VELOCITY COMPENSATED PASSIVE DAMPER SOLVES THERMAL GRADIENT DEPLOYABLE ISSUES

Scott Starin [(1)], Dennis Beaver [(2)], Joshua Cass [(3)]

[(1)] Avior Control Technologies, Inc,1198 Boston Ave, Longmont CO, USA 80501, sstarin@AviorControls.com
[(2)] Dynic Labs, Inc, 4814 Forman Rd, St. Louis, MO, USA 63123, Email: dennis.beaver@DynicLabs.com

ABSTRACT

One of the challenging aspects of spring-loaded deployable systems is the ability to control the deployment velocities over a potentially wide range of operating conditions. Passive dampers are often used to control the rate of deployment and kinematic energy absorption. Fluid dampers have extremely non-linear characteristics and have high Temperature Coefficients of Damping (KBτ). Eddy Current Dampers (ECDs) are much more reliable and provide superior linearity and KBτ compared to Fluid Dampers, however, variations of operational temperature and input torques often require thermal regulation or complicated deployment structures to tailor deployment characteristics.

Using proven technologies, an internal Velocity Control Module used in conjunction with a shorted alternator type ECD provides near-constant velocity over torque and temperature. This ability may eliminate the need for thermal heaters or expensive cable linkages to control synchronous deployment of multi-hinged arrays. This paper discusses the concept of operation as well as examples of deployment benefits and qualification status.

1. PASSIVE DEPLOYMENT SYSTEMS

One of the first operations on orbit of most satellite systems is to deploy solar arrays. Thermal gradients across a satellite typically require heaters to be employed to regulate and control the temperature of energy absorption devices in spring loaded deployment systems. In order to minimize battery consumption before the solar arrays are deployed, it is highly desired to utilize a passive deployment system for solar array deployment, rather than higher power draw and computerized motorized deployment systems.

Passively deployed systems, however, face challenges in minimizing variations in the rate of deployment of multiple arrays or multi-hinged arrays. If the “hot” side of a spacecraft arrays deploy at a considerably faster rate than a cold side, the vehicle could tumble or roll requiring considerable energy to correct the attitude. To control the centre of gravity of a spacecraft, it is often desired to implement a *critically timed deployment* of the arrays.

1.1 Fluid Dampers

Fluid Dampers offer the advantages of lower unit cost and low static friction. When considering the total cost of ownership, however, you must consider the additional testing, sorting, integration and heating regulation costs of the system.

Fluid Dampers have extremely non-linear torque versus damping rate performance. Their damping rates are considerably lower at both low and high velocities. Additionally, the Temperature Coefficient of Damping (KBτ), or the change in damping rate with temperature, is extremely high for Fluid Dampers, with very limited range of linear changes. In other words, Fluid Dampers have a very limited temperature range where the damping rates change with temperature exhibit a linear relationship.

1.2 Eddy Current Dampers

Eddy Current Dampers (ECDs), exhibit significantly more stable torque versus damping rate performance, compared to Fluid Dampers. Typically, the KBτ for ECDs is on the order of -0.4% per ºC. The dominant contributor to the KBτ is the conductivity change of copper with respect to temperature. As temperature goes down, copper is more conductive, resulting in a higher damping rate. The lubrication system and gearing configuration will have contributing factors to this coefficient, and may have non-linear effects at cold temperatures, but these are significantly less than those of a Fluid Damper.

If dry film lubrication is employed, you may significantly expand the operational temperature range of an ECD. Such ECDs can easily operate in temperature ranges of -125 ºC to +125 ºC, thus potentially eliminating the need for external heaters. At such a temperature variations, the damping rates (and hence deployment velocities) of uncompensated ECDs will vary by 100%.

Since the Torque-versus-damping relationship for an ECD is linear, a 100% variation in input torque will result in approximately a 100% variation in the velocity. This compounds the issue of variation with temperature of spring loaded hinge systems because input torque to the damper typically reduces at cold temperatures. Figure 1 below shows an uncompensated ECD velocity performance.

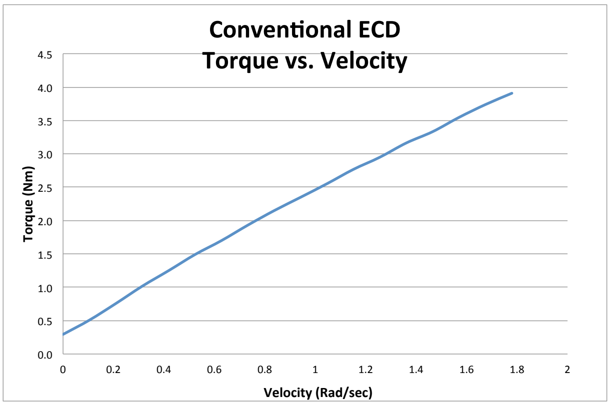

Figure 1 - Uncompensated Damper Torque vs. Velocity

1.3 Velocity Compensated Passive Dampers

Originally designed to provide pilot feel for a fly-by-wire commercial aircraft application, a Velocity Compensated ECD uses the back emf of a shorted-alternator type of damper and a regulation network to provide varying characteristics of the damper assembly. By regulating the "knee" of the damping characteristic through a passive compensating network, we are able to take one passive ECD and tailor the damping rate characteristic, and even provide a selectable performance with this passive network. The electronic regulation network requires no excitation to activate. The volume of the electronics module adds 25 mm diameter by 25 mm length to the back of our conventional ECD.

2.0 APPLICATION EXAMPLE

By adding the electronic Velocity Compensation Network (VCN) module, we can incorporate multiple velocity versus torque profile options within a single package. The desired damping characteristic may be factory set or configured to allow the system integrator to select the desired damping characteristic. Figure 2 shows the same ECD presented in Figure 1, with three option selects for the VCN. Each of these curves reflects actual performance, at +20º C unit temperature.

One of the benefits of implementing the VCN is a significant reduction of velocity change versus torque, as a percentage. In the damper presented here, as the input torque varies from 1.5 to 3.0 Nm, the velocity change varies by 140% for the uncompensated ECD to 33% for Damping Option 3.

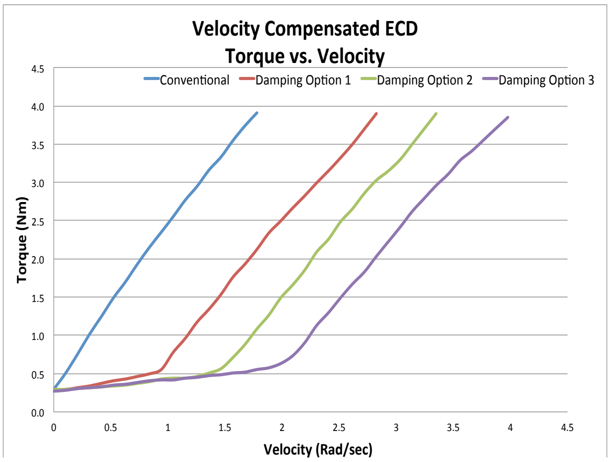

Figure 2 - Compensated Velocity Damper Options

2.1 Qualification and Environmental Testing

In order to prove the robustness of the damper assembly, the unit was subjected to a random vibration and thermal cycle test, prior to environmental testing at the operational temperature requirements.

Table 1 - Random Vibration Levels	
Frequency (Hz)	**Level (g^2 / Hz)**
20	0.019
60	0.500
450	0.500
2000	0.026
Overall	19.5 Grms

In addition to the vibration levels detailed in Table 1, the Damper assembly was subjected to three thermal cycles from -50º C to +80º C, and a room ambient endurance run-in of 100 cycles at 4.0 Nm.

After the conclusion of the endurance test, we tested the damper assembly in an environmental chamber at the operational temperature requirements of -25º C to +70º C. The unit under test was allowed to stabilize at each temperature for a minimum of one hour, after the desired temperature was reached.

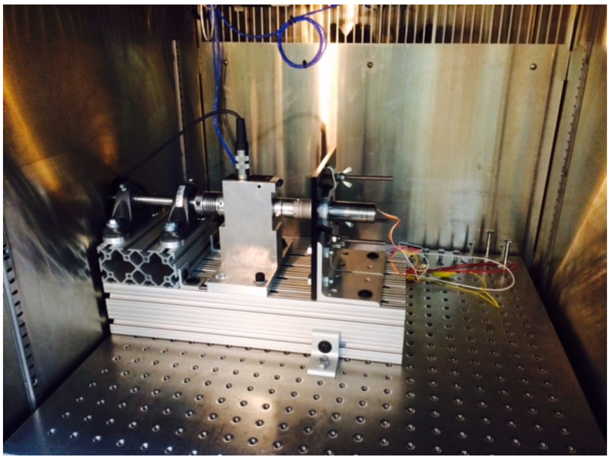

Figure 3 - Damping Rate Test in Chamber

Figure 4 - Outside the Chamber

Avior conducted the environmental test via two methodologies. Figures 3 and 4 show the initial test setup that hung weights external to the chamber. Method 2 utilized a geared servo-motor to drive the damper assembly entirely within the chamber. Both methods achieved similar results.

The temperature testing yielded extremely improved the Temperature Coefficient of Damping (KBτ) with the Velocity Compensated Network, as compared to the uncompensated ECD.

Table 2 – Temperature Coefficient of Damping – Various Options -	
Configuration	KBτ %□°□
Uncompensated	- 0.44
Damping Option 1	- 0.23
Damping Option 2	- 0.15
Damping Option 3	- 0.16

The values for the KBτ□ □□□ □□□□□□□□ □□□□□□□ □□□ □□□□□□□□□□□□□□□□□□□□□□□□□□□□□ □□□□□□□□□□□□□□□□□□□□□□

2.2 Calculating Variations in Deployment

By incorporating the Velocity Compensation Network, we are able to significantly reduce the disparity in deployment characteristics over torque and temperature extremes in the system. By testing the damper assemblies over temperature, we can characterize the performance, and simulate deployment time (t) variations over Torque (T) and temperature (τ).

The fist step is to characterize the damping rate versus torque input for each of the options, *over the torque range input of interest*. It is important in this linear simulation that you only characterize the performance over the input range because we want to ignore the non-linearity at low torque levels.

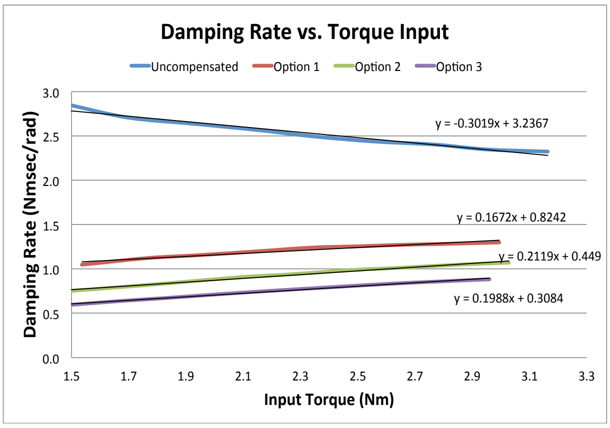

Figure 5 - Damping Rate vs. Torque Input

Figure 5 plots the damping rate versus torque from 1.5 to 3.0 Nm, the area of interest for our simulation. This plot is characterized from data at +20ºC. From the linear interpolation we have the following equations to predict the Dynamic Damping as a function of Torque Input (DBT_{IN}).

Table 3 – Dynamic Damping (DBT_{IN}) as Function of Torque Input (T_{IN}) for Considered Options +20º C	
Configuration	DBT_{IN}
Uncompensated	$- 0.302\ T_{IN} + 3.23$
Damping Option 1	$0.167\ T_{IN} + 0.824$
Damping Option 2	$0.212\ T_{IN} + 0.449$
Damping Option 3	$0.199\ T_{IN} + 0.308$

From the methodology presented in [1], we can calculate the position versus time and deployment times for a deployment system. These equations are simply based on the Galilean Equations of Kinematic Motion.

First, we start by calculating the velocity at the start and the end of the deployment, knowing the Torque

$$\omega_{IN\_S} = \frac{T_{IN\_S}}{DBT_{IN\_S}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

$$\omega_{IN\_E} = \frac{T_{IN\_E}}{DBT_{IN\_E}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Where:

- ω_{IN_S} = Velocity Input at Start of Deployment (rad/sec)
- ω_{IN_E} = Velocity Input at End of Deployment
- T_{IN_S} = Torque Input at Start of Deployment (Nm)
- T_{IN_E} = Torque Input at End of Deployment
- DBT_{IN_S} = Dynamic Damping at Start
- DBT_{IN_E} = Dynamic Damping at End

From here, we can calculate the average velocity, deployment time and deceleration over the deployment:

$$\varpi_{IN} = \frac{\omega_{IN\_S} + \omega_{IN\_E}}{2} \ldots\ldots\ldots\ldots (3)$$

$$\Delta t = \frac{\Delta\Theta}{\varpi_{IN}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

$$\alpha_{IN} = \frac{\omega_{IN\_E} - \omega_{IN\_S}}{\Delta t} \ldots\ldots\ldots\ldots(5)$$

Where:

- ϖ_{IN} = Average Velocity over Deployment (rad/sec)
- Δt = Time of Deployment (seconds)
- $\Delta\Theta$ = Deployment range (radians)
- α_{IN} = Deceleration over Deployment (rad/sec^2)

If desired, you may calculate the position at time "t":

$$\Theta_t = \Theta_s - \left(\omega_{IN\_S} \cdot t\right) - 0.5\alpha_{IN} \cdot t^2 \ldots\ldots\ldots(6)$$

Where:

- Θ_t = Position at time "t" (radians)
- Θ_s = Position at Start of Deployment

Table 4 summarizes deployment simulations for the various options for a 31.4 radian deployment.

Table 4 – Summary of Deployment Simulations +20ºC

Parameter	Uncomp.	Option 1	Option 2	Option 3
T_{IN_S} [Nm]	3.0	3.0	3.0	3.0
T_{IN_E} [Nm]	1.5	1.5	1.5	1.5
DBT_{IN_S} [Nms/rad]	2.324	1.325	1.085	0.905
DBT_{IN_E} [Nms/rad]	2.777	1.075	0.767	0.606
ω_{IN_S} [rad/sec]	1.290	2.260	2.765	3.315
ω_{IN_E} [rad/sec]	0.540	1.395	1.955	2.475
ϖ_{IN} [rad/sec]	.915	1.829	2.360	2.895
Δt [sec]	34.3	17.16	13.3	10.8

If we repeat the process for our maximum temperature (+70ºC)

Table 5 – Dynamic Damping (DBT_{IN}) as Function of Torque Input (T_{IN}) for Considered Options +70º C

Configuration	DBT_{IN}
Uncompensated	$- 0.245\ T_{IN} + 2.566$
Damping Option 1	$0.150\ T_{IN} + 0.686$
Damping Option 2	$0.167\ T_{IN} + 0.462$
Damping Option 3	$0.164\ T_{IN} + 0.304$

Table 6 – Summary of Deployment Simulations +70ºC

Parameter	Uncomp.	Option 1	Option 2	Option 3
T_{IN_S} [Nm]	3.0	3.0	3.0	3.0
T_{IN_E} [Nm]	1.5	1.5	1.5	1.5
DBT_{IN_S} [Nms/rad]	1.831	1.136	0.963	0.796
DBT_{IN_E} [Nms/rad]	2.199	0.911	0.713	0.550
ω_{IN_S} [rad/sec]	1.638	2.64	3.115	3.769
ω_{IN_E} [rad/sec]	0.682	1.647	2.100	2.727
ϖ_{IN} [rad/sec]	1.160	2.143	2.609	3.248
Δt [sec]	27.1	14.6	12.0	9.7

At the minimum temperature of -25ºC:

Table 7 – Dynamic Damping (DBT_{IN}) as Function of Torque Input (T_{IN}) for Considered Options -25º C

Configuration	DBT_{IN}
Uncompensated	$-0.532\ T_{IN} + 4.73$
Damping Option 1	$0.245\ T_{IN} + 0.698$
Damping Option 2	$0.246\ T_{IN} + 0.402$
Damping Option 3	$0.231\ T_{IN} + 0.258$

Table 8 – Summary of Deployment Simulations -25ºC				
Parameter	Uncomp.	Option 1	Option 2	Option 3
T_{IN_S} [Nm]	3.0	3.0	3.0	3.0
T_{IN_E} [Nm]	1.5	1.5	1.5	1.5
DBT_{IN_S} [Nms/rad]	3.13	1.433	1.14	0.951
DBT_{IN_E} [Nms/rad]	3.932	1.066	0.771	0.605
ω_{IN_S} [rad/sec]	0.958	2.090	2.630	3.155
ω_{IN_E} [rad/sec]	0.381	1.407	1.946	2.479
ϖ_{IN} [rad/sec]	0.670	1.749	2.290	2.817
Δt [sec]	46.8	18.0	13.7	11.7

By using the Velocity Compensation Network, we can significantly reduce the variation of deployment times over temperature.

Table 9 – Increase in Deployment Time as a Percentage From +70º C to -25º C	
Configuration	% Increase
Uncompensated	72.6
Damping Option 1	22.9
Damping Option 2	14.2
Damping Option 3	20.6

3.0 CONCLUSION:

Unpowered deployment systems face many challenges with respect to controlling the kinematic characteristics over varying torques and temperatures. By implementing an unpowered Velocity Compensation Network, used in conjunction with a shorted alternator style Eddy Current Damper, allows for customization and tailoring of the damping features to minimize variations in deployment characteristics over extremes of operating conditions. Qualification testing over environments and endurance cycling has proven the concept to be robust and reliable.

4.0 REFERENCES

1. Eddy Current Damper Product Catalog and Design Guidelines, (2015) Avior Control Technologies, Inc, Longmont CO, United States of America