Active Vibration Control of a Plate Type Element

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Abstract: -. Successful implementation of an active vibration control system is strictly correlated to the exact knowledge of the dynamic behavior of the the system, of the excitation level and spectra and of the sensor and actuator's specification. Only the correct management of these aspects may guarantee the correct choice of the control strategy and the relative performance. Within this paper, some preliminary activities aimed at the creation of a structurally simple, cheap and easily replaceable active control systems for metal panels is discussed. The final future aim is to control and to reduce noise, produced by vibrations of metal panels of the body of a car. The paper is focused on a preliminary study, in controlled laboratory conditions, on a simple test article, represented by a rectangular aluminum plate, to compare performances of two possible control approach: Synchronized Shunted Switch Architecture (SSSA) and a feed-forward control.

Key-Words: - Active vibration control, shunted switch, active feed forward, structure dynamics, piezoelectric

1 Introduction

The evolution of automobiles, as well as many other means of transport, is a process that concerns not only with the fields of performances and aesthetic qualities, but also with comfort and environmental aspects.

Looking at the automobile sector, as an example, the necessity to develop lighter cars and the use of downsized reshaped thermic engines to reduce CO_2 emissions implies the unsuitableness of the already-used soundproofing systems.

This is not a negligible problem, because high overall noise level, as well the presence in noise spectra of specific components (as those related to various rotating elements) could be perceived by buyers as a low quality indicator, in addition to represent a notable annoyance factor.

All these considerations give evidence of the importance to develop new and more efficient noise insulating materials and technologies as those generally referred as "active control technologies".

The opportunity to use these latter technologies could help to reduce the overall weight of the acoustic treatments that can produce an increment of consumption and a more considerable environmental impact.

2 Active control strategies

Before describing the specific functions and implication of this control technique, a first definition of "Active Control" and "Passive Control" concepts may be introduced.

Passive Control may be defined as the optimization of any mechanical system (in our particular case, a structure) to limit vibrations in its standard working conditions. So, passive control systems are essential parts of the structure.

Active Control is a technological approach based on the "destructive interference" phenomenon: the sum of two signals, which are equal in amplitude but opposite in phase. Under these assumption we could say that while in the first case (passive) the control system has to dissipate energy, in the second (active) it supplies more energy to the structure for counteracting vibrations.

The necessity of integrate passive control system with active ones descends from the issue that the thickness of a soundproofing material has to be of the same order of magnitude of the wavelength of the signal to damp for being efficient: this means that, for low frequencies (typically up to 500 Hz, in some conditions up to 1000 Hz), the panel could be too thick, overloading the structure. On the other hand, active systems show application limitations due to the computational effort of the real time algorithms as well as the large amount of transducers to be implemented that generally is strongly related to the number of modes of vibration that needs to be controlled; these issues limits the bandwidth to the above mentioned 500 Hz. In addition, passive control systems have the advantage of not needing energetic supply.

Generally speaking, an active control system needs sensors, actuators and controllers, that can be combined under different control strategies: a single couple actuator-sensor with a si ngle-channel controller or more couples with a multi-channel controller.

Three of the main categories in which we can classify the control structures are:

- Feed-Forward: ideal type for controlling deterministic-type disturbances (like engine noise). The sensors measure the disturbance signal before it arrives on the structure and send it to a pack of filters (control system), which calculates it and then generates the control signals. These are sent to the error speakers to emit the wanted control noise.

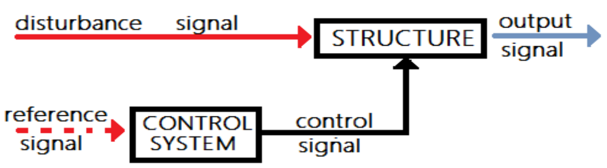

Figure 1- Block Diagram of the Feed-Forward Control System

- Feed-Back: specific for random disturbances (aerodynamic noise, rolling tyre noise). The error signal,that has to be sent to the control system, is directly extracted from the noise emitted by the error speakers and then is sent in loop.

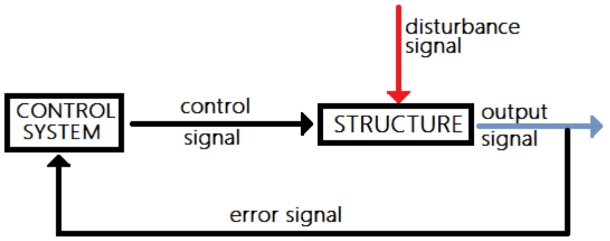

Figure 2 - Block Diagram of a Feed-Back Control System

- In some cases w e can create a m ixed-type control system, called Feed-Forward Closed Loop, specific for measurements of deterministic-type disturbances before they reach the structure. The control system receives one part of the signal directly from the disturbance and the other part from the error speakers.

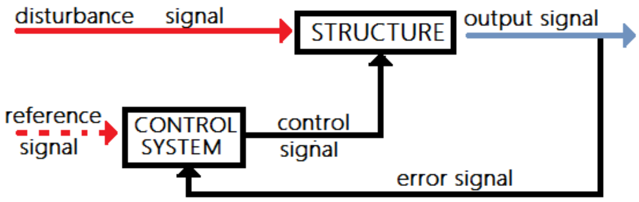

Figure 3 - Block Diagram of an adaptive Feed-Forward Control System with a feedback error evaluation

The opportunity to use one scheme or the other , strictly depend by the dynamic characteristic of the structure and the specific excitation field.

A possible alternative control strategy, which is assuming an increasing relevance, is based on shunted piezoceramic technologies to damp structural vibrations and to reduce sound pressure level as well.

The reason of the interest and demands of designing a shunt circuit can be summarized as follows: the shunt circuit should often minimize structural vibration efficiently, with a good robustness against system parameter variations and with stability. This last is a typical advantage of a semi-acrive control strategy, which is the control family of the shunted piezoceramic systems. Furthermore, the shunt circuit should not require power for operation and the weight and cost of the implemented circuit should be kept low.

Besides the system doesn't require a complex control strategy, which must be implemented and managed through a programming language by an expensive programmable digital hardware. Instead the management of the control strategy is totally of analogic type and it is guaranteed by few and very economic electronic components.

This approach of control through shunted piezoceramics considers different possible architectures:

- Resistive Shunts: t he connection of a piezoelectric transducer to a resistor dissipating structural energy by heat. This is a very cheap and easy solution to implement but damping performance is very poor [10].

- Capacitive Shunts: networks of capacitors which can be shunted on p iezoelectric transducers. This technique changes the stiffness of the transducer and therefore the natural frequency and modal damping ratio of a piezoelectric actuator are altered. In this method, the shunt circuit is only used to change the stiffness of the piezoelectric transducer and thus changing natural frequency of the piezoelectric mechanical damper [11, 12]

- Resonant Shunts: they are a more efficient family like single mode R−L or resonant multi-mode shunts [10, 13, 14, 15, 16].
  These types of shunts generate an electrical resonance with the piezoelectric capacitance. If this electrical resonance is tuned to one of the structural modal frequencies, a considerable effective damping of the corresponding mode is achieved.
  Generally, all resonant shunts suffer from the drawback that their damping performance is very sensitive to variations in the system's parameters. In this case, the resonant shunts get mistuned and do not damp anymore.
  Therefore, online tuned resonant shunts have been proposed in literature [17, 18]. However, the suggested tuning algorithms have not shown satisfying results, as they are very slow, difficult to implement and do not converge well.

- Switching Shunts: these circuits implement switches to change the dynamics of the shunt in such a way that the vibration damping can be improved. Switching shunts seem to be promising for an implementation that does not require power, because the switches can be realized with MOSFETs that require meaningless power to be switched and the small amount of power required to switch the MOSFETs that could be supplied by an additional piezoelectric patch.
  Switching R−L shunts have been proposed by [19, 20].

In the present work with the aim of obtaining a good performance without having to tune the system, it is considered a switching passive circuit which opens and closes at a precise timing. This system, which is the main object of this study, uses the electrical charge stored on the piezoelectric elements to counter the vibrations, with an effect similar to dry damping. As the switch timing is synchronized on the vibrations, no precise tuning is required, the system is selfadaptive and can be self-powered.

In the next pages it is described the experimental activity performed about the control of an alluminium plate, used as test article, adopting two different control strategies and comparing their results.

The first one will be a Synchronized Shunted Switch Architecture (SSSA), belonging to the fourth class of the previous list and an active control which is a feed-forward in an open loop system.

3 Test Article

As said in the previous sections, the final target of the proposed activity is framed in the context of improving the soundproofing in cars' cabin.

In a more detail, the final aim is to control and to reduce noise, produced by vibrations of metal panels of the body of a car. In fact, they are subjects to aerodynamic-type and rolling-type disturbances.

These perturbations depend on unpredictable factors (asphalt type, different aerodynamic conditions); sophisticated and expensive control structures, which have problems of reliability, stability and cost, are so often required.

For this reason the present activity tends to develop a structurally simple, cheap and easily replaceable active control systems. A possible approach will be the above mentioned Synchronized Shunted Switch Architecture (SSSA) or a feed-forward control. Both strategies will be implemented and compared.

Before the experimentation on the real test article that represents the final target of the study (panels of the body of a real car), a first preliminary study on an simpler test article and in more controlled laboratory conditions has been decided to be experienced.

The mock-up chosen as test article for this preliminary study is a simple aluminum plate, since metal panels in cars can be considered as plate-type components.

The aluminum plate has a thickness of 1,5mm, and total dimensions of 505 x 405 mm. The plate is clamped on the edges with two iron frames, which are applied to both faces and fixed with screws, which pass through the plate too (Fig. 4 and 5).

The free surface, which isn't covered by two iron frames has dimensions of 444 x 344 mm.

On the plate are installed three square-shaped piezoelectric components provided by Stelco GmbH. Two piezo (PPK- 23 material) are glued on the front face and marked with letters "A" and "B" (Fig.4). The first one will be used to excite the plate (exciting piezo) and the second one as actuator for the control strategies tested in the experimental activity (controller piezo)Another patch (PPK- 11 material) is glued on the back face and marked with letter "C" (Fig. 5). This last will be used as sensor piezo to convert local deformation, where it is applied in a voltage signal. The choice of piezo "C" as sensor derives from considerations that this element has the highest gain (conversion ratio) stated in a previous work [21].

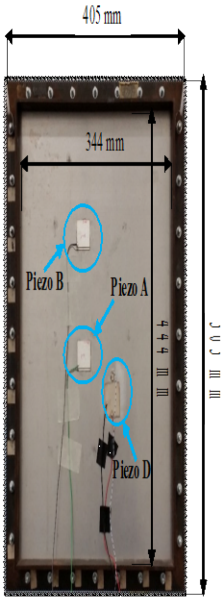

Figure 4: Front view of aluminum plate

Finally another piezo is installed on the front side of the plate, marked with letter "D", it was used as actuator to excite mechanically the plate in the dynamic characterization of the plate (Fig. 4) [21].

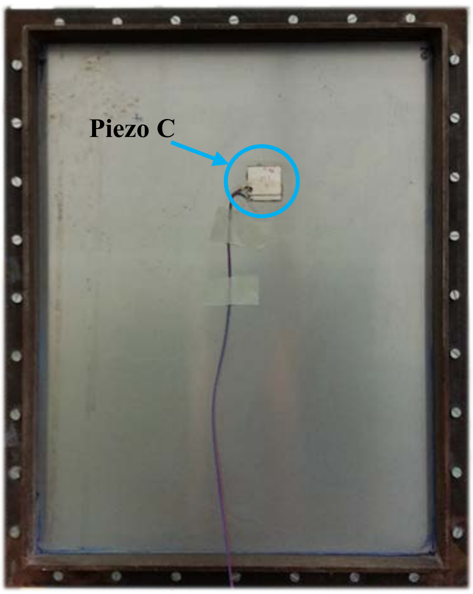

Figure 5: Back view of aluminum plate

4 Setup configuration

The experimental setup is composed by:

1. A "Polytec© PSV-400 scanning vibrometer": this is a laser doppler vibrometer, used to measure velocity of a grid of points of the plate, produced by vibrations.
2. An Ono-Sokki signal generator, which produces the perturbation signal, sent to a multi-channel amplifier and then to the Piezo A (exciting piezo).
3. A multiple-channel amplifier, which has for every channel the possibility of varying the gain and shifting the phase of outputted amplified signal against the input one.
4. An oscilloscope Infiniti Vision DSO7014A – Agilent Technologies.
5. An acquisition device LMS Scadas Mobile 05
6. An electronic circuit implementing the "synchronized switched shunt architecture" (SSSA) to regulate the controller (semi-active control).

5 Electronic circuit for SSSA

In this section is described the synchronized switched shunt architecture" (SSSA) and its implementation through an electronic circuit.

Figure 6 shows a schematic representation of the complete SSSA control system.

It consists of a switching control unit connected to the shunt branch RL and piezoelectric transducer device. The piezoelectric transducer is connected to the shunt branch through the switch control unit, which drives the CMOS switch device.

The switch control unit is described in detail as being made of a:

- Derivative & LPF (Low Pass Filter) unit: the input to the Derivative & LPF Unit is the PZT transducer voltage, converting the structural strain through the g_{31} (direct) piezoelectric constant. In fact, since the tachometer is sensitive to a zero crossing signal while the switch activation must be synchronized to the maximum strain, the input must be opportunely derived.

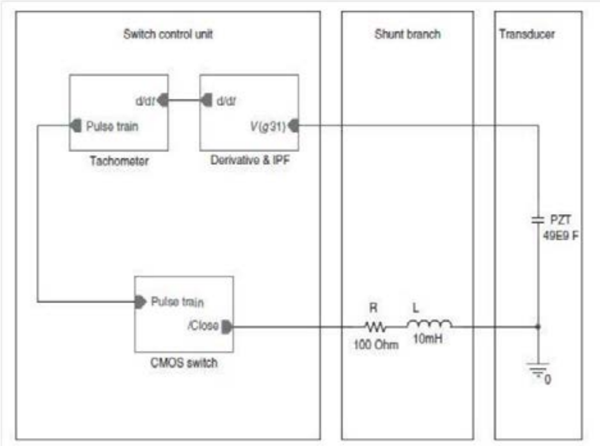

Figure 6: Scheme of the SSSA control system

- Tachometer: the tachometer input is the derived excitation signal. The tachometer output is a pulse train signal. The circuitry is able to produce the signal synchronized with the maxima deformations and with the width of 1/10 of the input signal period. The component used belongs to the LM2907 series. In keeping with the system building block concept, this device provides an output voltage which is proportional to input frequency and provide zero output at zero frequency.

- CMOS switch: the switch component is a solid state device, typically a C MOS transistor, in order to face the high frequencies and the high number of commutations. CMOS construction ensures ultra-low power dissipation, making the parts ideally suited for portable and battery-powered instruments. The CMOS switch driving input signal is a pulse train. The output is an off/on state.

The working principle consists of synchronizing the 'on state' of switch component with the maximum absolute values for the strains of the piezo sensor (blue curve of figure 7). When this event occurs, the switch device is on for about 1/10 of the highest excitation signal period to be controlled and the voltage from the switched shunt piezoelectric element (red curve in figure 7) inverts its sign.

During the on state, the piezo charge flows through the inductor which sends it back, reversed, to piezo leads, producing an impulsive strain, opposite to the vibration that generated it. Because C is fixed by the piezo element, a suitable value should be set for L, to optimize the device performance.

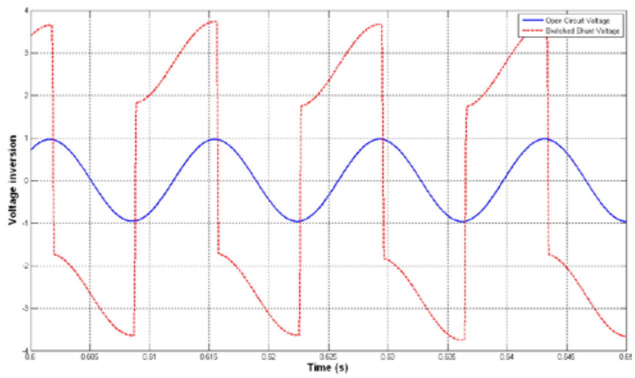

Figure 7: Synchronizing of switch activation with absolute maximum values of strains of the Piezo Sensor.

An upper limit for the inductance should be also considered, to ensure that the stored charge (inside the piezo element) remains approximately constant while the switch is on.

The lower limit for the inductance is quite arbitrary, apart the necessity to prevent the excitation of structural resonance modes by the switch action.

The inductance is calculated by:

$$L = \frac{1}{4\pi^2 * C * (f_{Ele})^2} \quad (1)$$

$$f_{Ele} = 10 * f_{Mec} \quad (2)$$

With:

f_{Mec} = Maximum mechanical frequency which must be controlled by the system (in our case fMec = 500 Hz)

C = capacity of the system

Because in our case f_{Mec} = 500 Hz and C = 15 ηF (which is the capacity of the B Piezo Controller), results a value of inductance L= 67 mH.

Figure 8 illustrates the electronic circuit, created in the laboratory of Department of Industrial Engineering.

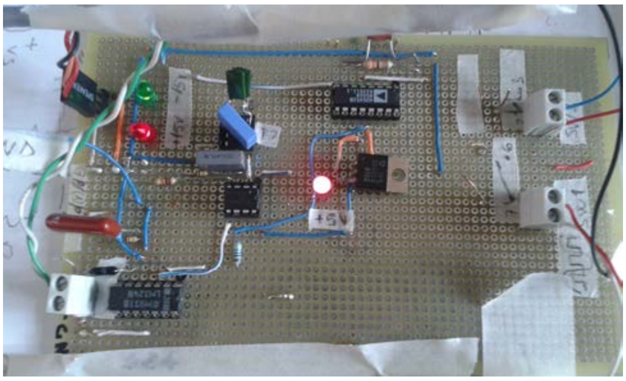

Figure 8: Electronic circuit built in the Industrial Engineering Department for SSSA implementation.

6 Experimental Activity and Results

As first step, we proceeded to the complete dynamic characterization of the plate, both under the numerical and experimental point of view, as widely described in the previous work [21].

In the present section we describe the experimental activity performed, which is divided in two parts. The first one is addressed to active control and the second one to SSSA system. Then results of two approaches are compared.

First of all, we analyze the plate's behavior when the controller is of feed-forward type.

To excite the plate an electric signal, produced by generator, is sent to the first channel of amplifier and after to the exciting piezo "A" of the plate. In more detail, to excite different modal shapes of the plate we sent to the piezo a sine wave with an amplitude of 250 V and in a first test with a frequency of 69 Hz for the first vibrating mode and after 122 Hz for the second vibrating mode. The same signal is send to the second channel of the amplifier and then to the controller piezo "B". When the actuator vibrates with a certain amplitude and frequency, we excite the controller varying the gain and the phase knob on the amplifier: this one is useful to create a phase difference between the actuator and the controller, in order to damp the vibrations ("destructive inference" phenomenon). To reveal vibrations of the plate we used the signal from the sensor piezo "C" and from the Polytec laser doppler.

The sensor piezo "C" is able to reveal a voltage signal related with the local deformations of the point, where it is applied, instead the laser, through a scanning operation on a grid of points can reveal velocities of those points.

In the subsequent pictures are reported first a comparison of the signal by sensor piezo "C" and afer a comparison of color map for velocity and displacement of grid points, both in the situations of control activated and deactivated (gain of the second channel equal to zero).

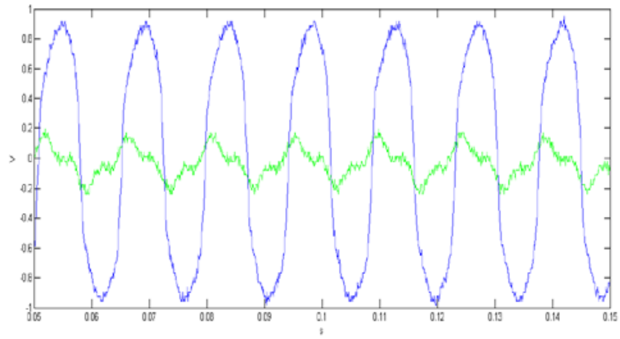

Figure 9: Signal by Sensor Piezo "C". Without control (blue), with control (green)

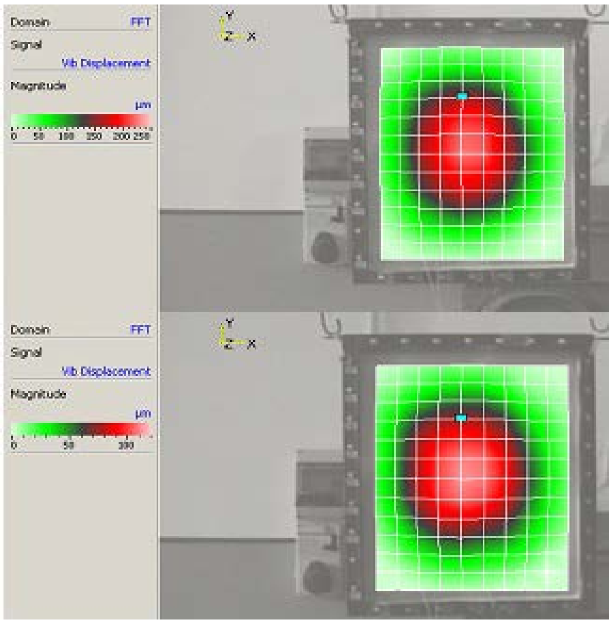

Figure 10: Color Map of Displacement (69 Hz) without control (up) and with control (down).

As we can see from the previous images there is a strong reduction of the signal from sensor piezo "C" when the control is active and of displacement too. In fact the maximum value for the Color Map of displacement (red region) decreases from 250 µm to 120 µm. A reduction is gained also in the case of excitation at 122 Hz where the maximum value for the Color Map of displacement decreases from 10 µm to 7 µm.

The same behavior is for velocity as showed in table 1 where all results of this first experimental step are summarized (displacement are not referred to maximum value but to the point of the grid where is located the sensor piezo "C".

Freq. (Hz)	Control	Velocity (mm/s)	Displacement in the location of Piezo C (µm)	Sensor (mV)
69	OFF	67,6	156,0	966,7
69	ON	33,7	77,2	176,2
69	% Difference	-50%	-50%	-82%
122	OFF	8,2	10,7	793,2
122	ON	5,3	6,9	74,6
122	% Difference	-35%	-35%	-91%

Table 1: Summary results Active Feed-Forward at 69Hz

After we have analyzed the plate's behavior when the controller is the "synchronized switched shunt architecture" (semi-active control), comparing the structure's behavior when the SSSA is activated and when is deactivated. In this configuration we use the same exciting signal but a different level of voltage, sent to exciting piezo "A" of the previous experimentation but now the second channel of amplifier doesn't feed the controller piezo "B", which is connected the RL branch to the SSSA. The scan grid and the scan parameters for the laser are the same of the previous active control case.

In the SSSA case the maximum value for the Color Map of displacement (red region) decreases from 400 µm to 160 µm. A reduction is gained also in the case of excitation at 122 Hz where the maximum value for the Color Map of displacement decreases from 8 µm to 6 µm

The results at a frequency value of 69 and 122 Hz, are summarized in the table 2. We observe, with a frequency value of 122 Hz, an increase of the velocity and the displacement values +12% when we use the controller but the local deformation, measured by piezo sensor, presents however a good reduction produced by the control system. However the maximum of reduction is gained in the case of 69 Hz where the system shows a better performance.

Table 2:Summary results Active Feed-Forward at 122Hz

Freq. (Hz)	Control	Velocity (mm/s)	Displacement in the location of Piezo C (µm)	Sensor (mV)
69	OFF	125,61	289,72	264,76
69	ON	48,734	112,41	135,52
69	% Difference	-61%	-61%	-49%
122	OFF	6,079	7,93	24,031
122	ON	6,83	8,9	13,8
122	% Difference	12%	12%	-43%

It is evident that also the SSSA carries a good reduction of signal by sensor piezo C but we must note that the performance of the SSSA system is smaller than Active Feed-Forward Control.

7 Conclusions

To improve the soundproofing in cars' cabin, it is required the development of a structurally simple, cheap and easily replaceable active control systems for metal panels of the body of a car. Before the experimentation on the real test, represented by panels of the body of a real car, a first preliminary study on a n simpler test article and in more controlled laboratory conditions has been performed, comparing two possible approach: Synchronized Shunted Switch Architecture (SSSA) and a feed-forward control.

After the experimental phase it is evident that the SSSA carries a good reduction of signal by sensor piezo C but we revealed that the performance of the SSSA system is smaller than Active Feed-Forward Control.

However in the present activity, the two control systems were evaluated only for two values of exciting frequency, corresponding to the two first natural frequencies of the plate. For this reason the next step will be is to refine the control system performance continuing experiments exciting other natural frequencies of the structure and more natural frequencies simultaneously.

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