active Seat Mount system showed that it was able to reduce the vibration experienced by the manikins simultaneously at the head and body locations in the X, Y and Z directions, with the dominant 1/rev and 4/rev peaks reduced by 70-90%. Moreover, the performance was consistent across all three manikins, which demonstrated that the prototype multi-axis seat mount system was not only capable of reducing vibrations experienced by the pilot in single directions, but also capable of reducing vibrations in multiple directions. Therefore, the Active Seat Mount system has the potential to suppress the whole-body vibration exposure of the helicopter aircrew to enhance their ride experience and improve their health protection in helicopter flight conditions [10].

3. DESIGN IMPROVEMENTS OF ACTIVE SEAT MOUNT FOR FLIGHT TESTING

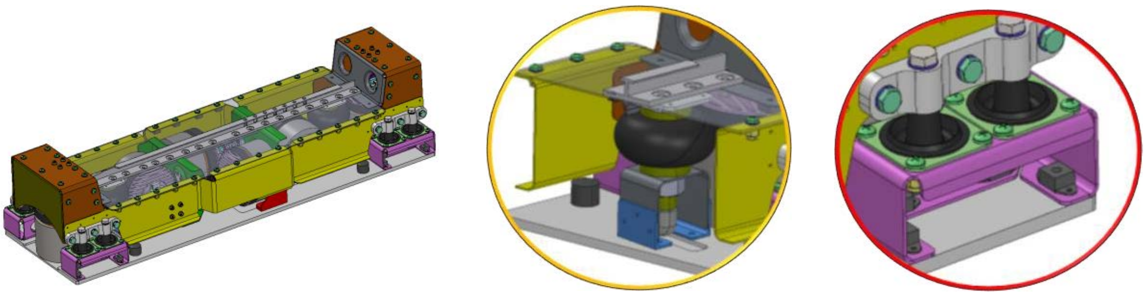
Evidenced by the promising performance of the prototype Active Seat Mount system, it was decided to further explore the potential of the Active Seat Mount technology through flight testing on the NRC Bell-412 helicopter testing platform using human or manikin occupants at representative flight conditions. Test conditions would include the helicopter engine ground run, hovering in or out of ground effect, as well as level flights at various representative speed of the vehicle.

To achieve this objective, the two Active Seat Mount assemblies required installation in the Bell-412 helicopter cabin, while meeting stringent airworthiness requirements and maintaining the full functionality of the prototype Active Seat Mount design. Therefore, modifications of the prototype design were required. It is important to note that the modifications focused mainly on the installation of the Active Seat Mount assemblies to fit within the NRC Bell-412 helicopter rear cabin for flight demonstration purposes, and it is reasonable to expect that additional structural modifications and further optimizations are required before the technology ready for commercial product development.

Since the Bell-412 helicopter pilot seat was already designed and certified to meet crashworthiness requirements, the Active Seat Mount design had to be reviewed critically to maintain this status. Through consultation with airworthiness engineers, it was determined that Active Seat Mount structure has to be evaluated as part of the airframe of the NRC Bell-412 helicopter test platform, and therefore all designs and changes are required to meet applicable FAA strength criteria for helicopter airframe structures. However, installation of the Bell-412 non-armored pilot seat on top of the Active Seat Mount system does not alter the airworthiness or the crashworthiness status of the seat as there is no change to the its design or usage.

The first structural requirement was to reduce the weight and dimension of the prototype Active Seat Mount in order to fit into the limited space of the Bell-412 helicopter cabin. The candidate installation locations were the cockpit or the rear cabin. Specifically, the height of the prototype Active Seat Mount needed to be reduced in order for human occupants or anthropomorphic test device (ATD) to be seated in the Bell-412 helicopter cabin. The prototype design involved two actuators for vertical vibration control, which were positioned in the middle of the Active Seat Mount assembly, and significantly increased the height of the Active Seat Mount frame. Moreover, based on experimental results of the prototype design, the actuator rated force capacity in the vertical direction was required to control authority of high vibration levels of the helicopter at high speed flight and ground run conditions. In the redesign of the Active Seat Mount, two larger and more powerful actuators were relocated to the two ends of the Active Seat Mount assembly to allow for the centre top frame of the mount assembly to be lowered significantly in height. These structural modifications reduced the height of the Active Seat Mount assembly by 127 mm (5”) at the seat rail sections, which provided the required vertical space for the Bell-412 non-armored pilot seat frame and occupant wearing a flight helmet to be fitted into the NRC Bell-412 rear cabin with adequate head room clearance.

The second structural requirement was centred on the fact that the prototype Active Seat Mount assembly was made of segmented aluminum bars for proof-of-concept demonstration purposes in order to reduce fabrication cost and lead time. Unfortunately, this design was not able to meet airworthiness requirements for aircraft flight testing. Therefore, the aluminum bar frames were replaced with 2024-T3 aluminum sheet metal structural components. The high strength sheet metal structural design was shown to achieve greater strength and stiffness while reducing weight by 16 lbs.



a. seat mount assembly   b. vertical tunable isolator   c. rubber mounts

Figure 2: redesigned Active Seat Mount assembly

To avoid excessive displacement of the Bell-412 pilot seat and occupant during aircraft flight maneuvers, the stiffness of the prototype Active Seat Mount was redesigned in all three orthogonal directions. Two tunable stiffness vibration isolators were included to replace the original soft elastomeric supporting elements in the vertical direction. These tunable isolators not only provided the required passive stiffness and damping for support in the vertical direction, but also offset the compressive displacement due to the static weight of the Bell-412 pilot seat and occupant. Additionally, the soft elastomeric supporting elements in the X and Y directions were also replaced with multiplane rubber mounts. These off-the-shelf rubber mounts were expected to provide predictable and reliable vibration isolation to limit the displacement in all three directions. The Active Seat Mount assembly and the new isolators are schematically shown in Figure 2.

These structural modifications reduced the system’s height and weight significantly, with the weight of each assembly reduced from 124 lbs to 51 lbs. The improved Active Seat Mount became sufficiently compact and was able to fit into the NRC Bell-412 helicopter rear cabin for flight testing and demonstration purposes. The Active Seat Mount system installed with the Bell-412 non-armored pilot seat frame inside the NRC Bell-412 rear cabin is shown in Figure 3a.

a. Active Seat Mount assembly b. Active Seat Mount tested on shaker table

Figure 3: Active Seat Mount and Bell-412 pilot seat installations

Aerospace airworthiness authority of NRC Flight Research Laboratory performed an independent review of the improved Active Seat Mount structure, and confirmed that the crashworthiness compliance status of Bell-412 seat frame was not altered by installing it on top of the new Active Seat Mount system. The design of Active Seat Mount structure was shown to satisfy applicable airworthiness requirements regarding the integrity of Bell-412 airframe through finite element analysis. In addition, the control computer and other electronic equipment were powered and tested using the NRC Bell-412 helicopter project power supply, and shown to satisfy applicable safety and functionality requirements for flight testing. Therefore, the improved Active Seat Mount was approved for installation on the NRC Bell-412 helicopter test platform for experimental flight test and demonstration purposes.

4. AIRCREW WBV MITIGATION ON THE SHAKER TABLE

Before flight testing on the NRC Bell-412 helicopter, validation testing of the improved Active Seat Mount system was performed on a human-rated shaker table using human occupants. Bell-412 floor vibration profiles measured during actual flights were used as the shaker vibration profiles in the laboratory, with the approval of NRC Research Ethics Board since testing was being performed using human subjects.

The human-rated shaker table was designed to provide simulated vibration excitations in the vertical direction only. The improved Active Seat Mount was fastened to a baseplate matching the Bell-412 floor interface pattern, and then installed on the shaker table. A Bell-412 non-armored pilot seat was mounted on the upper frames of the Active Seat Mount assembly through two Bell-412 floor rails. A 178 cm tall male volunteer weighing 180lbs was seated on the Bell-412 pilot seat as the occupant, and secured using a four-point pilot seat harness. This human subject closely represented a 50th percentile male per US anthropometric data. The shaker test configuration is shown in Figure 3b.

The shaker table provided a statistically stationary vibration input to excite the Active Seat Mount assemblies vertically. The simulated vibration profile, which was derived from Bell-412 floor vibration measurements, included eight N/rev harmonic peaks each scaled to match with the Bell-412 floor vibration spectrum at 120kts. In addition, a low-level random vibration between 3 and 50Hz was superimposed to simulate broadband aerodynamic excitations.

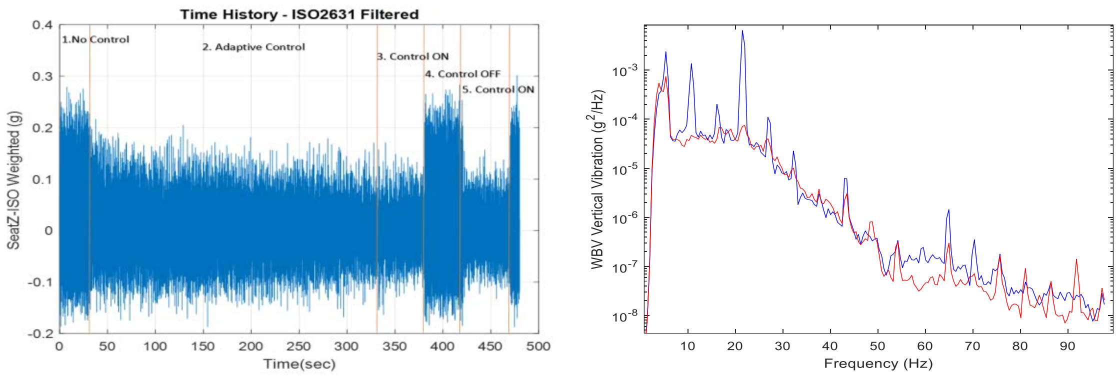
Closed-loop tests have been performed to reduce the whole-body vibrations per metrics suggested in ISO2631-1 standard. First, the WBV responses of the human subject on the Bell-412 seat were recorded and used as the baseline parameters. Next, the Filtered-x Least Mean Square (FxLMS) adaptive controller was activated to control the Active Seat Mount assembly in the vertical direction to reduce the WBV of the occupant. The vibration responses of the occupant and Active Seat Mount system were monitored and recorded throughout the experiment. When the controller converged, the WBV levels of the occupant were compared with the baseline parameters to evaluate the WBV mitigation performance.

4.1 WBV Vibration at Seat Cushion Interface

The vibrations measured at the interfaces between the seat cushions and the human body were frequency weighted using the Wk factor defined in ISO2631-1:1997 and then used as the metrics to determine the occupant WBV exposure levels. Test result of the 50th percentile male subject, including the time history of the Wk-weighted WBV at the bottom seat cushion interface, is shown in Figure 4. The entire duration of the test in Figure 4 was 480 seconds, which followed the below sequence: 1. during the first 30 seconds, the occupant experienced the vertical WBV level without control; 2. the actuator was then powered by the FxLMS controller starting from 30s and adaptation of the controller terminated at 330s; 3. next, the converged adaptive controller stopped the adaptation but maintained control between 330s and 380s; 4. the control voltage was then stopped between 380s and 420s; 5. the control voltage was activated again at 420s and stopped at 470s; 6. finally, the controller was disconnected at 480s.

When the Active Seat Mount was not activated, it was clearly shown that the human occupant was subjected to relatively high WBV levels, and the time history also showed unsymmetric vibration which may be related to the periodical N/rev harmonic excitations from the shaker table. Based on ISO2631-1, the ISO Wk-weighted rms level of the vertical vibration was 0.786 m/s^2, and the ride comfort level was qualitatively rated as “Fairly Uncomfortable”. Based on the health guidance in ISO2631-1, the permitted daily exposure time was 1.6 hrs.

Despite running at a relatively conservative convergence rate, the FxLMS controller was able to quickly reduce the WBV vibration and converged within 20 seconds by adaptively suppressing the dominant N/rev peaks, which resulted in significant reduction of the Wk-weighted WBV vibration. By evaluating the response between 330 and 380th seconds, the Wk-weighted rms WBV level decreased to 0.43 m/s^2, and the ride comfort level was qualitatively rated as “A Little Uncomfortable”. Per ISO standard, the WBV level was reduced by 45.2%, extending the daily permitted exposure time to 18.4 hrs, which effectively eliminated the daily exposure time limit for this simulated flight condition.



a. time trace of vertical vibration b. spectral plot of Wk weighted vibration

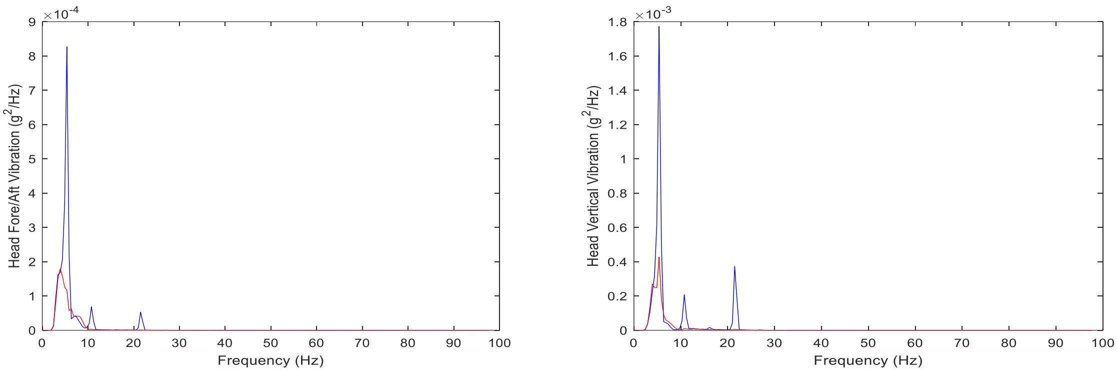
Figure 4: vertical vibration level at the occupant and seat cushion interface

Spectral analysis of the ISO-weighted WBV for the “No Control” and “Controlled” segments is shown in Figure 4b. It was clearly shown that the dominant WBV peaks including 1/rev, 2/rev and 4/rev were effectively suppressed by the Active Seat Mount. In particular, the amplitudes of the 1, 2 and 4/rev peaks were reduced by 68.7%, 96.5% and 98.9%, respectively. There was no significant control spillover within the frequency range below 80Hz, indicating that the FxLMS controller was effective and robust in the control of the Active Seat Mount on the human-rated shaker table.

4.2 Aircrew Head Vibration Evaluation

Besides the WBV levels, the vibration levels of the occupant head were also evaluated. The head vibrations were measured by a tri-axial accelerometer bonded to the top of the HGU-56P helicopter flight helmet worn by the occupant. Spectral analysis of the occupant's head vibration is shown in Figure 5.

The plots indicated that human biodynamics was critical in the transmission of vibration from the seat cushion interfaces to the occupant head. Different from the vibration at the bottom seat cushion interface in Figure 4b, which was dominated by multiple N/rev peaks, it was clearly shown that the occupant head vibration was dominated by a single 1/rev peak in both fore/aft and vertical directions. Evident in ISO2631-1 for the Wk-weighting factor, the human spine biodynamics introduces significant amplification between 5 and 8Hz. Coupled with the 1/rev frequency of the Bell-412 main rotor speed at 5.4Hz, the occupant head vibration showed a distinctively high peak at the 1/rev frequency. Compared to the fore/aft direction, the vertical vibration level was higher although both were characterized by a dominant 1/rev peak. The overall rms vibration was 0.33 in the fore/aft direction and 0.47 m/s^2 in the vertical direction. Since only vertical excitation is provided on the shaker table, the head vibration results indicated that significant human biodynamic coupling existed in the head fore/aft and vertical directions.



a. fore/aft vibration b. vertical vibration

Figure 5: occupant head vibration on the shaker table

With the adaptive control of the Active Seat Mount in the vertical direction, not only were WBV vibration levels at the bottom seat cushion interface reduced, but the occupant head vibration levels were also reduced simultaneously. As shown in Figure 5b, the amplitude of 1/rev peak was reduced by 85.9% for fore/aft and 75.9% for vertical direction. As a result, the overall rms vibration level was reduced by 27.6% in the fore/aft and 35.9% in the vertical direction, respectively.

The shaker test results clearly demonstrated that the active helicopter seat mount system was able to reduce the occupant WBV at the bottom seat cushion interface to improve the ride quality, and also reduced the head vibrations simultaneously. The enhanced ride comfort and head/helmet stabilization would improve the aircrew performance by reducing their neck muscle fatigue, increasing visual clarity of the instrument panel and enhancing situational awareness in flight operations.

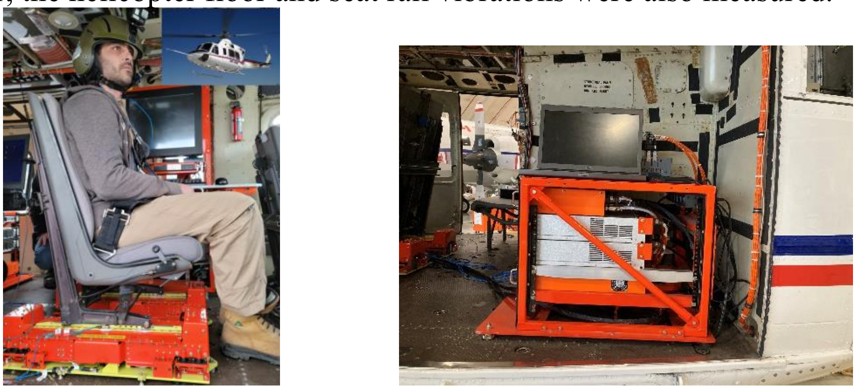
5. AIRCREW WBV MITIGATION THROUGH FLIGHT DEMONSTRATION

5.1 Flight Test Configuration

Satisfied with the Active Seat Mount performance on the human-rated shaker table, the Active Seat Mount system and related control equipment were installed in the rear cabin of the NRC Bell-412 helicopter for flight test and assessment. A 50th percentile healthy male occupant was seated on a Bell-412 non-armored pilot seat and secured using a standard 4-point harness; the test configuration is shown in Figure 6.

Compared to the human-rated shaker table, it is important to note that the Bell-412 rear cabin floor structure was relatively flexible in stiffness, which leads to differences in the dynamics of the two test configurations. In addition, as opposed to the statistically stationary vibration excitations on the shaker table, the Bell-412 helicopter floor vibration spectrum and level are expected to vary significantly due to many factors including weather conditions, ground effect and pilot operations in flight conditions.

A total of 4 representative flight conditions were tested in this flight test campaign, including: Engine Ground Run at 100% Nr; Hovering within ground effect; and Level Flight at 100kts and 120kts. At each condition, only the vertical actuators were activated with the objective to reduce the aircrew WBV levels at the bottom seat cushion interface. The aircrew head vibrations were measured by a tri-axial accelerometer installed on the HGU-56P flight helmet. Moreover, the helicopter floor and seat rail vibrations were also measured.



a. occupied Active Seat Mount b. control equipment

Figure 6: Active Seat Mount configuration in flight demonstration

Three flight trials were completed on the 15th and 16th of March 2023. Restricted by the unfavorable gust and weather conditions (snowfall), only one flight was completed for the 4 flight conditions, and the other two flights were only completed for the Engine Ground Run at 100% Nr and Hovering within ground effect conditions.

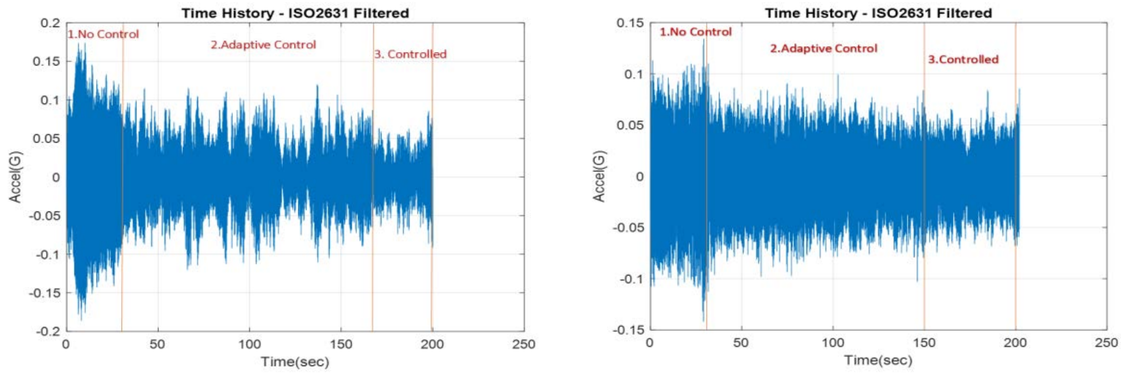
5.2 Preliminary Flight Test results

The control sequence and procedure were similar to that used in shaker testing. In each flight test segment, the Active Seat Mount was not activated at the beginning, and the uncontrolled test segment was maintained for 30 seconds. Then the vertical actuators of the Active Seat Mount were activated to suppress the occupant vibration level at the bottom seat cushion interface. The vibration levels of the helicopter floor, seat rail, seat cushion interface and the flight helmet locations were measured continuously.

Preliminary analysis has been performed to evaluate the functionality of the active helicopter seat mount during the flight tests. The time trace of the occupant vertical WBV at the bottom seat cushion interface during Engine Ground Run at 100%Nr is shown in Figure 7a.

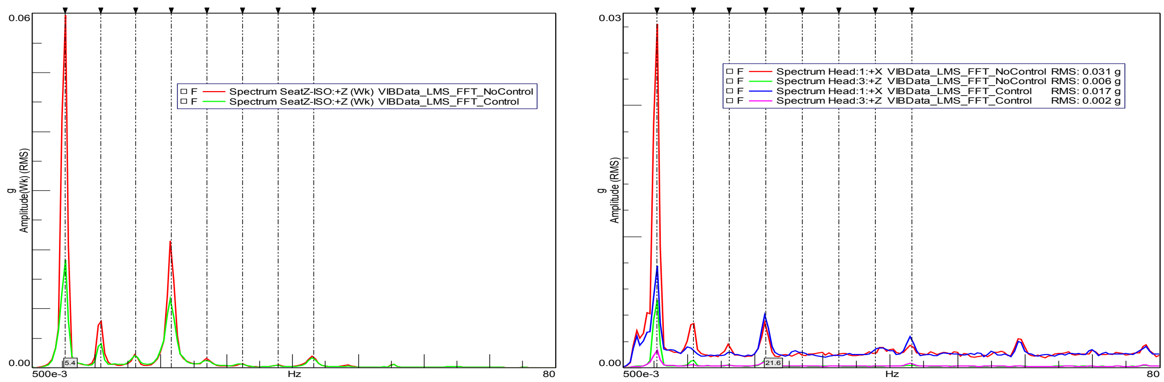
It was evident that during the engine ground run, the Bell-412 helicopter experienced relatively high level of unsteady vibrations for the first 30 seconds due to the strong and gusty side wind. The Wk-weighted WBV at the bottom seat cushion interface was 0.687m/s^2, which was qualitatively rated as “Fairly Uncomfortable”, and the permitted daily exposure time was 2.82hrs per ISO2631-1 standard. When the Active Seat Mount was activated, the occupant vibration reduced quickly and stayed relatively stable. By calculating the vibration levels between 160s and 200s, the Wk-weighted WBV was 0.260 m/s^2, representing a significant reduction of 62.2%. The ride comfort level was qualitatively rated as “Not Uncomfortable”, and the permitted daily exposure time became “unlimited”.

Spectral plots of the occupant WBV are shown in Figure 8a. Similar to the shaker test results, it was shown that the dominant WBV peaks were the 1/rev, 2/rev and 4/rev. The active seat helicopter mount effectively reduced these dominant peaks simultaneously by 69.4%, 49.3% and 45.3%, respectively. Note that there was no significant control spillover occurred below 80Hz for human WBV assessment.



a. Engine ground run at 100%Nr b. level flight at 100kts

Figure 7: Wk weighted vertical vibration at the bottom seat cushion interface



a. seat bottom cushion vibration b. helmet vibration

Figure 8: spectral plot of vertical vibration at bottom seat cushion interface (Engine Ground Run at 100%Nr)

The spectral plots of the occupant flight helmet vibrations are shown in Figure 8b. Due to the occupant biodynamics, the occupant head vibration was dominated by 1/rev at 5.4Hz in both the fore/aft and vertical directions, with the fore/aft vibration level 520% higher than that in the vertical direction. This indicated that floor vibration in the fore/aft direction may have played a dominant role than the vertical direction in the excitation of aircrew head vibrations, which was not be accurately reflected the human shaker table test results. Therefore, the effect of human biodynamics on the helicopter aircrew head vibrations should be further investigated.

Nevertheless, the reduction of the occupant WBV at the bottom seat cushion interface did result in effective and simultaneous mitigation of the occupant head vibration by 45.2% in the fore/aft direction and 66.7% in the vertical direction.

The occupant WBV in level flight conditions were also significantly reduced, and the time history of the Wk-weighted WBV at the bottom seat cushion interface at 100kts level flight condition is shown in Figure 7b. Detailed analysis of the flight test results in all of the tested flight conditions is currently being performed.

Preliminary analysis of flight test results of the 50th male occupant on the NRC Bell-412 helicopter in four representative flight conditions verified that the NRC-patented Active Seat Mount technology performed very well in general. Through adaptive suppression of the dominant multiple N/rev vibration peaks at the bottom seat cushion interface, it achieved significant and simultaneous reductions of the occupant WBV and the head vibrations, and demonstrated consistent performance in tested flight conditions. The ISO weighted WBV levels suggested that occupant ride comfort was improved from “Fairly Uncomfortable” to “not Uncomfortable”, and the daily exposure time was effectively extended from 2.8 hrs to “Unlimited” in the Ground Run condition, an impressive improvement over the current Bell-412 pilot seat.

6. CONCLUSION

The redesign and flight testing of the NRC-patented Active Seat Mount technology to reduce aircrew whole-body vibration levels on the NRC Bell-412 helicopter is presented. The flight worthy Active Helicopter Seat Mount Assembly was integrated into the Bell-412 rear cabin with a Bell-412 non-armored pilot seat installed on top of it. The WBV mitigation performance was evaluated using human subjects through extensive tests on a human-rated shaker table and three flight tests on the NRC Bell-412 helicopter.

Through adaptive suppression of multiple major N/rev vibration peaks at the bottom seat cushion interface, the NRC-patented Active Seat Mount system was successful in reducing the occupant WBV as well as head vibrations simultaneously in accordance with ISO 2631-1 metrics. The Active Seat Mount performed reliably and consistently for all of the human subjects in all of the four flight test conditions. The extensive shaker and preliminary flight test results on the NRC Bell-412 helicopter convincingly demonstrated that the Active Seat Mount technology was able to significantly enhance the ride quality of helicopter pilot seats, mitigate adverse WBV effects on the pilot and improve their operational performance in realistic flight conditions.

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