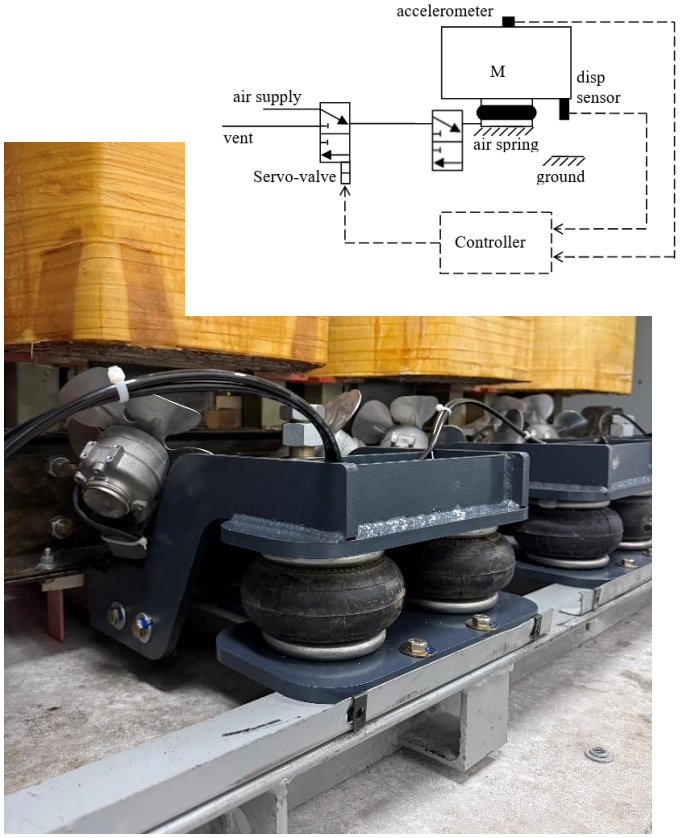
DEICON
Dynamics & Controls

ENGINEERING WHITE PAPER

Smarter Vibration Isolation:

Air-Spring Mounts with Real-Time Stiffness and Damping Adjustment

How one active control layer lets a single air spring deliver best-in-class vibration isolation and shock isolation without the usual trade-offs of a passive mount.



Executive Summary

Every engineer who has specified a vibration mount has run into the same wall: the softer and less damped a mount is, the better it isolates vibration but the worse it handles shock. Add damping to tame a shock event and you quietly degrade the very vibration isolation you designed the mount to deliver. Passive mounts, whether rubber or steel, without or with viscous dampers, are all locked into this trade-off because their stiffness and damping are fixed the moment they're built.

Air springs break that lock. Because air can be metered in and out in real time, an air spring is really a controllable mount. DEICON's Controlled Air Isolation System takes advantage of this by layering active damping control and active stiffness control on top of an air spring's normal height/pressure regulation. A small computer, a high-speed servo valve, and a few sensors continuously adapt the mount's behavior to changing conditions. The system remains soft and lightly damped when vibration isolation is most important, adds damping when shocks occur, and temporarily increases both damping and stiffness to prevent bottoming out and protect the installation. Once the disturbance has passed, it automatically returns to its optimal vibration-isolation state.

This white paper walks through the physics behind the trade-off, explains how DEICON's active control scheme resolves it, and shows the test-bench data that back it up. In bench testing, the system produced up to 300% on-demand change in effective mount stiffness and boosted damping more than eight-fold (from about 2.5% to 21% of critical damping), all without touching the underlying air spring hardware.

Why this matters

- Passive mounts force a compromise between vibration isolation and shock isolation.
- Air springs are naturally adjustable — the ideal platform for real-time control.
- Active damping and active stiffness control let one mount serve both roles on demand.
- Demonstrated results: up to 300% stiffness change and >8x damping increase, on command.

1. The Isolation Dilemma

Strip any isolation problem down to its essentials and you get the simple spring-mass-dashpot system in Figure 1: a mass M sitting on a spring and damper, excited either by a force F acting directly on the mass (think of the firing forces in an engine) or by motion of the base x_base (think of a truck driving over a rough road, or a boat pounding through waves). The job of the mount is to keep the force transmitted to the base, Ft, and the motion of the mass, x, both as small as possible — in engineering terms, to minimize the transmissibility between excitation and response.

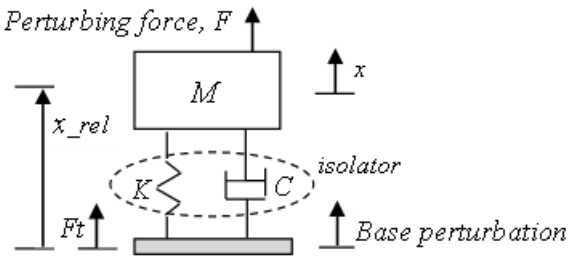


Figure 1. *A single mount reduced to its essentials: mass, spring, and damper.*

Softer mounts with little damping give the lowest transmissibility away from resonance, which is why practitioners deliberately design vibration isolation systems to be lightly damped and to keep the resonant frequency well below

the frequencies they need to isolate. That works well for steady vibration. The trouble starts when the same mount also has to survive shock (a broadband, impulsive event that always has some energy sitting right at the isolation system's resonant frequency). A highly underdamped mount responds to that energy by ringing, and if the shock happens to be rhythmic (with the wrong frequency) rather than random, the mount can amplify it instead of absorbing it.

Adding damping is the obvious fix for the shock problem, and it works — but it comes at the cost of high-frequency vibration isolation, which is exactly the performance the soft, lightly damped mount was chosen for in the first place. Stiffness cuts the same way: a soft mount isolates vibration beautifully but allows excessive low-frequency motion under shock or startup transients (a diesel engine lurching on start-up is a familiar example). A stiffer mount controls that motion but raises the resonant frequency and undercuts vibration isolation.

> *A mount can be soft and lightly damped, or it can be stiff and damped, but a passive mount can't be both, when needed.*

2. The Physics

Before getting into the control scheme, it's worth seeing the trade-off directly. The frequency response functions of Figure 2 show the effect of damping on transmissibility (a) and motion of the isolated mass (b). Lower damping lowers high-frequency transmissibility but drives up the response at resonance; which is fine as long as excitation is much higher than that resonant frequency. When the excitation is broadband (as shock usually is), some energy always lands on resonance, and an lightly damped mount lets the mass bounce excessively.

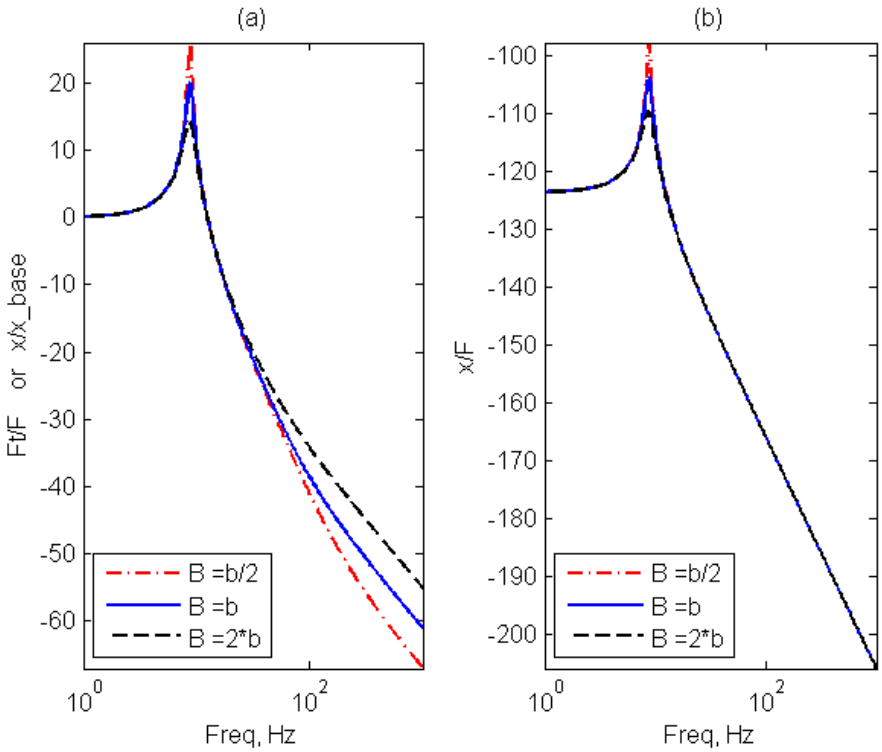


Figure 2. *Effect of damping on transmissibility. Lower damping enhances high-frequency vibration isolation, but sharply raises the response at resonance; higher damping tames resonance at the cost of high-frequency isolation.*

Frequency response functions of Figure 3 show the effect of isolator stiffness on vibration isolation. Softer mounts reduce transmissibility over most of the frequency range that matters in real installations, including at resonance, which is why air springs, the softest practical isolators available, are so effective. The catch is that the same softness allows more low-frequency motion of the mass, which can be a problem if the excitation is impulsive rather than smoothly periodic, or if the mount's resonance sits close to the excitation frequency.

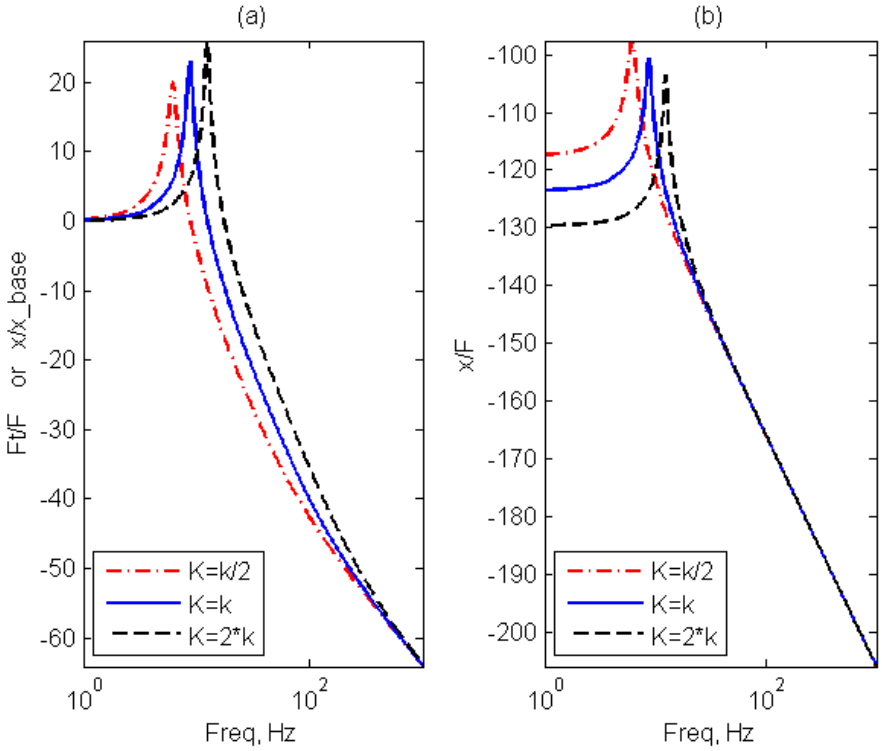


Figure 3. *Effect of stiffness on transmissibility. Softer mounts reduce transmission across most of the useful frequency range, but allow larger low-frequency motion of the mass under vibration inputs.*

The takeaway

- Damping helps shock isolation but hurts high-frequency vibration isolation.
- Softness helps vibration isolation but allows more low-frequency motion under shock.
- A fixed mount has to pick one operating point and live with it.
- An adjustable mount can pick the right operating point moment to moment.

3. Why Passive Fixes Fall Short

Engineers have been chasing a way around this trade-off for decades and several passive approaches are in wide use. None of them fully escapes the compromise.

Double (two-stage) mounting

Stacking two mounts with a mass in between improves high-frequency isolation, but it does so at the expense of low-frequency isolation, and its shock isolation is worse than a single mount. It also costs more weight and space, often a dealbreaker in vehicular or shipboard applications.

Hydraulic engine mounts (hydro-mounts)

Widely used in high-end automobiles, hydro-mounts pair an lightly damped elastomeric isolator with a hydraulic Helmholtz resonator that adds damping tuned to a specific resonant frequency. A bi-fluid Helmholtz resonator built into an air spring achieves a similar effect. Tuned damping is elegant, but it's tuned to one mass — the moment the isolated mass changes (a truck cab with a different driver, a seat with a different occupant, a machine that loads and unloads), the tuning drifts off target.

Any fixed, non-adjustable mount

The common thread is that every passive fix is a fixed compromise. In a time-varying application (anything where the isolated mass, the operating condition, or the disturbance environment changes during use) a fixed mount optimized for one set of vibration isolation parameters would not remain optimal when parameters change. Real, on-demand adjustability is the only way out.

4. Why Air Springs Are the Right Foundation

Adjustability could, in principle, come from an actuator paired with any type of mount. In practice, that adds cost, weight, and packaging complexity that most applications can't absorb. Air springs sidestep the problem because they're already inherently adjustable — their stiffness and effective damping are functions of the air inside them, which can be metered in real time without any extra actuator placed alongside the mount. Three other attributes make air the natural starting point for an adjustable isolation system:

- Very low stiffness, giving air springs the lowest achievable natural frequency, and hence the best low-frequency vibration isolation, of any common isolator type.
- High load-bearing capacity without the large static deflection a coil or elastomeric spring of similar stiffness would need.
- Negligible inherent damping, which is exactly what preserves high-frequency vibration isolation and keeps structure-borne noise transmission low.

Those same properties are, of course, what make shock isolation with a plain air spring underwhelming. This is precisely the gap DEICON's active control layer is built to close.

5. Inside DEICON's Controlled Air Isolation System

The system starts with the control architecture most air-mounted applications already use: a pseudo-static (low-bandwidth) height or pressure control loop that keeps the mount at its design height and supports time-varying loads. This loop always stays closed. On top of it, DEICON adds two dynamic control layers (active damping control and active stiffness control) that engage and disengage on demand, orchestrated by a supervisory controller, to address the vibration/shock trade-off described above, while maintaining the robustness of the installation.

The hardware is intentionally lean. A servo-valve, under the controller command, meters the flow of air between the source (or atmosphere) and the air spring. Feedback comes from an accelerometer and a displacement (or pressure) sensor.

The key insight: an air spring is already an integrator

The physics that makes this work is simple once you see it. The flow of air into or out of a spring accumulates (integrates) into a change in internal pressure, and that pressure, multiplied by the spring's effective area, becomes a force acting on the mass. So:

- Making the valve's flow command proportional to the mass's acceleration produces a force proportional to velocity — i.e., active damping.
- Making the valve's flow command proportional to the mass's velocity produces a force proportional to displacement — i.e., active stiffness.

In other words, the same servo-valve and the same air spring can deliver both damping control and stiffness control — the only thing that changes is what signal is fed back to the controller.

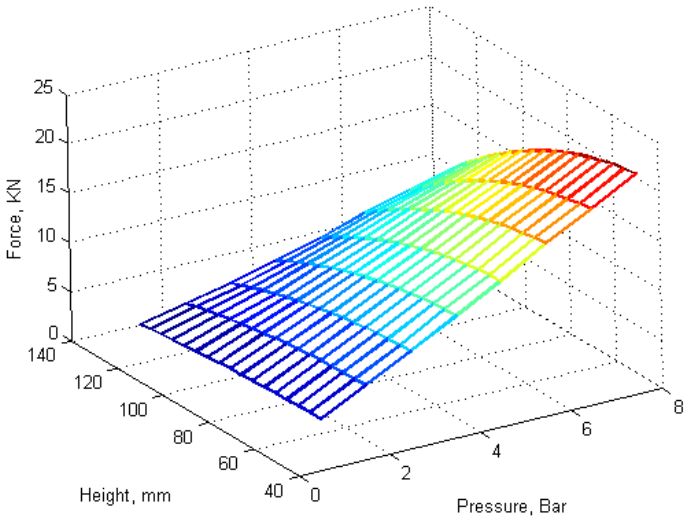


Figure 4. *Measured force generated by a convoluted air spring as a function of internal pressure and mount height.*

One wrinkle: in convoluted air springs, the effective area isn't perfectly constant — it changes with mount height, which itself changes with the motion being controlled. Figure 4 shows how nonlinear that relationship actually is. Because height and pressure don't swing wildly during normal operation, the system can safely treat the effective area as constant for a given operating condition, which keeps the control design tractable without sacrificing accuracy.

6. Active Damping Control

Low damping is what gives most mounts (air, elastomeric, or metal) their high-frequency vibration isolation, and it's usually built in on purpose. The side effect is a sharp, underdamped resonance that undermines shock isolation. Passive fixes for that resonance all cost high-frequency performance. DEICON's active damping control avoids that cost by adding damping only through the control loop, on demand, only when needed.

Broadband damping

Feeding back the relative acceleration of the isolated mass, through a proper controller, makes the air spring behave like a viscous damper while it keeps its normal resilience; the servo-valve's flow command tracks acceleration, the air spring integrates that into a pressure proportional to velocity, and the result is a control force that behaves just like viscous damping. Because the servo-valve has a finite bandwidth that naturally low-pass filters the acceleration signal, the active damping has a smaller impact on high-frequency isolation than an equivalent passive viscous damper. Moreover, the applied damping can be scaled to match the magnitude of the disturbance.

Tuned damping

An alternative is to feed back velocity through a second-order controller tuned to the isolation system's resonance, producing narrowband damping much like a tuned mass damper. It's more complex to implement than broadband damping, but it adds damping only where it's needed, i.e., at resonance, leaving high-frequency isolation completely untouched. For applications where the isolated mass changes over time, a self-tuning routine inside the supervisory controller can keep the tuned damper locked onto the moving resonance.

7. Active Stiffness Control

Smaller single-convoluted air springs, under proper load, achieve vertical natural frequencies as low as 2.5 Hz, providing excellent vibration isolation on their own. Active stiffness control can push that even lower, softening the mount further without growing the air spring or connecting to an auxiliary reservoir. It works the same way in reverse, too: when low-frequency motion becomes excessive, the same control loop can stiffen the mount, then relax back to its natural soft state once the disturbance has passed.

This is especially useful with pneumatic (rather than convoluted) air springs, which use thicker, steel-reinforced walls for extra lateral stiffness, a construction that also raises the resonant frequency and quietly costs some vibration isolation. Active stiffness control gives that performance back on demand, without changing the hardware.

Stiffness control is realized by feeding back the mass's relative velocity — but velocity is hard to measure directly and cleanly. Off-the-shelf velocity sensors are low-bandwidth, and simply differentiating a displacement signal is too noisy to be usable. DEICON's solution is a kinematic Kalman filter: unlike a conventional (dynamic) Kalman filter, it doesn't need a model of the system's dynamics — it estimates velocity purely from measured acceleration (as the input) and measured displacement (as the output). That keeps the estimate accurate without requiring a detailed, application-specific dynamic model.

8. Supervisory Control — The Conductor

Height or pressure control in most air-isolated system runs continuously. Active damping and active stiffness control are different; they need to switch between states (or between degrees of effectiveness) depending on what the mount is being asked to do at that moment. A supervisory controller manages that switching, and DEICON's architecture supports the full range of automation:

- Manual — an operator or a simple selector switch commands the system to change state.
- Automatic — sensors feed the supervisory controller directly, and the system switches states on its own whenever a signal crosses a defined threshold, with no operator input required.

In practice, most installations land somewhere between these two ends: automatic detection with a manual override, so the system reacts quickly on its own but an operator can always take control when local knowledge calls for it.

9. Putting It to the Test: Experimental Results

The stiffness and damping control schemes are demonstrated, on two types of air springs, pneumatic and convoluted, using an instrumented hammer and a dynamic signal analyzer to measure frequency response functions (force in, acceleration out). Figure 5 shows such frequency responses for the convoluted air spring. As depicted in this figure, the air spring’s stiffness experienced 300% change in effective stiffness, purely through control-loop gain, with the physical air spring untouched.

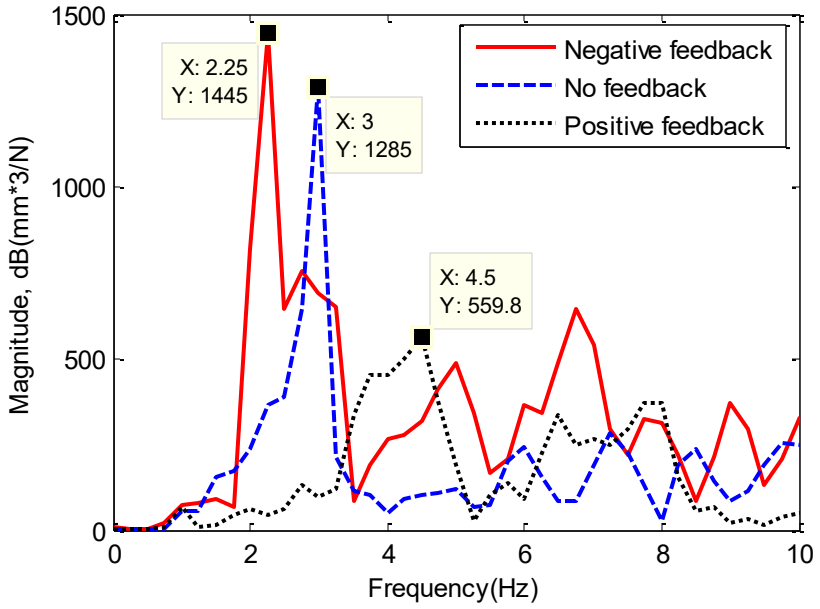


Figure 5. *Measured frequency response of the convoluted air-mounted system at different stiffness feedback gains.*

A separate test was conducted to demonstrate the control system's ability to introduce damping into the air spring. In this test, the isolated mass was displaced from its equilibrium position and released, and the resulting acceleration response was recorded with and without active damping engaged. Figure 6 compares the two responses. With active damping enabled, the system settled significantly faster, with effective damping increasing from 2.5% to 21% of critical, an enhancement of around eight-fold. This level of damping is more than sufficient to suppress resonant bounce during a shock event.

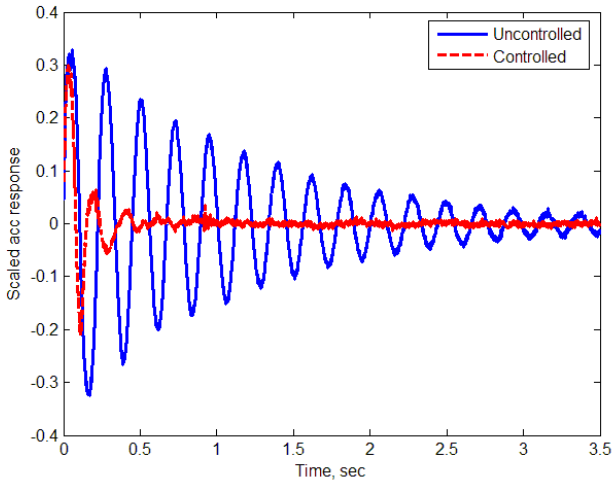


Figure 6. *Measured impulse response of the air-mounted system, with and without active damping control engaged.*

Bench-test results at a glance

- Stiffness: up to 125% change (pneumatic spring), up to 300% change (convoluted spring) — on demand, via control gain alone.
- Damping: increased from ~2.5% to ~21% of critical (>8x) when active damping was engaged.
- All changes achieved with the same physical air spring hardware with no mechanical reconfiguration.

10. What This Means for Your Application

Because the underlying hardware (an air spring, a servo-valve, a couple of sensors, and a control computer) is generic, the same architecture adapts to a wide range of isolation problems where vibration and shock both, as well as installation integrity matter and where fixed passive mounts are forced into a compromise:

- Vehicular cab and seat suspensions, where ride comfort (vibration isolation) and road-shock control fight for the same mount, and occupant mass changes from trip to trip.
- Diesel generators and gensets on marine or mobile platforms, which need soft, quiet isolation while running and stiffer, damped support while the platform is underway or in rough conditions.
- Industrial equipment such as coordinate measuring machines and MRI systems, where isolation height and vibration performance both need to be held to tight tolerances despite floor-borne disturbances.
- Mechanical presses and other machinery where shock originates at the isolated mass itself, calling for damped, stiffened support during the event and soft, lightly damped support the rest of the time.

In every case, the value proposition is the same: one adjustable mount, controlled in real time, replacing the fixed compromises that any passive mount is stuck with.

11. Summary

Lightly damped, compliant mounts provide superior vibration isolation but offer poor shock isolation and reduced installation robustness. Increasing damping and stiffness improves shock performance and combined with increased stiffness enhances installation integrity, but at the expense of vibration isolation effectiveness. DEICON's Controlled Air Isolation System resolves this conflict, not by selecting a fixed compromise, but by adjusting the mount's dynamic behavior on demand.

- Active damping control adds damping only when and where it's needed (broadband or tuned), taming shock-induced resonance without sacrificing high-frequency vibration isolation.
- Active stiffness control softens or stiffens the mount on demand, using a kinematic Kalman filter to reliably estimate velocity for the feedback loop.
- A supervisory controller — manual, automatic, or a blend of both — decides when each control layer engages.

The result, verified in hardware testing, is a single air-spring mount that performs like the ideal, uncompromised isolator engineers have wanted all along: soft and lightly damped when vibration isolation is the priority, damped the instant shock isolation takes over, and damped with added stiffness when bottoming out and installation integrity become a concern.

About DEICON

DEICON designs and builds passive and active vibration and shock isolation systems, including the Computer Controlled Air Isolation System described in this paper. A patent application covering this technology has been submitted to the U.S. Patent and Trademark Office.

Learn more or discuss your application: www.deicon.com