DYNAMICS OF A VIBRATION ISOLATION SYSTEM INCLUDING INERTIA OF THE HUMAN BODY

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Introduction

- Exercising in a spacecraft may transmit an unacceptable amount of vibration to the vehicle. This is commonly mitigated by a Vibration Isolation System (VIS), whose dynamics must be modeled to confirm that forces on the spacecraft remain within an allowed range (see, e.g., [1]).
- It is not enough to record the force and moment applied on the floor while exercising, and then simply apply these loads to the VIS platform. The force and moment on a moving platform will differ from that on the stationary floor due to inertial effects involving the human body. For example, standing up on a platform as it gives under the subject's feet reduces the foot force on it, and rotational inertial effects are especially complex.
- In principle, one could model both the human body and the VIS mechanism in a combined simulation. The joints of the human body would be driven kinematically along prescribed exercise trajectories while the dynamics engine computed the response of the VIS degrees of freedom.
- However, mechanism designers and biomechanics experts have their own established tools, making it very desirable to have a way of decoupling the biomechanics from the VIS modeling, simulation, and analyses.
- We have derived equations that rigorously accomplish this goal, and have implemented them as an interface function in a VIS simulation that accepts input from a data file containing the required time-stamped human motion and inertia terms corresponding to the specific exercise in question.
- This data file is generated by an OpenSim plugin written for that purpose. The existing VIS analytical simulation is developed using NASA's Trick Simulation Environment [2], as well as its MBDyn multibody dynamics package [3].

Equations of motion for a platform with a moving mass on top

$$M\dot{\vec{V}}_{SR} - M\vec{\rho}_{cm}\times\dot{\vec{\omega}} + \vec{\omega}\times(\vec{\omega}\times M\vec{\rho}_{cm}) + 2\vec{\omega}\times\frac{d}{dt}(M\vec{\rho}_{cm})\Big|_{SR} + \frac{d^2}{dt^2}(M\vec{\rho}_{cm})\Big|_{SR} = \vec{F}_{external}$$

$$M\vec{\rho}_{cm}\times\dot{\vec{V}}_{SR} + \boldsymbol{J}\cdot\dot{\vec{\omega}} + \vec{\omega}\times\boldsymbol{J}\cdot\vec{\omega} + \frac{d\boldsymbol{J}}{dt}\Big|_{SR}\cdot\vec{\omega} + \vec{\omega}\times\vec{L}_{internal} + \frac{d\vec{L}_{internal}}{dt}\Big|_{SR} = \vec{M}_{external}$$

- M - mass of the VIS platform + the moving subject exercising on it
- $\vec{V}_{SR}$ - inertial velocity of the origin of the platform's structural frame (SR)
- $\dot{\vec{V}}_{SR}$ - inertial acceleration of the origin of the SR frame
- $\vec{\rho}_{cm}$ - platform + subject system center of mass location relative to the SR frame
- $\vec{\omega}$ - angular velocity of the SR frame relative to the inertial frame
- $\dot{\vec{\omega}}$ - angular acceleration of the SR frame
- $\boldsymbol{J}$ - moment of inertia of the system relative to the SR frame
- $\vec{L}_{internal}$ - angular momentum due to the moving subject, relative to the SR frame
- $\frac{d}{dt}\Big|_{SR}$ - time derivative with respect to the rotating SR frame
- $\vec{F}_{external}$ - total external force on the system
- $\vec{M}_{external}$ - total external torque on the system relative to the SR frame origin

Equation derivation and content

- The equations are derived by starting with expressions for linear and angular momenta and differentiating, taking rotating frame effects into account
- The equations contain the usual rigid-body terms (but with time-varying mass properties) and additional "motion terms"
  - Coriolis force term: $-2\vec{\omega}\times\frac{d}{dt}(M\vec{\rho}_{cm})\Big|_{SR}$
  - Inertial force term: $-\frac{d^2}{dt^2}(M\vec{\rho}_{cm})\Big|_{SR}$
  - "Figure skater spins up when pulling in her arms" torque term: $-\frac{d\boldsymbol{J}}{dt}\Big|_{SR}\cdot\vec{\omega}$
  - Gyroscopic torque term: $-\vec{\omega}\times\vec{L}_{internal}$
  - Inertial torque term: $-\frac{d\vec{L}_{internal}}{dt}\Big|_{SR}$

Implementation in a VIS sim

- The key assumption is that the subject's trajectory is prescribed relative to the moving platform
- The equations then determine dynamics of the platform degrees of freedom
- To use these equations in a multibody code, mass properties must be frequently updated and the "motion terms" treated as external forces and torques
- Mass properties and the motion terms are generated by an OpenSim plugin and provide time-dependent mass properties, force, and torque to the VIS sim
- Momentum conservation numerical issues were resolved by fitting $\vec{\rho}_{cm}$, $\boldsymbol{J}$, and $\vec{L}_{internal}$ with quintic splines, and obtaining their derivatives from the splines
- Using the splines with a 4th order Runge-Kutta integration scheme led to very good linear and angular momentum conservation

Conclusions

- We have separated the kinematics of human motion from the dynamics of the VIS sim, encapsulating their "interaction" in just a few quantities generated by OpenSim
- The approach hinges on assuming that the subject's trajectory remains unaltered relative to the platform as the platform moves

Challenges

- To understand the limits of the assumption of a prescribed exercise trajectory relative to the platform
- To devise an approach when the subject modifies his/her trajectory as the platform moves

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References

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