Simulation for Squat Exercise of an Active Controlled Vibration Isolation and Stabilization System for Astronaut's Exercise Platform

Ziraguen O. Williams, Shield B. Lin, Fouad N. Matari, Leslie J. Quiocho

***Abstract*—**In a task to assist NASA in analyzing the dynamic forces caused by operational countermeasures of an astronaut's exercise platform impacting the spacecraft, feedback delay and signal noise were added to a simulation model of an active controlled vibration isolation and stabilization system to regulate the movement of the exercise platform. Two additional simulation tools used in this study were Trick and MBDyn, software simulation environments developed at the NASA Johnson Space Center. Simulation results obtained from these three tools were very similar. All simulation results support the hypothesis that an active controlled vibration isolation and stabilization system outperforms a passive controlled system even with the addition of feedback delay and signal noise to the active controlled system. In this paper, squat exercise was used in creating excited force to the simulation model. The exciter force from squat exercise was calculated from motion capture of an exerciser. The simulation results demonstrate much greater transmitted force reduction in the active controlled system than the passive controlled system.

***Keywords*—**Astronaut, counterweight, stabilization, vibration.

I. Introduction

THE microgravity environment that astronauts encounter while in space poses a unique health challenge. Since humans have evolved on earth, our bodies are used to counteracting gravity to make any sort of movement. In a microgravity environment, astronauts have little resistance when moving about the spacecraft. It is this lack of resistance that leads to a loss in muscle and bone mass. We can see this type of atrophy here on Earth in bedridden hospital patients; prolonged rest leads to muscle loss. Even with exercise, astronauts can see changes of -13% to -17% in muscle mass during long-term spaceflight [1].

Exercise allows muscles and bones to experience resistance which is key for new muscle and bone formation. Since a deficit is undesirable, exercise is mandatory for astronauts. However, exercise in a spacecraft generates loads and vibrations, that if left uncompensated for, end up being transmitted to the spacecraft. This can create all sorts of problems such as damage to microgravity-sensitive equipment and damage to the spacecraft coming from either impact or hitting a resonant frequency. To counter these effects, a Vibration Isolation and Stabilization (VIS) system is designed to minimize the transmitted forces [2]-[4]. Back squat exercise is one of the common exercises that astronauts do in space as illustrated in a photo shown in Fig. 1 [5].

Fig. 1 A Squat Exercise in Space [5]

The main objective of this study was to build simulation programs that would aid in evaluating applications of control theory to a single degree of freedom (DOF) VIS system. Multiple simulation environments, MATLAB/Simulink, Trick, and MBDyn, were used to verify the simulation model. Comparison of simulation results between pairs of environments was studied. Realistic behavior such as signal noise and feedback delay were considered and modeled as well as using life-like masses and input forces.

The three simulation environments used in this study are described further in the following:

(1) Simulink simulation environment: Simulink was created from MathWorks that allows users to use a visual block diagram-based environment to quickly test systems [6]. A lumped-sum model of a single DOF VIS system was simulated by Lin et al. [7]. This study would build upon the model and add more realistic conditions, such as feedback delay, signal noise, use of real excited forces and full-scale system parameters.
(2) Trick simulation environment: Trick is a physics-based simulation environment developed at NASA Johnson Space Center (JSC) [8]. It builds executable simulations with a common architecture using user supplied model

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files. This simulation environment allows users to focus on developing in their specific area of study by handling scheduling of jobs, input files, data recording, data plotting, and math functions like integrations. Trick does offer a standard library of functions that users can use to implement things like Gaussian distributions and Monte Carlo simulations [9].

(3) MBDyn simulation environment: MBDyn is an advanced multibody dynamics math modeling package that is used in conjunction with the Trick simulation environment. The addition of the articulated multibody capabilities makes MBDyn very useful. Bodies are linked to each other using linear or rotational linkages. These bodies have what are called in-board nodes, out-board nodes, and center of masses. Bodies are then set to free or fixed in all six degrees of freedom, depending on the needs of the person using the program. The user must give the bodies properties like mass, dimensions, and inertia. All these combined allow the program to calculate the position, velocity, and acceleration of the bodies along with the forces and torques acting on the bodies which is useful for all sorts of analysis. This package can be used in this case to simulate multiple rigid bodies [10].

II. Description of VIS System

VIS systems apply control methods to minimize vibrations and stabilize the plant. Common components used in a VIS include spring, damper, actuator, counter-mass, inertial mass, and sensor. A VIS can be used in scenarios that need vibration isolation or stabilization such as reducing motion blur in photography, keeping buildings safe during earthquakes, and exercise machines in space. In each application, the control unit is the VIS and the plant is the system being acted on. Previous studies have been performed studying VIS systems in spacecraft [2]-[4], [7]. These studies have used passive and active control systems. Some of the authors suggest the use of linear actuators and a Proportional-Integral-Derivative (PID) controller for the active control system.

The proposed model will follow the framework of a one-dimensional VIS system developed previously [7]. The passive system would be controlled by springs and dampers. The active controlled system will have weak springs and damper, and a linear actuator with a throw mass attached to it to counteract the input forces. First, the Simulink simulation will be converted to a Trick-based simulation. The same inputs and system parameters will be used to make sure the two simulation environments have good agreement with the results. Once the Trick simulation has been verified then a rigid multibody model can be created using MBDyn. This allows the lumped-sum model from Trick to be compared with the multibody model from MBDyn. The proposed control methods are a passive control system and an active control system that has passive elements to connect it to the spacecraft. Two controllers can be used to control the linear actuator in the active control system. These controllers are a traditional PID controller and a newer Piecewise-Linear-Integral-Derivative (PWLID) controller. The passive control method will be compared to the performance of the two active control methods. The PID was chosen because it is built on a previous study [7]. The PWLID was chosen because it is a form of adaptive control, and it is similar to the PID which requires less additional coding and testing. A low-pass filter is used on both of these controllers.

Realistic behavior would be accomplished by modeling a sensor and incorporating signal noise and delay. The proposed sensor is similar to one that is used for experiments at NASA JSC. The sensor is made by a company called Banner [11]. The model number is: Q4XTULAF100-Q8. Fig. 2 shows an illustration of the sensor that was selected for this study. The sensor has specific accuracy and time delays as stated by the manufacturer. Fig. 3 shows the accuracy graph by distance provided by the manufacturer.

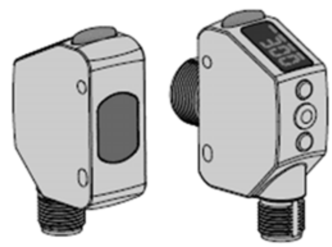

Fig. 2 Laser Sensor Illustration [11]

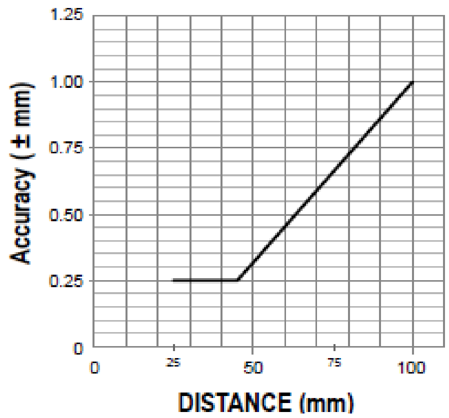

Fig. 3 Laser Sensor Accuracy Graph [11]

Source code must be written to incorporate this sensor's accuracy/noise along with the time-delay it has. Because there are no current data on noise for this model of sensor; statistical noise will be added and modeled as a Gaussian function with 3-sigma of noise based on the accuracy graph provided by the manufacturer. Trick includes a Gaussian distribution function that can be used to model the noise.

To model feedback delay, the time sampling of the laser sensor and the calculation time needed by the computer to run the controllers and sensor will be added up. A worst-case scenario will be assumed for the settings chosen. In order to compensate for integrational drift, the adjusting by envelopes method will be used because it can achieve good results and the implementation is straightforward [12].

III. System Diagram and Equations

Simple diagrams of the VIS were drawn to provide visuals of the mechanics of the system. Fig. 4 is a schematic diagram which represented a system when an astronaut exercises on a platform. Two Free Body Diagrams (FBDs) would be drawn: one is a passive system without a linear actuator and a throw mass, and the other an active system with a linear actuator and a throw mass.

Fig. 4 was used to produce FBDs that could be used to develop the equations of motion. In the FBD for the entire system, the Linear Actuator is fixed on the platform; therefore, the Linear Actuator is considered as a part of the VIS platform and not separately modeled in a single DOF simulation.

Fig. 5 shows the FBD for the passive VIS system. In this FBD the astronaut's mass is rigidly attached to the VIS platform, the total mass, m_t, represents the combined mass of astronaut and the platform. The input force to the system is the excited force by astronaut's exercise, f_{hu}. The platform is attached to the spacecraft via a spring and damper and free to move in the x-axis. We assume that the spacecraft wall is fixed in this simulation model. In the passive system, linear actuator and throw mass are not included.

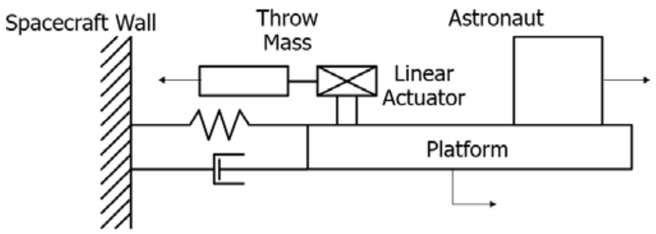

Fig. 4 VIS Schematic Diagram

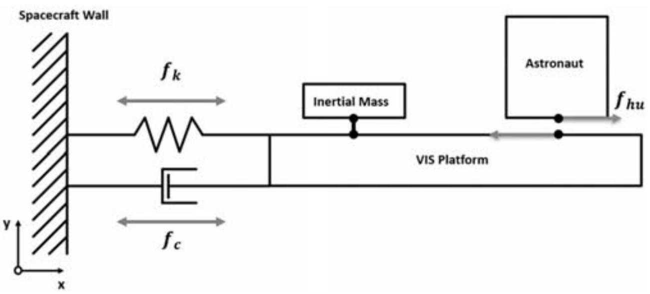

Fig. 5 Passive VIS Free Body Diagram

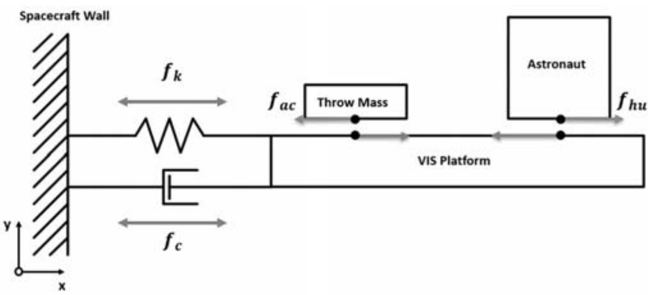

Fig. 6 Active VIS Free Body Diagram

Fig. 6 shows the FBD for the active VIS system. The throw mass and astronaut are free to move in the x-axis and the VIS platform is attached to the spacecraft via a weak spring and damper and free to move in the x-axis. The forces acting on the VIS platform are the excited force by the astronaut's exercise activity, f_{hu}, the reaction forces from the spring and damper, and the force from the linear actuator acting on the platform, f_{ac}. The total mass, m_t, for the active system is the combined mass of astronaut, the platform, linear actuator, and the throw mass.

Equations of motion were developed for both of the FBDs. These equations serve as the mathematical basis of the code for the simulations. The Passive VIS System is governed by the following equations, where $x_1$is the displacement of the VIS platform in horizontal direction, m_t is the total mass of astronaut's mass and the mass of VIS platform, c is the damping coefficient, k is the spring constant, and f_{hu} is the excited force applied to the VIS platform by the astronaut:

Force equation:

$$m_t \cdot \ddot{x}_1 = -c \cdot \dot{x}_1 - k \cdot x_1 + f_{hu}$$

Acceleration:

$$\ddot{x}_1 = \frac{-c \cdot \dot{x}_1 - k \cdot x_1 + f_{hu}}{m_t}$$

Velocity:

$$\dot{x}_1 = \int_0^t \ddot{x}_1 \, dt + \dot{x}_o$$

Displacement:

$$x_1 = \int_0^t \dot{x}_1 \, dt + x_o$$

The Active VIS System is governed by:

Force equation:

$$m_t \cdot \ddot{x}_1 = -c \cdot \dot{x}_1 - k \cdot x_1 + f_{ac} + f_{hu}$$

Acceleration:

$$\ddot{x}_1 = \frac{-c \cdot \dot{x}_1 - k \cdot x_1 + f_{ac} + f_{hu}}{m_t}$$

Velocity:

$$\dot{x}_1 = \int_0^t \ddot{x}_1 \, dt + \dot{x}_o$$

Displacement:

$$x_1 = \int_0^t \dot{x}_1 \, dt + x_o$$

The equations of discrete PID controller and PWLID controller are listed in the end of this paragraph. The equations served as the basis of the code used for these controllers. Both controllers use a Low Pass Filter (LPF) on the derivative term. The process used to convert these equations into something the computer can easily read was developed by Toochinda [13].

PID Controller:

$$C(z) = K_p + K_i \cdot T_s \frac{1}{z-1} + K_d \frac{N}{1+N \cdot T_s \frac{1}{z-1}}$$

PWLID Controller:

$$C(z) = \begin{cases} K_1 + K_i \cdot T_s \frac{1}{z-1} + K_d \frac{N}{1+N \cdot T_s \frac{1}{z-1}} & |e| \leq e_o \\ (K_2 + (K_2 - K_1)e_o) + K_i \cdot T_s \frac{1}{z-1} + K_d \frac{N}{1+N \cdot T_s \frac{1}{z-1}} & |e| > e_o \end{cases}$$

IV. Simulation Results and Discussions

The force calculated from squat exercise was used as exciter force to the VIS system. It is labeled as RUN 2 in the simulation runs. Fig. 7 shows two MBDyn simulation plots of the performance of the passive control system when simulating the squat exercise. The displacement of the VIS is shown in (a) and the astronaut displacement is shown in (b) in Fig. 7. The plots show acceptable control of the VIS platform and reasonable displacement of the astronaut based on the expected displacement of an exercise like squats.

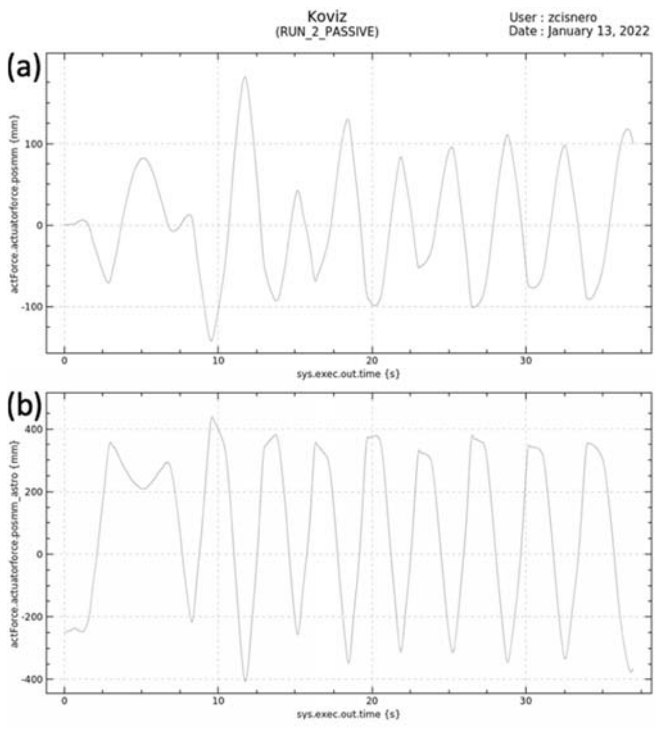

Fig. 7 MBDyn RUN 2: Passive – VIS and Astronaut Displacement (mm)

Fig. 8 shows a MBDyn simulation plot of the performance of the passive control system when simulating the squat exercise. The variable being plotted is the force being transmitted to the spacecraft wall. The plot shows about a 75% or more reduction in forces being transmitted. This shows decent performance from the passive control system.

Fig. 9 shows a Trick and MBDyn co-plot of the performance of the PID active control system with a squat exercise. The variable being plotted is the displacement of the VIS platform. The total displacement of the VIS platform is less than 15 mm. This shows extremely good performance considering the magnitude of the input forces. The plot also shows good agreement between the two simulation models.

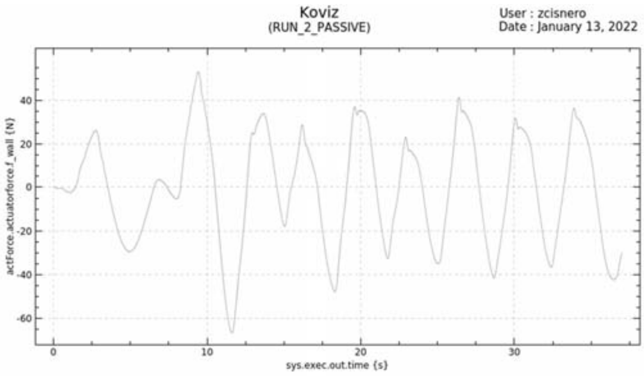

Fig. 8 MBDyn RUN 2: Passive – Transmitted Force to Wall (N)

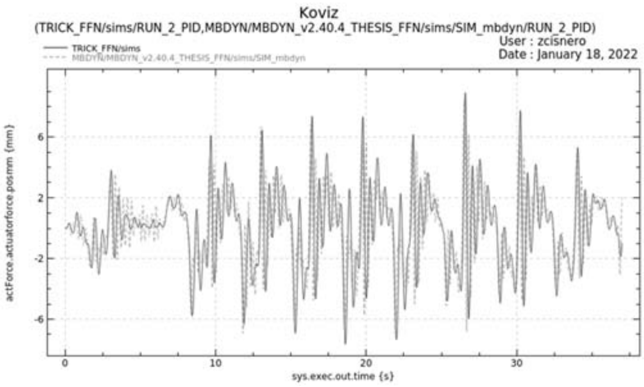

Fig. 9 Trick vs. MBDyn RUN 2: PID – VIS Displacement (mm)

Fig. 10 shows a Trick and MBDyn co-plot of the performance of the PID active control system with a squat exercise. The variable being plotted is the force being transmitted to the spacecraft wall. The max peak-to-peak force is around 3.3 N. The plot shows around a 99% reduction in transmitted force. This shows extremely good performance. The plot shows good agreement between the two simulation models.

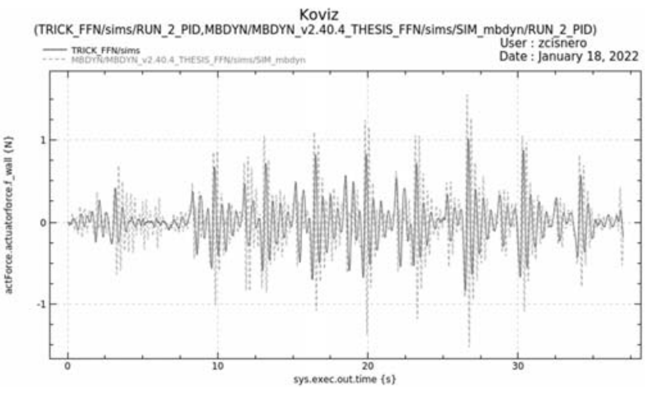

Fig. 10 Trick vs. MBDyn RUN 2: PID – Transmitted Force to Wall (N)

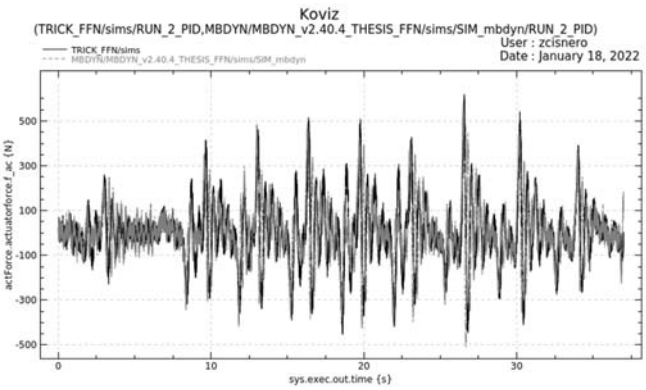

Fig. 11 Trick vs. MBDyn RUN 2: PID – Actuator Force (N)

Fig. 11 shows a Trick and MBDyn co-plot of the performance of the PID active control system with a squat exercise. The variable being plotted is the force being exerted by the linear actuator. This plot shows us the force output performance needed by the linear actuator in order to compensate for the astronaut's exercise. This is important in order to find a linear actuator that can meet this level of performance. The plot also shows good agreement between the two simulation models.

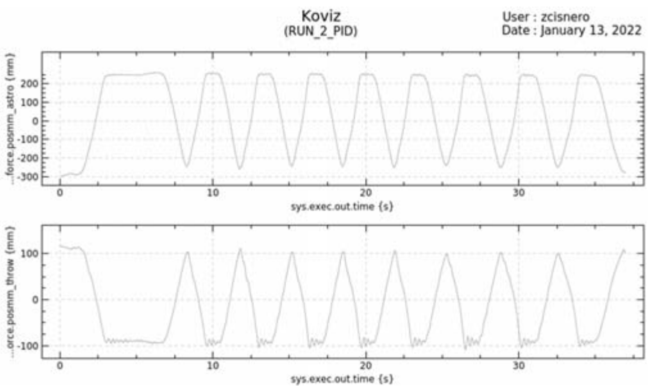

Fig. 12 MBDyn RUN 2: PID – Astronaut and Throw Mass Displacement (mm)

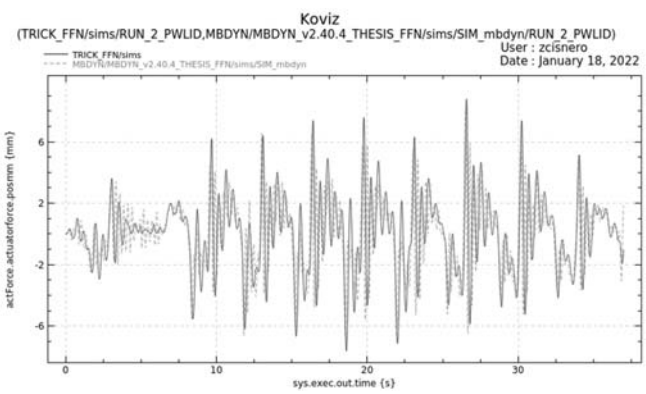

Fig. 13 Trick vs. MBDyn RUN 2: PWLID – VIS Displacement (mm)

Fig. 12 shows MBDyn plots of the astronaut and throw mass displacement for the squat exercise. The plot shows reasonable displacement for both masses. This magnitude of displacement would be possible within the volume of a spacecraft like the ISS. It is important that we look at these displacements so that large displacements do not exceed given volumetric constraints.

Fig. 13 shows a Trick and MBDyn co-plot of the performance of the PWLID active control system with a squat exercise. The variable being plotted is the displacement of the VIS platform. Similar to the PID controller, the total displacement of the VIS platform is less than 15 mm. This shows extremely good performance considering the magnitude of the input forces. The plot shows good agreement between the two simulation models.

Fig. 14 shows a Trick and MBDyn co-plot of the performance of the PWLID active control system with a squat exercise. The variable being plotted is the force being transmitted to the spacecraft wall. The max peak-to-peak force is around 3.3 N. The plot shows around a 99% reduction in transmitted force. This shows extremely good performance. The plot also shows good agreement between the two simulation models.

Fig. 15 shows a Trick and MBDyn co-plot of the performance of the PWLID active control system with a squat exercise. The variable being plotted is the force being exerted by the linear actuator. The plot also shows good agreement between the two simulation models. The force from the actuator ranges from around 700 N to -400 N. An appropriately sized actuator would need to be found that can exert these magnitudes of forces.

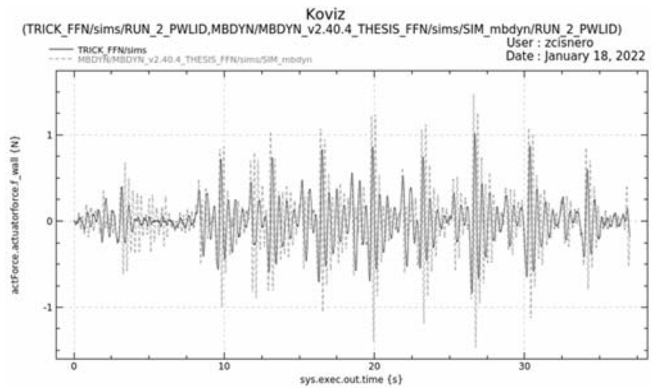

Fig. 14 Trick vs. MBDyn RUN 2: PWLID – Transmitted Force to Wall (N)

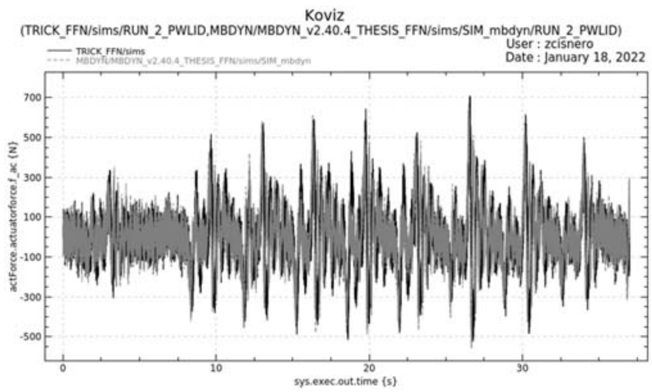

Fig. 15 Trick vs. MBDyn RUN 2: PWLID – Actuator Force (N)

Fig. 16 shows a MBDyn co-plot of the VIS displacement of all three control methods: passive, PID, and PWLID. The plot shows that the active control systems have far better performance than the passive control system. The PID and PWLID controllers have similar performance.

Fig. 17 shows a MBDyn co-plot of the force being transmitted to the spacecraft wall for all three control methods: passive, PID, and PWLID. The plot shows that the active control systems reduced the force transmitted by approximately 96% more than the passive control system. The PID and PWLID controllers have similar performance.

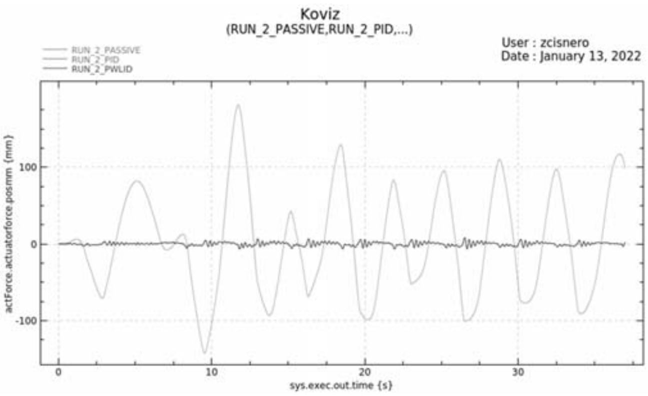

Fig. 16 MBDyn RUN 2: Controls Comparison – VIS Displacement (mm)

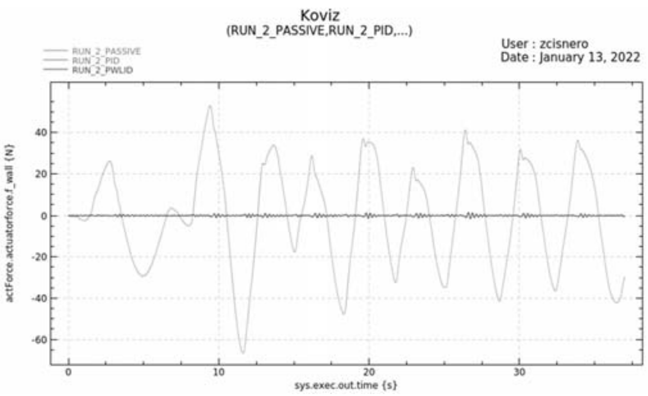

Fig. 17 MBDyn RUN 2: Controls Comparison – Transmitted Force to Wall (N)

V. Conclusions and Recommendations

The purpose of this study was to evaluate the performance of an actively controlled VIS system and compare it to a passively controlled VIS system. This was done using multiple simulation environments in an attempt to ensure that correct assumptions were made and modeling was valid. If the active VIS system performed the same or worse than the passive VIS system, then it would show there is no need for the application of this technology in spacecraft exercise equipment. Conversely, if the active VIS system outperformed the passive VIS system even with the addition of feedback delay and signal noise, then it shows it would merit to continue studying the application of active control VIS systems to exercise devices used by astronauts.

This study provided several outcomes such as a comparison of common simulation environments, the application of a PWLID active control method on VIS systems designed for space applications, and a demonstration that active control can outperform passive control in space-bound VIS systems. The results suggest that active control systems, even when using what could be considered off-the-shelf components, can be very effective at reducing transmission of vibrations and loads while staying within reasonable volume restrictions. More research can be done to support the use of actively controlled VIS systems in spacecraft.

Work on this subject can be expanded on by considering factors like friction, power, heat dissipation, flexible bodies, and by adding additional degrees of freedom. The addition of rotational degrees of freedom would be highly advantageous to the research on this subject since astronauts can and do move rotationally on current ISS exercise devices. If rotational degrees of freedom are added to this work, then actual modeling of the linear actuator would be good since it would produce torques based on its location and offset.

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References

[1] J.R. Bagley, K.A. Murach, and S.W. Trappe, "Microgravity-Induced Fiber Type Shift in Human Skeletal Muscle." Gravitational and Space Biology, Volume 26(1), pp. 34-40, May 2012.

[2] Niebuhr, J.H. and Hagen, R.A., "Development of the vibration isolation system for the advanced resistive exercise device." 2011.

[3] GRODSINSKY, C., and BROWN, G., "Nonintrusive inertial vibration isolation technology for microgravity space experiments," In *28th Aerospace Sciences Meeting*, American Institute of Aeronautics and Astronautics, 1-8.

[4] Yang, B. J., Calise, A., Craig, J., & Whorton, M., "Adaptive control for a microgravity vibration isolation system," in *AIAA guidance, navigation, and control conference and exhibit*, American Institute of Aeronautics and Astronautics, 1-19.

[5] Tech Briefs, International Space Station Advanced Resistive Exercise Device (ARED), https://www.techbriefs.com/component/content/article/tb/pub/briefs/bio-medical/39434.

[6] MATLAB Simulink, written in C/C++ and Java, is a multi-paradigm numerical computing environment and proprietary programming language developed by MathWorks.

[7] S.B. Lin and S. Abdali, "Simulation of Active Controlled Vibration Isolation System for Astronaut's Exercise Platform," International Journal of Mechanical and Mechatronics Engineering, Vol. 15, No.2, pp.107-112, 2021.

[8] J.M. Penn and A.S. Lin, "The Trick Simulation Toolkit: A NASA/Open source Framework for Running Time Based Physics Models," in *AIAA Modeling and Simulation Technologies Conference*, American Institute of Aeronautics and Astronautics, 1-13. 2016.

[9] S. Fennell, "Monte Carlo Tutorial," GitHub pages public repositories website. May 2019.

[10] Huynh, A., Brain, T.A., MacLean, J.R., and Quiocho, L.J., 2016, "Evolution of Flexible Multibody Dynamics for Simulation Applications Supporting Human Spaceflight", ASME 2016 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, DETC 2016-60108, Charlotte, NC.

[11] Banner Engineering Corp., "Q4X Stainless Steel Analog Laser Sensor: Instruction manual," Author, Minneapolis, MN, 2017.

[12] Y. Yang, Y. Zhao, and D. Kang, "Integration on acceleration signals by adjusting with envelopes," *Journal of Measurements in Engineering*, 4(2), pp. 117-121, Jun 2016.

[13] Toochinda, D., *Discrete-time PID Controller Implementation*, 2015. Available: https://www.scilab.org/discrete-time-pid-controller-implementation