

Background



The world's tallest building and the world's fastest elevator:

Taipei 101 in Taipei

Height: 508 m (1,667 ft)

Floor: 101

Max. Speed: 1010m/min

1st~90th: 39 sec

The vibration and noise problem has been a severe problem in the design and operation of high-rise, high-speed elevators. To improve the design of elevators, one of the major tasks is to develop a better understanding of elevator cable dynamics and a new method to effectively reduce the vibration and noise level.

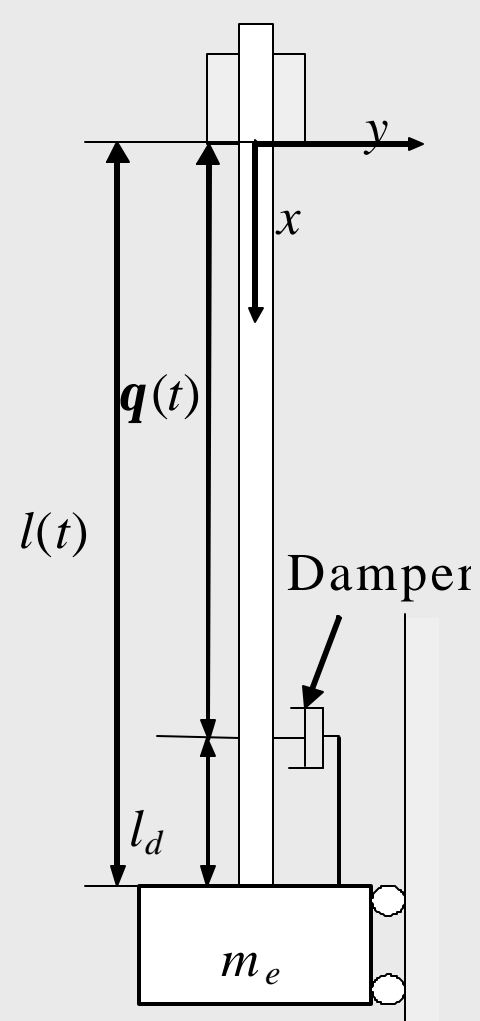
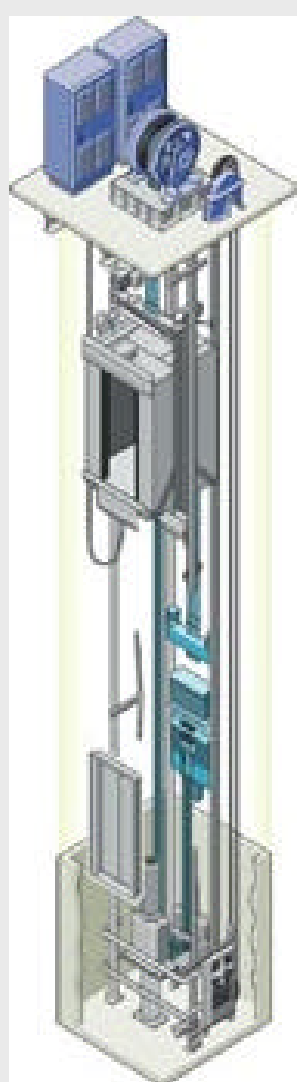
Elevator design challenges include:

Efficiency: increase of the speed limit to over 1000 m/min

Ride comfort: vertical and lateral vibrations within 8-10 millG

Positioning accuracy: 6 mm for rises up to 500 m

Model and Equation of Motion



The elevator cable-car system is modeled as a fixed-fixed beam with small bending stiffness and a rigid body attached at the lower end. By using Hamilton Principle, the governing equations are derived:

$$\mathbf{r} \frac{D^2 y}{Dt^2} - \frac{\partial}{\partial x} [T(x, t) \frac{\partial y}{\partial x}] + EI \frac{\partial^4 y}{\partial x^4} + c \frac{Dy}{Dt} = 0, \quad x \neq \mathbf{q}$$

$$EI \frac{\partial^3 y(\mathbf{q}^+, t)}{\partial x^3} - EI \frac{\partial^3 y(\mathbf{q}^-, t)}{\partial x^3} = C_v \frac{Dy(\mathbf{q}, t)}{Dt}$$

$$T(x, t) = T_0 + \mathbf{r}[l(t) - x]g + \{m_e + \mathbf{r}[l(t) - x]\}a(t)$$

Vibratory energy and rate of change of energy

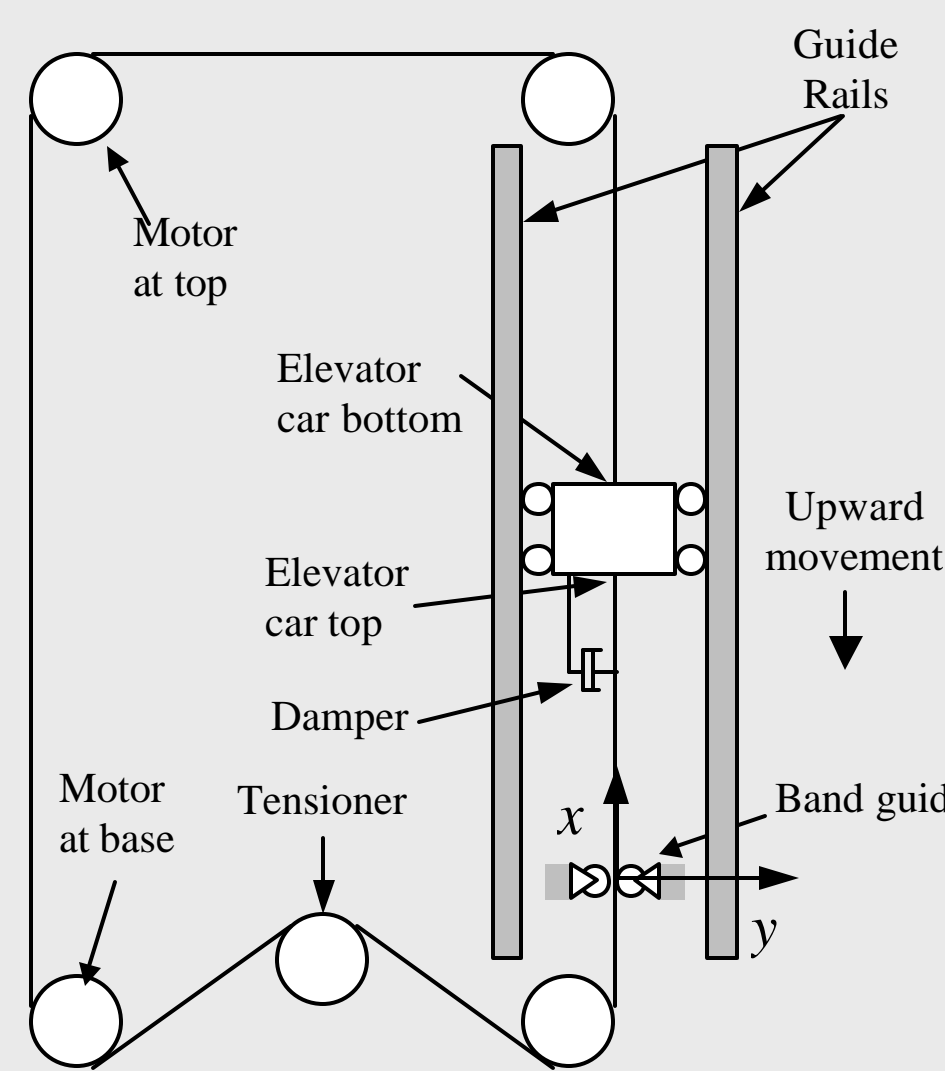
$$E_v(t) = \frac{1}{2} \int_0^{l(t)} [\mathbf{r} (\frac{Dy}{Dt})^2 + T(x, t) (\frac{\partial y}{\partial x})^2 + EI (\frac{\partial^2 y}{\partial x^2})^2] dx$$

$$\frac{dE_v}{dt} = -\frac{1}{2} \ddot{v}(t) \int_0^{l(t)} \{m_e + \mathbf{r}[l(t) - x]\} (\frac{\partial y}{\partial x})^2 dx$$

$$-\int_0^{l(t)} c \left(\frac{Dy}{Dx} \right)^2 dx - c_v \left[\frac{Dy(\mathbf{q}, t)}{Dt} \right]^2 - \frac{1}{2} EI v(t) \left[\frac{\partial y(0, t)}{\partial x} \right]^2$$

Note that the third term on the RHS of the above equation is negative semi-definite, which means the damper guarantees dissipation of the energy. The last term is positive semi-definite when $v < 0$, which means the vibratory energy increases during upward movement - the "unstable shortening cable behavior".

Scaled Model Elevator

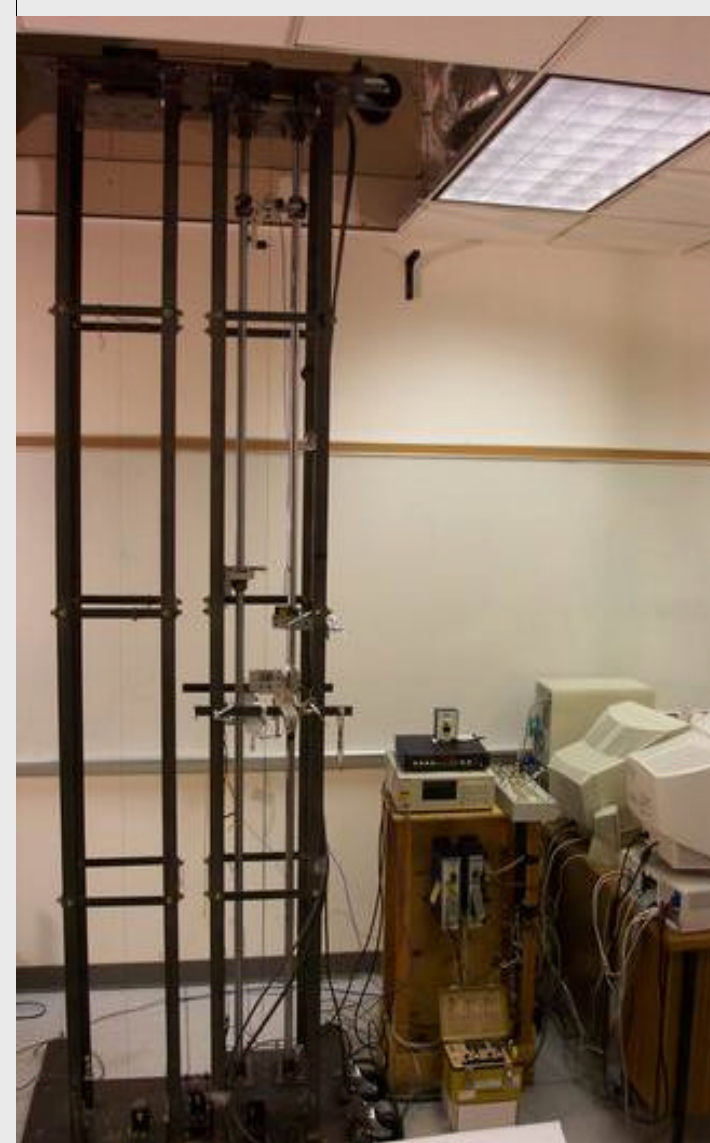


To experimentally validate the theoretical predictions, a scaled model is designed and fabricated. By using the Buckingham pi theorem, a 162 m prototype elevator is scaled down to a 2.5 m model elevator by the following scale laws.

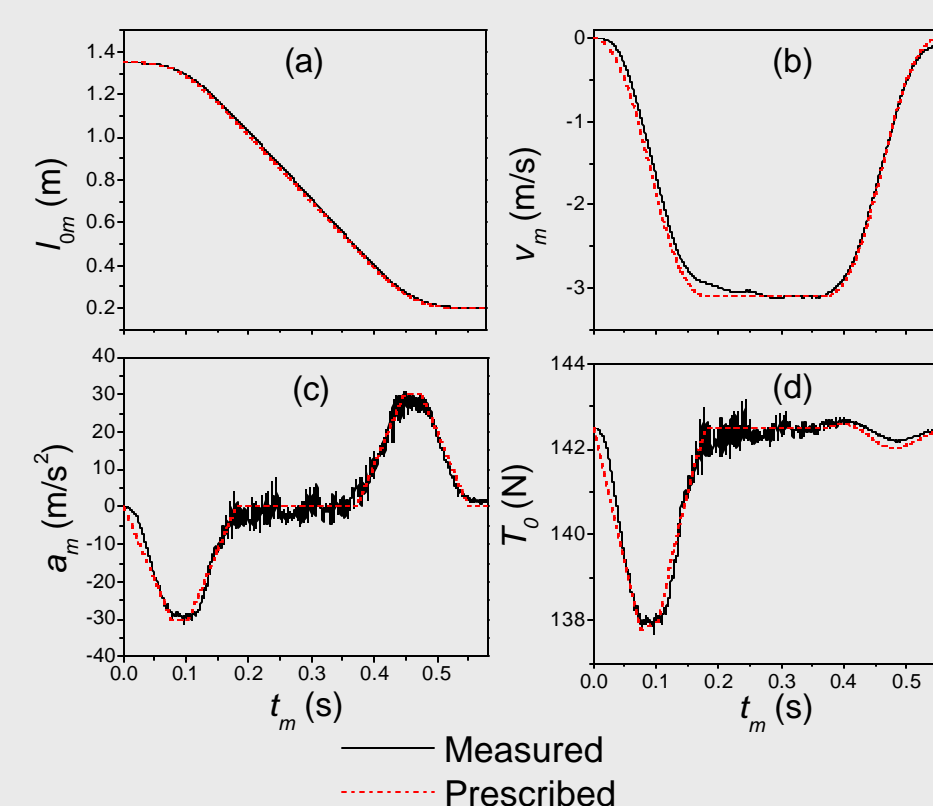
$$\begin{aligned} \Pi_1 &= \frac{y(x, t)}{l_0} & \Pi_2 &= \frac{x}{l_0} & \Pi_3 &= \frac{t}{l_0} \sqrt{\frac{T_0}{\mathbf{r}}} \\ \Pi_4 &= \frac{l(t)}{l_0} & \Pi_5 &= \frac{l_c(t)}{l_0} & \Pi_6 &= v(t) \sqrt{\frac{\mathbf{r}}{T_0}} \\ \Pi_7 &= a(t) \frac{\mathbf{r} l_0}{T_0} & \Pi_8 &= c_v \sqrt{\frac{1}{\mathbf{r} T_0}} & \Pi_9 &= c l_0 \sqrt{\frac{1}{\mathbf{r} T_0}} \\ \Pi_{10} &= \frac{EI}{T_0 l_0^2} & \Pi_{11} &= \frac{g \mathbf{r} l_0}{T_0} & \Pi_{12} &= \frac{m_e}{\mathbf{r} l_0} \end{aligned}$$

Parameter	Description	Prototype	Model
l_0	length of elevator cable at the beginning	162 m	2.531 m
l_{end}	length of cable at the end	24 m	0.375 m
m_e	mass of one-fourth of the car	957 kg	0.8 kg
\mathbf{r}	linear density of the cable	1.005 kg/m	0.037 kg/m
v_{max}	maximum velocity	5 m/s	3.20 m/s ²
a_{max}	maximum acceleration	0.66 m/s ²	3.20 m/s ²
EI	bending rigidity of the cable	1.39 Nm ²	0.966x10 ⁻² Nm ²
g	gravitational acceleration	9.81 m/s ²	9.81 m/s ²
t_{total}	total traveling time	42 sec	1.025 sec
l_c	distance between damper and car	8.4 m	13.1 cm
c_v	damping coefficient	2050 N.s/m	48.5 Ns/m
c	natural damping coefficient	0.0375 Ns/m	0.057 Ns/m ²

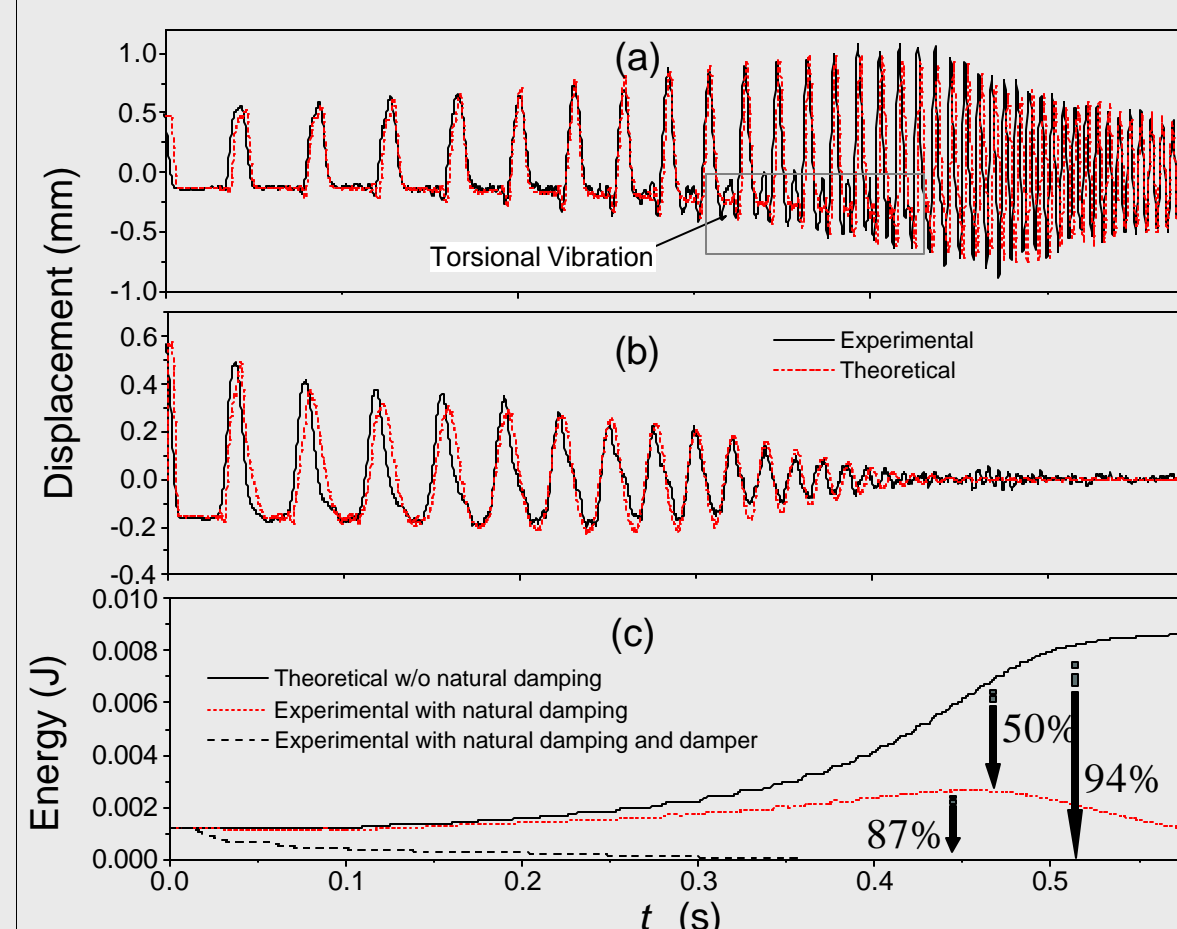
Experimental setup and results



Movement profile



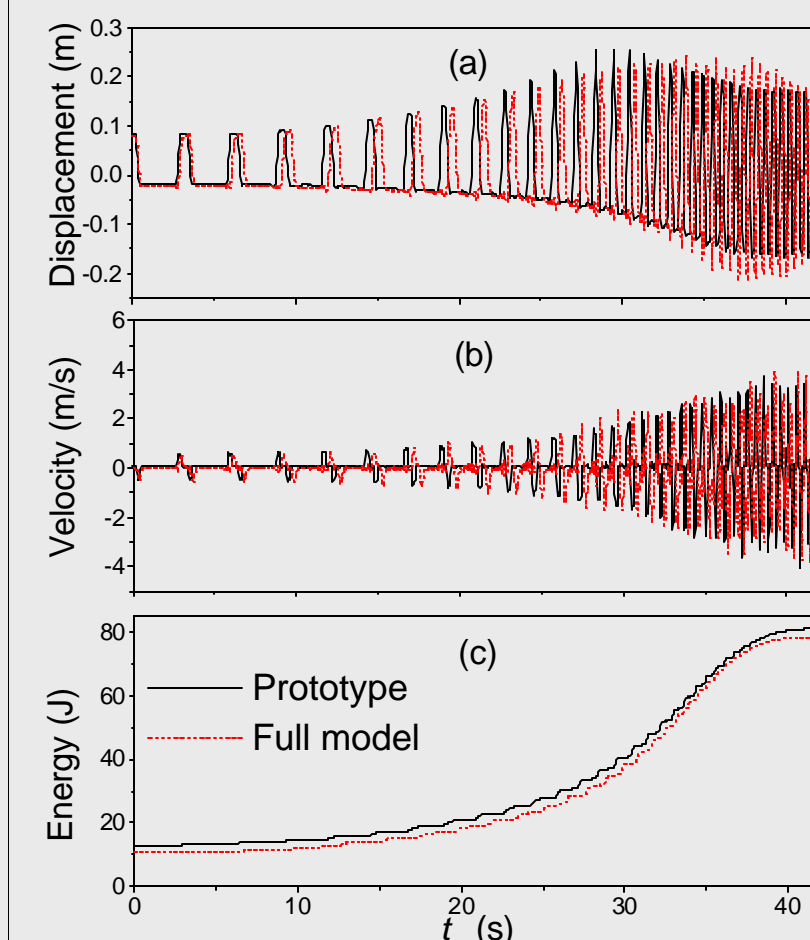
Comparison of experimental and theoretical results



Natural damping alone dissipates 50% of the overall energy, but the energy density at the end of movement is 7 times higher than that at the start of movement. The attached damper is able to dissipate an additional 87% of the overall energy, and almost 100% of the energy density at the end of movement.

Scaled Model Elevator

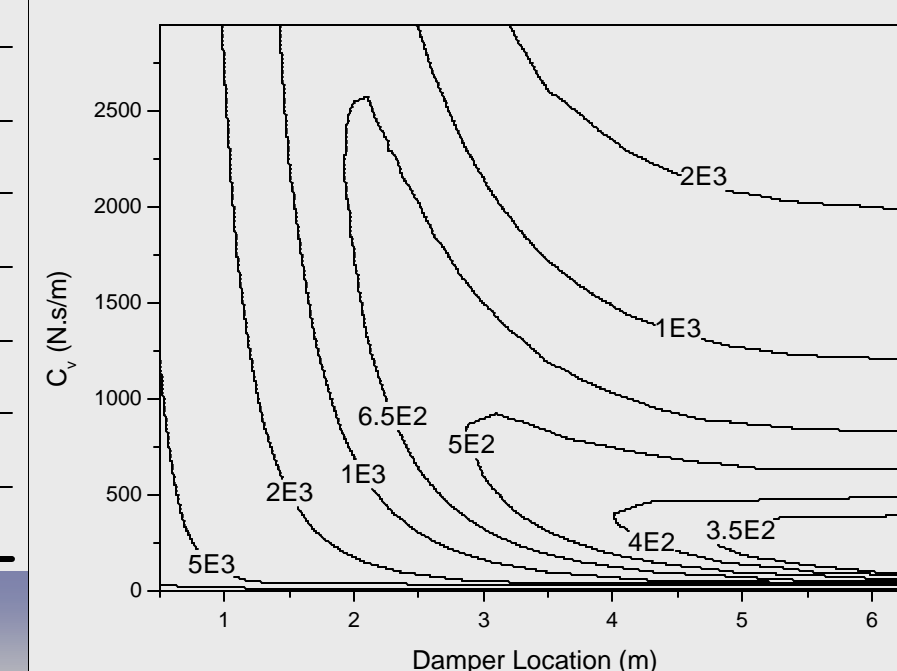
Versus Prototype Elevator



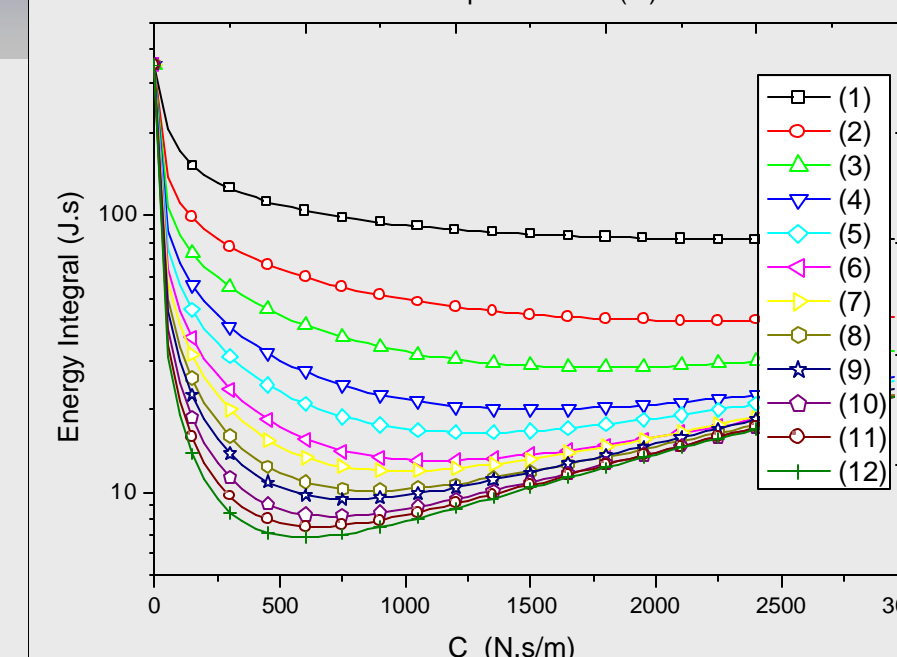
Due to the limitations of the size and available material for the model, the model elevator can not be fully scaled. However, the scaling error between the prototype and model elevators is minimized to about 5.9%, in the terms of the vibratory energies.

Optimal Damper Design

The optimal damper location and damping coefficient are found by minimizing the overall energy during upward movement. Given the initial displacements corresponding to the first 12 modes, the optimal values are obtained numerically.



A typical overall energy contour plot with respect to the damper location and the damping coefficient. The initial displacement corresponds to the 6th mode.



The overall energy with respect to the damping coefficient and the mode number used as the initial displacement.

Conclusions

1. The vibratory energy in an elevator cable increases in general during upward movement.
2. The scaled elevator can accurately predict the lateral response of a prototype elevator.
3. A damper attached to the car and moving with the cable can effectively dissipate the vibratory energy of a moving elevator cable during upward movement.
4. Experimental results validated the theoretical predictions.
5. The damper is designed by minimizing the overall vibratory energy during upward movement.

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