SmartSkin
Intelligent Surfaces
Controlling Noise & Vibration
125 Columbia Court, Suite 6
Chaska, MN 55318
952.556.5205 fax 952.556.5206
www.smartskininc.com

Methods of Controlling Energy Flow

Energy flow in a vibrating system can be controlled passively, actively and proactively (i.e. intelligently). Passive Energy Flow Control™ techniques include alterations of the mass and stiffness distributions throughout the structure to channel the energy to pre-selected regions. Active Energy Flow Control™ techniques include moving the energy with intelligent materials and the sensor/actuator systems described below. Proactive Energy Flow Control™ techniques combine passive techniques with the active techniques. In all cases, the energy is directed to pre-selected regions where first, the energy is not a disturbing feature or, secondly, it can be managed more efficiently. This approach is inherently both mass and energy efficient. **We have shown[1] that the performance of conventional active noise/vibration control systems can be improved over 90% when combined with passive Energy Flow Control™ techniques.**

There are two fundamental methods of intelligently controlling energy flow in a vibrating system: (i) introducing spatial decay and (ii) inducing power flow vortices. Both methods rely on spatial arrays of sensors and actuators attached to the surfaces of the system.

Energy Flow Control™ by Inducing Spatial Decay

This technique differs from currently available methods of active vibration cancellation in that the actuators introduce a set of properly designed special forces in addition to the forces applied by conventional active control systems.

A computer simulation showing how Energy Flow Control™ by spatial decay can be used to steer energy in a vibrating plate is discussed here. The structure consists of a flat thin plate with pinned boundary conditions. In this example, the thin rectangular plate with pinned boundary conditions was formulated and modeled using in-house developed simulation programs running on commercially available MATLAB packages. Both free and forced vibration analyses were formulated. Sensory and active layers were then added.

The equation of motion of a thin rectangular plate subjected to bending loads is expressed in Eq. (1a). In this equation, u(x,y,t) is the plate displacement field as a function of spatial and temporal variables. f_a and f_d are the actuator and disturbance forces, respectively. These forces are described in Eqs. (1a) and (1b)

[1] References will be furnished upon request.

$$D_p\left[\frac{\partial^4 u(x,y,t)}{\partial x^4}+\frac{\partial^4 u(x,y,t)}{\partial x^2\partial y^2}+\frac{\partial^4 u(x,y,t)}{\partial y^4}\right]+\rho h\frac{\partial^2 u(x,y,t)}{\partial t^2}=f_a+f_d \qquad (1a)$$

$$D_p=\frac{Eh^3}{12\left(1-\mu^2\right)} \quad , \quad f_d=F_d e^{(j\omega t)} \qquad (1b)$$

In the above, f_a is the control force. To summarize, the behavior of an *Energy Flow Control* system containing sensors and actuators mounted on a vibrating plate can be completely synthesized and modeled by us. This and other models allow us to determine optimum system energy flow configurations.

Figure 1 shows a sample displacement field of the plate with the energy steering system activated. Note that the vibration energy has been moved and is concentrated toward the
right side of the plate while the left region is quiet. Controlling the energy within a skin structure in this manner results in a totally different radiated noise pattern when compared with a conventionally vibrating skin. Velocity dependent terms may also be added to introduce simultaneous confinement and dissipation of vibration energy. **What is significant about this example is that the displacement field is fully controlled and the smallest radiating displacement (or velocity) fields are present This concept is the fundamental basis for one of our approaches.**

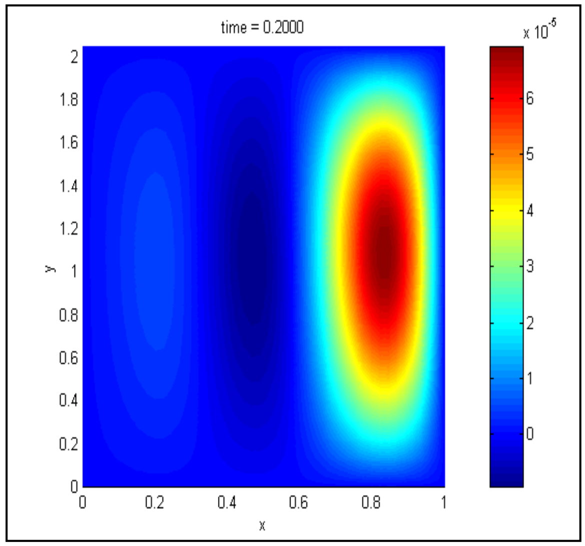

Figure 1 Confined displacement response of a plate

***Energy Flow Control*™ by Vortex Power Flow**

This technique also differs from currently available methods of active vibration cancellation in that the actuators introduce a different set of properly designed special forces in addition to the forces applied by conventional active control systems.

Vortex-type intensity response patterns generated in a structure subjected to steady-state vibrations have a strong potential for confining the vibration power flow into specific regions of the structure. In recent years, theoretical and experimental studies (references furnished upon request) have shown that structural power flow can have both translational and vortex components. Vibration intensity distribution patterns (also referred to as power flow patterns) may appear in a low damping planar structure (i.e., plate) in the form of straight, S-shape, or vortex patterns. Vortex-type power flow patterns have the potential to be used to confine excess sound and vibration energy to restricted areas or for diverting power flow away from specified sections of a structure into other areas. In both cases, critical sections of the structure remain at low vibration levels. Our main interest is in the cases when the characteristics of the structural power flow are dominated by vortex-type patterns. However, other patterns may be found beneficial as we continue our development of this exciting technology.

Inducing power flow vortices by an active control system is an effective way to divert vibration power flow away from critical sections in a structure. In certain applications, such diversion of vibration power flow is more effective than the conventional methods used to suppress or dissipate vibration energy. **The**

power required to actively divert vibration energy is significantly less than actively suppressing energy.

The input of each actuator in an actuator array is used to induce Vortex Power Flow in order to trap the vibration energy near the input source. Contrary to conventional methods that usually make an attempt to suppress, dissipate, or cancel excess vibration energy, confinement by the Vortex Power Flow approach traps vibration energy around the disturbance source and away from critical areas while dissipating some of the energy during the process. Eqs. (2a) and (2b) display the basic model that can be applied to a plate structure to simulate Vortex Power Flow. In this case, f_a are the actuator forces. The location, phase and displacement magnitude of a set of actuators can be used as controlling parameters in a simulation.

$$D_p\left[\frac{\partial^4 u(x,y,t)}{\partial x^4}+\frac{\partial^4 u(x,y,t)}{\partial x^2 \partial y^2}+\frac{\partial^4 u(x,y,t)}{\partial y^4}\right]+\rho h\frac{\partial^2 u(x,y,t)}{\partial t^2}=f_a+f_d \qquad (2a)$$

$$D_p=\frac{Eh^3}{12\left(1-\mu^2\right)}\ , \quad \mathrm{f}_d=F_d e^{(j\omega t)} \qquad (2b)$$

Figure 2 shows an example of the Vortex Power Flow that can be induced by controlling the magnitude, phase, and distribution of a rectangular array of actuators attached to the plate.

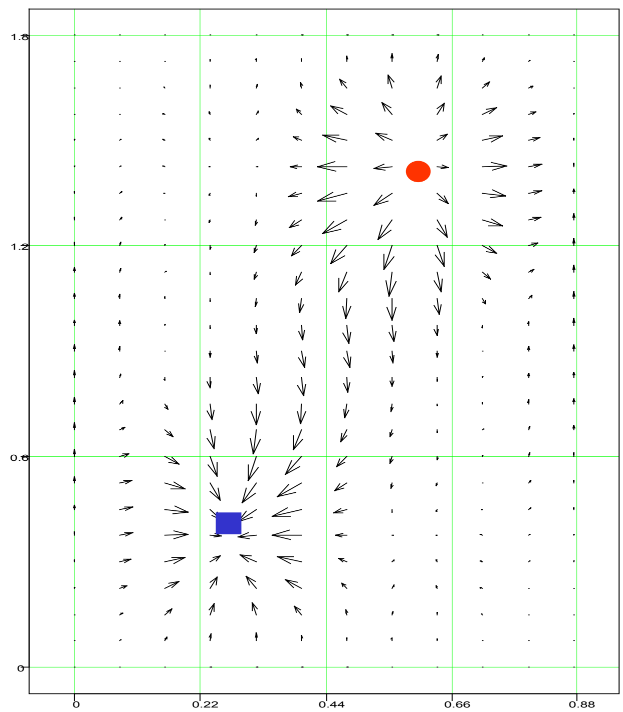

Figure 2. Straight power flow from the source (round dot) to an energy sink (square dot)