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A FUNDAMENTAL INVESTIGATION OF THE ACTIVE CONTROL OF SOUND TRANSMISSION THROUGH SEGMENTED PARTITION ELEMENTS

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INTRODUCTION

For over a decade, there has been a significant effort in active noise control research to find feasible methods to actively reduce sound transmission through partitions. Active control of sound transmission at lower frequencies has been investigated with particular interest, because of both inherent deficiencies in passive treatments and capabilities of active control in this frequency region. In recent years, a few active sound transmission control (ASTC) strategies have been proposed that involve the physical segmentation of larger partitions into arrays of stiff subpanels. This paper explores merits and problems of such partition segmentation through an introductory theoretical investigation. Three idealized models will be presented that provide useful insights into general properties of individual actuated segment configurations.

The modeling of segment/actuator configurations will be realized using analogous electro-mechano-acoustical circuits. These circuits provide a convenient link between transducers, structures, and acoustical elements, yielding holistic insights that are difficult to envision in other ways. For the purposes of this work, mechanical devices are modeled as lumped elements; acoustical devices are modeled with elements accounting for one-dimensional wave effects. The control objective for each segment/actuator configuration is to minimize the normal velocity amplitude of its principal transmitting surface. The analysis reveals how certain configurations are unable to simultaneously control the vibration of a transmitting subpanel, its surrounding interstices, and resilient suspension. However, it also points out methods of enhancing their transmission loss performances. Further investigation demonstrates that a simple dual diaphragm configuration facilitates efficient global control of these transmitting surfaces. This latter configuration leads to the construction of relatively lightweight active partitions capable of achieving high transmission loss over a broad frequency range. Experiments have been conducted that verify the usability of the arrangement and will be the subject of an upcoming publication.

Before exploring properties of the selected partition segment/actuator configurations, the following section will address the general significance of ASTC. It will also consider the importance of partition segmentation and actuation as an ASTC strategy.

ACTIVE SOUND TRANSMISSION CONTROL AND PARTITION SEGMENTATION

Because active control of sound transmission involves various aspects of sound *and* vibration control, research in this area has been related to many important developments. As a discipline, it unites various active noise control technologies. A working definition of active sound transmission control (ASTC) might serve to broaden one's understanding of this subject. Sound transmission through a nonporous structural partition that completely separates two adjacent fluid regions may be defined as follows. It is the vibro-acoustic process in which fluid-borne sound waves incident upon the partition from one side (source side) force it to vibrate and consequently radiate transmitted fluid-borne sound waves into the space on the opposite side (receiving side). Accordingly, active reduction of sound transmission through a partition is the minimization of transmitted sound waves through the action of electro-mechano-acoustical devices regulating *any or all* stages of the vibro-acoustic sound transmission process. In certain analyses, this branch of active noise control has had reference to cases in which electro-mechanical actuation is applied only *to* the partition through which sound is transmitting. However, since ASTC may be achieved by other means, and since much research in the field has utilized other techniques, this limitation is clearly too restrictive.

The great majority of prior ASTC work has focused on the reduction of sound transmission through distributed parameter partitions (e.g., plates or shells separating two fluid media). Frequently, research has addressed the behavior and spatial optimization of error sensors and actuators in conjunction with these partitions and the surrounding media. The attention to these issues often stems from control problems associated with observability, controllability, and control spillover that occur using common sensors and actuators. In certain ways, these common transducers are ill-suited to the physical systems requiring control. As a result, various authors have proposed specialized sensors and actuators to reduce such problematic effects. Unfortunately, these devices are sometimes relatively complicated, and may be practical only for certain physical systems. Another solution, which has received very little attention, would be to construct special partitions or modify existing partitions (if possible) in a way that makes common transducers more functional.

To further the capabilities and commercialization of ASTC, it may be useful for researchers to consider the following issues more thoroughly:

1. Simplification of actuation and error sensing schemes.
2. Practicality of systems (including facility of installation, adjustment, and maintenance).
3. Applicability of strategies to a wide variety of sound transmission problems (e.g., different types of source and receiving spaces).
4. Further development of lightweight active partitions.
5. Capability of active partitions to produce very high transmission loss over the broad audio frequency range.
6. Ability of active partitions to avoid significant increase in flanking transmission — or to simultaneously decrease it.
7. Capability of simultaneous near-field and far-field sound transmission control (i.e., *absolute* global control).
8. Allowance for convenient addition of passive enhancements (e.g., for high frequency control).
9. Further reduction of problems associated with observability, controllability, and control spillover.
10. Development of partition, actuator, and sensor combinations that simplify adaptive controller requirements.

In consideration of these issues, an attractive ASTC strategy might be one that does the following:

1. Utilizes common sensors and actuators that are self-contained on or within a partition, require no on-site optimization, and are easy to access and maintain.
2. *Efficiently* minimizes the global normal surface velocity of the transmitting side of the partition.
3. Accommodates relatively lightweight partition constructions without ASTC performance limitations.
4. Adds little or no sound energy to the source space that can increase flanking transmission.
5. Allows for simple passive enhancements.
6. Has a partition construction that minimizes problems with observability, controllability, and control spillover using common transducers.
7. Minimizes coupling between adjacent partition segments, facilitating the use of multiple single-channel controllers.

In the past, researchers have found that exclusive attempts to actively reduce vibration of distributed partitions can lead to ineffective control of sound transmission.[1-5] This is true because attempted *suppression* of partition modes —*as allowed by a given actuation scheme*—may sometimes produce less of a decrease in sound transmission than a *restructuring* of modes.[6] A restructuring implies a modification of relative amplitudes and phases of partition modes to produce a normal surface velocity distribution that transmits inefficiently into the receiving space. In general, the reduction of sound transmission into a receiving space will be affected to an extent by both partition modal amplitude reduction *and* modal restructuring.[7] The weight of each mechanism will depend upon various geometric and structural/acoustic system parameters.[8,9] To a certain extent, the complexities of distributed partition ASTC result from the fact that these partitions must be actuated with secondary force or moment distributions not matching those produced by a primary disturbance. In the search for new ASTC strategies, this is a basic but important issue to keep in mind.

The notion that active suppression of partition vibration yields inadequate control of sound transmission should not be applied as a generalization to all types of partitions. Obviously, if the normal transmitting surface velocity of a partition everywhere tends to zero, the sound energy transmitted through that partition will likewise become very small. With appropriate partition construction, actuation, and error sensing, it may be possible to *efficiently* control the normal velocity over the *entire* transmitting surface of the partition. This would in turn produce high sound transmission loss.

In recent years, some authors have proposed that active partitions be segmented into stiff lightweight subpanels.[9-22] The specific rationales reported for such an approach have varied from author to author. However, generally speaking, an important objective of such segmentation has been to simplify control requirements while maintaining low partition mass. The concept of segmenting larger continuous partitions into stiff lightweight subpanels does not originate with active noise control. For example, in 1962, R. S. Jackson suggested a machinery enclosure with partitions constructed of several small, lightweight subpanels mounted into a rigid framework.[23] The purpose of this construction was to produce a relatively lightweight enclosure with sufficient overall partition stiffness to improve passive control of low frequency sound transmission. Nonetheless, it is important to note that partition segmentation as applied to ASTC is unique, and it is promising in light of the research considerations mentioned above.

Of the segmented active partition constructions that have been proposed, measured ASTC performances have varied, depending on physical configurations, actuation, error sensing, and other factors. The inconclusive nature of these performances has, in part, prompted the current investigation. The following section explores the properties of partition segment/actuator configurations in an attempt to understand their general characteristics and performance limitations. While considering the configurations, it is useful to keep in mind the seven points listed above for an attractive ASTC strategy.

SELECTED PARTITION SEGMENT CONFIGURATIONS AND THEIR PROPERTIES

In this section, simplified models of three configurations are presented that provide useful insights into general behavior of actuated partition segments. Some of the problems associated with partition segmentation for ASTC will become apparent through the analysis of the first two configurations. However, the analysis will also reveal how transmission loss limitations caused by these problems may be lessened. The third configuration incorporates a novel approach to partition segmentation and actuation that will be shown to be a more efficient ASTC strategy. To model the various configurations with manageable equivalent circuits, it will become necessary to make simplifying assumptions. These assumptions are addressed in the configuration analyses. The following list is included as a glossary of symbols used throughout the investigation.

List of Symbols.

B	magnetic flux density in magnet air gap of moving-coil actuator
c	speed of sound in fluid media (assumed the same in source and receiving spaces)
C_{MC}	mechanical compliance coupling actuator diaphragm to actuator frame
C_{MI}	mechanical compliance of interstice
C_{MP}	mechanical compliance connecting actuator support panel to rigid interstice in third configuration
C_{MS}	mechanical compliance of resilient diaphragm suspension
C_{MT}	mechanical compliance connecting passive transmitting diaphragm to rigid interstice in third configuration
e	input voltage applied to actuator
e_n	input voltage for nth configuration required to satisfy control objective
f	frequency, in Hz
G_A	acoustical ground (ambient reference pressure)
G_M	mechanical ground (zero reference velocity)
j	$= (-1)^{1/2}$
k	acoustic wave number, $= \omega/c$
L	length of cavity (i.e., distance between active and passive diaphragms) in third configuration
l	length of voice coil conductor in magnet air gap of moving-coil actuator
M_{MD}	mechanical mass of active actuator diaphragm
M_{MI}	combined mechanical mass of surrounding interstice and objects (e.g., actuator frame and magnet) rigidly attached to it
M_{MP}	mechanical mass of panel supporting actuator in third configuration
M_{MS}	effective mechanical mass of resilient suspension
M_{MT}	mechanical mass of passive transmitting diaphragm in third configuration
p_i	constant normally incident pressure amplitude
p_r	normally reflected pressure amplitude
p_t	normally transmitted pressure amplitude
$p_{t,n}$	residual normally transmitted pressure amplitude for controlled nth configuration
R_{MC}	mechanical resistance coupling actuator diaphragm to actuator frame
R_{MI}	mechanical resistance of interstice
R_{MP}	mechanical resistance connecting actuator support panel to rigid interstice in third configuration

R_{MS}	mechanical resistance of resilient diaphragm suspension
R_{MT}	mechanical resistance connecting passive transmitting diaphragm to rigid interstice in third configuration
R_n	pressure-amplitude reflection coefficient of source side face for controlled nth configuration
S	total transmitting surface area of isolated partition segment configuration, $= S_D + S_I$ in first configuration, $= S_D + S_S$ in second configuration, $= S_T + S_S$ in third configuration
S_D	active actuator diaphragm surface area
S_I	interstice surface area
S_P	actuator support panel surface area in third configuration
S_S	resilient suspension surface area
S_T	passive transmitting diaphragm surface area in third configuration
$u_{D,3}$	velocity of active actuator diaphragm for controlled third configuration
$u_{I,1}$	velocity of interstice for controlled first configuration
$u_{P,3}$	velocity of actuator support panel for controlled third configuration
$u_{S,n}$	velocity of resilient suspension for controlled nth configuration
$u_{T,3}$	velocity of passive transmitting diaphragm for controlled third configuration
TL_n	estimated transmission loss of controlled nth configuration
Z_{A1}	$= j(\rho_0 c/S)\tan(kL/2)$
Z_{A2}	$= -j(\rho_0 c/S)\csc(kL)$
Z_E	electrical impedance of moving coil actuator
Z_{MI}	total mechanical impedance of isolated interstice, $= R_{MI} + j(\omega M_{MI} - 1/\omega C_{MI})$
Z_{MS}	total mechanical impedance of isolated resilient suspension, $= 2R_{MS} + j(\omega M_{MS} - 2/\omega C_{MS})$
ρ_0	ambient density of fluid media (assumed the same in source and receiving spaces)
σ_{MI}	effective mass surface density of interstice, $= M_{MI}/S_I$
σ_{MS}	effective mass surface density of resilient suspension, $= M_{MS}/S_S$
ω	angular frequency, $= 2\pi f$

Integrated Actuator With a Single Snugly-Fitting Diaphragm. As a first attempt to actively control sound transmission through a partition using segmentation, one might consider integrating an array of actuators into the partition as indicated in Figure 1. The actuators shown are a moving-coil type, much like common loudspeakers. (Moving-coil actuators are used in this analysis for convenience, but the pertinent ASTC concepts developed for moving-coil actuators are applicable to most other actuators types, if mounted comparably.) The actuator frames (baskets) and magnet

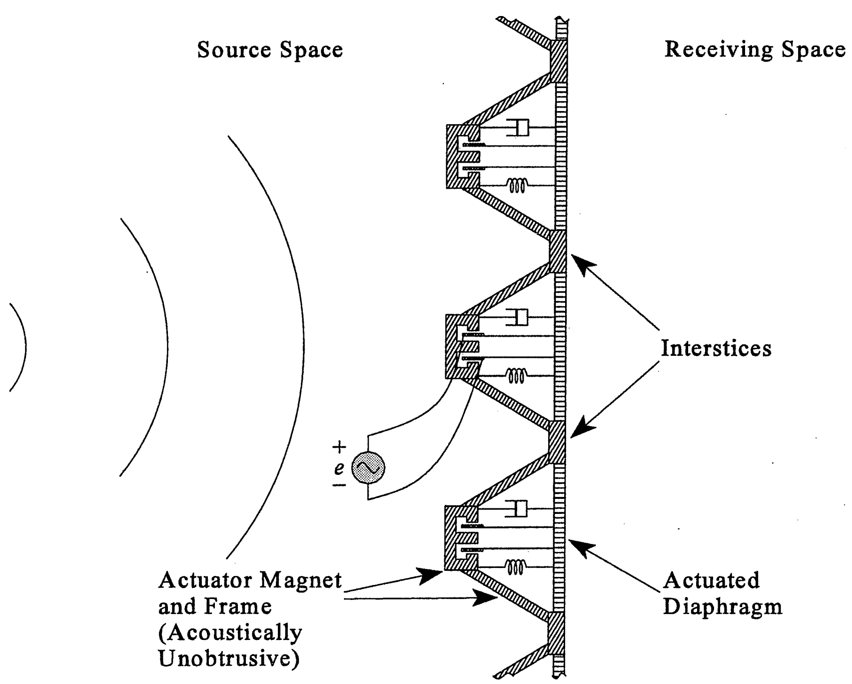

Figure 1. *Active partition consisting of moving-coil actuators with frames rigidly mounted to partition interstices.*

structures are assumed to be acoustically unobtrusive and are rigidly affixed to the interstitial partition segments (mutual interstices).

Now consider just one of the actuators in the array, along with the interstices to which it is connected, as shown in Figure 2. The interstices are assumed to be rigidly coupled around the periphery of the diaphragm to form a single rigid body with effective mechanical mass, compliance, and resistance. The actuator diaphragm is also assumed to be perfectly stiff. Both the complete surrounding interstice and the actuator diaphragm are further assumed to vibrate only in normal translational rigid body modes. The entire surface area of the discretized partition is thus assumed to be composed of piston-like segments. These may be of lightweight construction. For this first configuration, the diaphragm is assumed to vibrate freely, but fit snugly within the surrounding interstice such that no sound will transmit through an intervening crack.

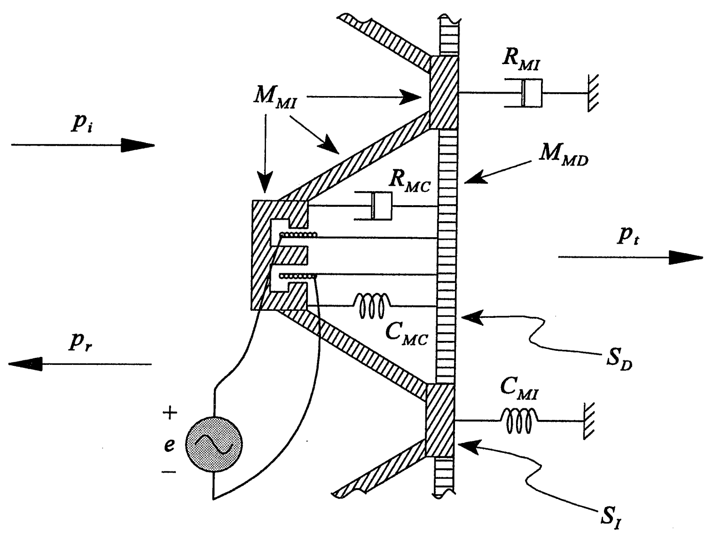

Figure 2. *Isolated view of single actuator and surrounding interstice. Plane waves are normally incident and reflected in source space, and transmitted in receiving space. Diaphragm is assumed to vibrate as a snugly-fitting piston in interstice opening.*

The source and receiving spaces are both assumed to be semi-infinite, having the same characteristic fluid impedance. A constant incident pressure plane wave impinges normally upon the partition segments from the source space. A reflected plane wave returns normally into the source space and a transmitted plane wave propagates normally into the receiving space.

An equivalent circuit representing this arrangement is shown in Figure 3. The circuit includes four ideal area gyrators[24] coupling the mechanical mobility portion of the circuit to the acoustical impedance portions, the latter representing the source and receiving spaces. Acoustic radiation from the vibrating diaphragm and surrounding

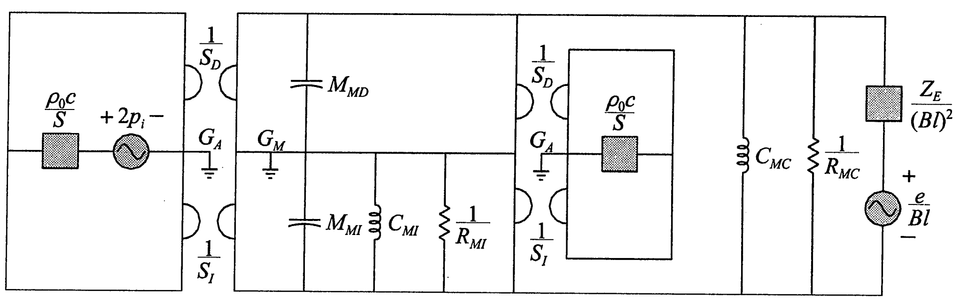

Figure 3. *Equivalent circuit representing configuration shown in Figure 2.*

interstice, as well as acoustic coupling between them, is represented in the circuit strictly for normal one-dimensional plane waves. The control voltage input and actuator electrical impedance, often appearing in the electrical impedance domain, have been "carried through" an ideal transformer to the mechanical mobility portion of the circuit. Time-harmonic excitation and control are assumed.

The velocities of the actuator diaphragm and surrounding interstice are found from the circuit by (1) writing the defining equations for the ideal gyrators and ensuring they are satisfied with appropriate flow and potential senses, (2) writing the equations of motion in all domains using Kirchhoff's flow law (i.e., writing the nodal equations for all nodes except the ground reference nodes), and (3) solving the simultaneous algebraic equations for the velocities. The velocities are functions of both incident pressure and electrical input voltage.

As a practical control scheme, the chosen objective is to minimize the velocity of the transmitting actuator diaphragm. Setting this velocity to zero allows one to determine the required input control voltage for the configuration:

$$e_1 = -2p_i\left(\frac{Z_E}{Bl}\right)\left[\frac{\left(R_{MC}+\frac{1}{j\omega C_{MC}}+\frac{(Bl)^2}{Z_E}\right)(S_D+S_I)+Z_{MI}S_D}{2\rho_0 c S_I+Z_{MI}}\right] \tag{1}$$

If the actuator is capable of handling this input voltage at all frequencies, it will drive the diaphragm velocity to zero. However, forces due to the impinging incident wave, coupling, and the reaction of the actuator motor against the finite impedance interstice will cause it to vibrate with the following velocity:

$$u_{I,1} = \frac{2p_i(S_D+S_I)}{2\rho_0 c S_I+Z_{MI}} \tag{2}$$

This result shows that force due to incident pressure on the actuator diaphragm is transferred by the actuator motor to the surrounding interstice. The transmitted pressure caused by the residual volume velocity is accordingly

$$p_{t,1} = p_i\left[\frac{2\rho_0 c S_I}{2\rho_0 c S_I+Z_{MI}}\right] \tag{3}$$

and the controlled sound transmission loss of the configuration is

$$TL_1 = 10\log\left|1+\frac{Z_{MI}}{2\rho_0 c S_I}\right|^2 \tag{4}$$

Significantly, this is the same normal-incidence transmission loss that would be found for a *passive* single leaf partition with mechanical impedance Z_{MI} but smaller surface area S_I—instead of the total surface area $S = S_D + S_I$. If the interstice is mass-controlled,

$$Z_{MI} \approx j\omega M_{MI} = j\omega\sigma_{MI}S_I \tag{5}$$

where σ_{MI} is the *effective* mass surface density of the interstice. In this case, Eq. (4) becomes

$$TL_1 \approx 10\log\left[1+\left(\frac{\omega\sigma_{MI}}{2\rho_0 c}\right)^2\right] \tag{6}$$

which is the well-known normal-incidence mass law for a homogeneous single-leaf partition with surface density σ_{MI}.[25] It is important to note in Eqs. (5) and (6) that the interstice mass M_{MI} includes the mass of the actuator frame and magnet structure. Thus, this result implies that if the interstice is mass-controlled, the active control implemented for this configuration provides no added benefit to what could be achieved by a *passive* partition constructed solely of the interstitial material with a mass equivalent to that of the actuator frame and magnet structure added to it.

For the general case, Eq. (4) indicates several important things. First, the transmission loss is independent of the diaphragm surface area. The scheme reduces the effective transmitting surface area of the overall section to that of the interstice alone. Second, the transmission loss is independent of the actuator diaphragm mass. Hence, any piston-like diaphragm of desired dimensions could be used. Third, the transmission loss will increase with increased interstice impedance. Significantly, the interstice does not have to be massive to be stiff in the direction normal to the partition. The interstices depicted in Figures 1 and 2 might be rotated 90 degrees so that they are deeper from the source to receiving side, and narrower in the plane of the partition. This would increase stiffness in the normal direction without increasing mass. It would have a simultaneous benefit of decreasing the transmitting interstice surface area S_I, which as seen in Eq. (4), would increase the transmission loss even more.

Another important property of the controlled configuration is its pressure-amplitude reflection coefficient R_1 as seen from the source space. If $|R_1| > 1$, the configuration adds energy to the source enclosure.[26,27] If $|R_1| < 1$, it absorbs energy. The total pressure on the source side face of the arrangement is solved from the equivalent circuit in terms of the incident pressure. Once this quantity is known, the reflected pressure and reflection coefficient are readily available. For this configuration, the reflection coefficient is

$$R_1 = \frac{Z_{MI}}{2\rho_0 c S_I + Z_{MI}} \qquad (7)$$

which satisfies a desirable requirement that $|R_1| \le 1$.

Based on the above analysis, it is clear that a suitable construction for a lightweight segmented partition should incorporate interstices that are as narrow as possible in the plane of the partition and as stiff as possible in the direction normal to the partition. If one can make the interstitial surface area vanishingly small and/or its normal stiffness extremely large, it would appear that the sound transmission through the controlled partition would become extremely small. However, an important detail has been overlooked that will significantly limit the configuration performance. This detail is addressed in the following section.

Integrated Actuator With a Single Diaphragm and Resilient Suspension. As demonstrated above, if the interstitial area is made small enough and its effective mechanical impedance large enough, one can neglect its vibration and contribution to sound transmission. This then allows a more careful focus on transmission through the actuator diaphragm assembly.

It was assumed that the actuator diaphragm vibrated freely and yet fit snugly within the surrounding interstice so that no sound transmission was possible through an intervening crack. In practice, these simultaneous requirements would be quite difficult—if not impossible—to achieve. For a practical configuration, an airtight seal between the actuator diaphragm and the surrounding interstice must be realized by a mechanical connection. With regard to this connection, an important requirement for reducing mechanical coupling between adjacent actuator diaphragms is to attach the diaphragms *resiliently* to typical interstices. Accordingly, a resilient airtight suspension with finite surface area is introduced between the actuator diaphragm and surrounding interstice as indicated in Figure 4. This suspension is analogous to the surround of a typical moving-coil loudspeaker. It has additional benefit when used in conjunction with an adequately-spaced rear suspension (e.g., a spider), as it helps restrict the motion of the diaphragm to a translational rigid body mode. Because of its compliant nature, the resilient suspension will vibrate in response to an impinging sound

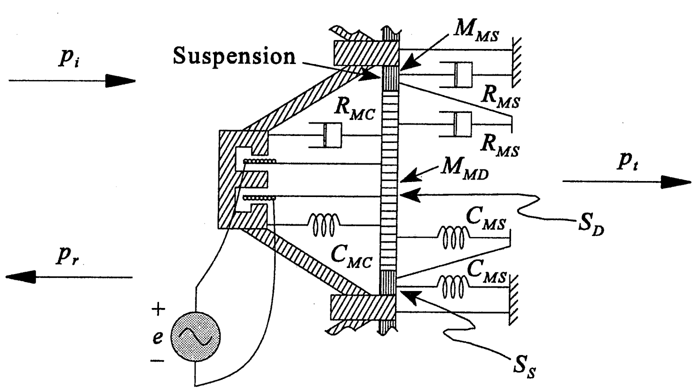

Figure 4. *Isolated view of single actuator and rigid surrounding interstice. Diaphragm is connected to interstice by a surrounding resilient suspension, here modeled with lumped mechanical elements.*

wave. Accordingly, an important issue to consider is how detrimental this vibration is to ASTC when the actuator diaphragm velocity is driven to zero.

If the interstice is assumed to have infinite mechanical impedance, the equivalent circuit in Figure 5 gives a first approximation to the configuration with the resilient suspension in place. The suspension is modeled as an effective mass connected to the both the actuator diaphragm and the interstice with identical compliances and resistances.

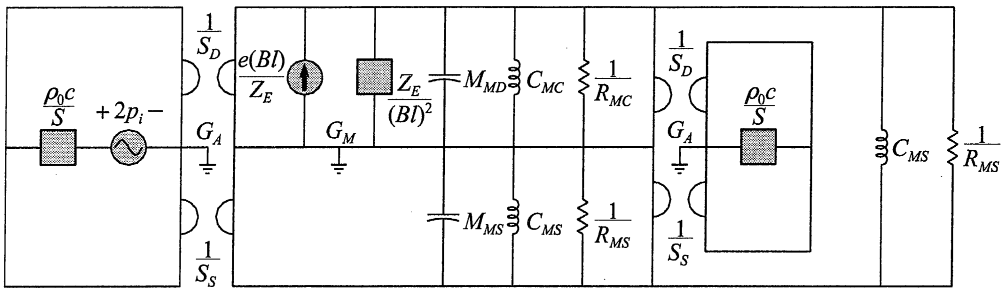

Figure 5. *Equivalent circuit representing configuration shown in Figure 4.*

Solving the circuit as described in the preceding section leads to the following results:

$$e_2 = -2p_i\left(\frac{Z_E}{Bl}\right)\left[\frac{\left(R_{MS}+\frac{1}{j\omega C_{MS}}\right)S_S+Z_{MS}S_D}{2\rho_0 c\frac{S_S^2}{S}+Z_{MS}}\right] \tag{8}$$

$$u_{S,2} = 2p_i\left[\frac{S_S}{2\rho_0 c\frac{S_S^2}{S}+Z_{MS}}\right] \tag{9}$$

$$TL_2 = 10\log\left|1+\frac{Z_{MS}S}{2\rho_0 c S_S^2}\right|^2 \tag{10}$$

$$R_2 = \frac{Z_{MS}}{2\rho_0 c\frac{S_S^2}{S}+Z_{MS}} \tag{11}$$

Once again, the controlled configuration satisfies the requirement that $|R_2| \leq 1$. If the suspension has an effective surface density σ_{MS} and is mass-controlled, Eq. (10) becomes

$$TL_2 \approx 10\log\left[1+\left(\frac{\omega\sigma_{MS}}{2\rho_0 c}\right)^2\left(\frac{S}{S_S}\right)^2\right] \tag{12}$$

The results above indicate that the way to reduce sound transmission through the resilient suspension is to reduce its surface area or increase its mechanical impedance. However, increasing its mechanical mass, stiffness, and/or resistance has important disadvantages. Dramatically increasing its mass is probably not a good option if one is trying to minimize overall partition mass. The amount that its stiffness or resistance can be increased will likewise be limited if the suspension is to remain sufficiently resilient. Thus, though these quantities may be increased within prescribed limits, the most important approach to reducing transmission through the suspension may be to minimize the suspension surface area. However, this too will have limitations.

Integrated Configuration with Supported Actuator, Air Cavity, and Passive Diaphragm. The preceding sections have provided guidelines for maximizing transmission loss through representative single diaphragm actuators and surrounding interstices. It is clear that despite these measures, there will always be fundamental limitations to the ASTC performance that can be achieved using these arrangements. In the search for improved methods to simultaneously control sound transmission through actuator diaphragms, mutual interstices, and resilient suspensions, several other configurations have emerged.[14] One that has not been previously reported is depicted in Figure 6. It is worth noting that the guidelines from the preceding analyses are intrinsically incorporated into this arrangement. The surface area of the transmitting diaphragm suspension is small and its impedance may be chosen to be as large as possible within prescribed limits. Similarly, the surface area of the surrounding interstice in the plane of the partition is small and its stiffness normal to the partition is very great. Parenthetically, it is also important in this configuration that the mutual interstices have sufficient stiffness parallel to the partition plane. This is required to minimize sound transmission between adjacent cavities, thereby reducing coupling that may be detrimental to simple adaptive controllers.

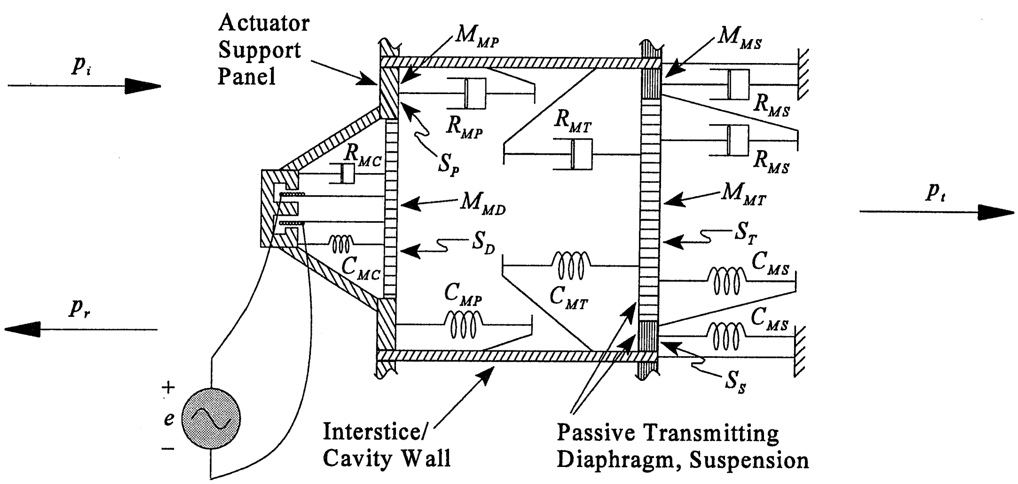

Figure 6. *Isolated view of proposed segment/actuator configuration. Active diaphragm is assumed to vibrate as a snugly-fitting piston in support panel opening. Support panel is assumed to vibrate similarly in surrounding interstice opening. Passive diaphragm is connected to interstice by a surrounding resilient suspension, here modeled with lumped mechanical elements, and a rear suspension. Support panel is connected to interstice with a resilient suspension. Active and passive diaphragms are separated by an acoustically small cavity.*

The novel characteristics of this configuration include the pair of piston-like diaphragms—one active and one passive—and the acoustically small air chamber between them. Notably, the concept of acoustically actuating the cavity of a *distributed* double panel partition is not new.[28-35] However, important distinctions of this last configuration make it unique in several ways. First, the overall partition is mechanically segmented. Second, within each partition element, the primary and secondary diaphragms of the configuration vibrate as discrete translational pistons. Third, the overall partition cavity is segmented by the interstices into acoustically smaller cavities. This has the important effect of spatially *constraining* primary and secondary pressure distributions within each cavity, and therefore on the inner faces of the transmitting diaphragms and suspensions. These distributions are thus compelled to match more closely, yielding improved active cancellation. In actuality, the pressure within a given cavity is never completely uniform and will become less uniform with increasing frequency. Nonetheless, if the transmitting diaphragm is constrained to vibrate only in a translational rigid body mode, it will respond to the total *spatially averaged* pressure across its face. Control of its velocity will consequently produce a useful effect: the same actuation that minimizes its velocity via spatially averaged pressure will also suppress the surrounding suspension velocity over a broad frequency range. Accordingly, the approach described here is not merely one of acoustic cavity actuation, but an important combination of mechano-acoustical actuation and segmentation.

As shown in Figure 6, a suspension joins the primary actuator support panel to the interstice instead of a rigid connection. This suspension is intended to control effects of mechanical coupling between the panel, interstice, and adjacent partition segments. The actuator motor may react against the supporting panel, but subsequent vibration of the panel is mechanically "isolated." The panel is assumed to fit snugly within the surrounding interstice opening to neglect sound transmission through an intervening crack or suspension into the cavity. (Transmission through a realistic suspension would be relatively unimportant in the given model anyway.) Thus, the panel supporting the actuator is characterized as a snugly-fitting translational piston of finite mechanical impedance. The principal (active) actuator diaphragm is similarly assumed to vibrate snugly within the opening of the support panel with mechanical resistance and compliance coupling it to the actuator frame. However, the transmitting (passive) diaphragm is modeled with both a rear and a surrounding resilient suspension, as described previously, permitting an evaluation of the surrounding suspension under transmitting diaphragm velocity control.

An equivalent circuit representation of the configuration is shown in Figure 7. Once again, radiation and coupling in the acoustical impedance portions of the circuit are represented strictly for one-dimensional plane waves. (This simplification neglects higher-order cavity modes and certain near-field coupling effects.) The surrounding mutual interstice is assumed to have infinite impedance normal to the partition. This simplification is made noting that sound transmission via the deep, narrow interstice is inherently minimal. As suggested above, performance limitations imposed by a resilient suspension are more difficult to control passively and are therefore of greater significance.

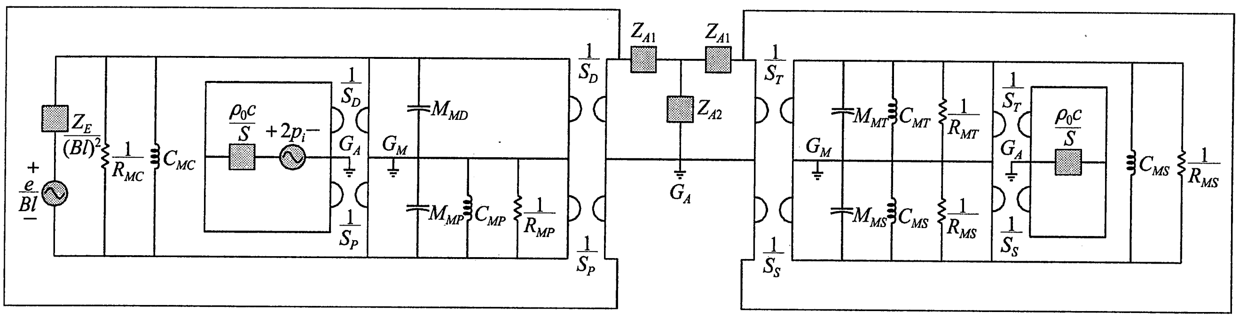

Figure 7. *Equivalent circuit representing configuration shown in Figure 6.*

Parenthetically, in the formulation of this and the previous equivalent circuits, the various modeling assumptions have been made to simplify diagrams that would otherwise become unwieldy. However, in each case, those elements that demonstrate the important characteristics of the respective configurations have been preserved.

Setting the transmitting diaphragm velocity in this last configuration to zero and solving for the required control voltage yields the following relationship:

$$e_3 = 2p_i\left(\frac{Z_E}{Bl}\right)\left[\frac{\left(R_{MC}+\frac{1}{j\omega C_{MC}}+\frac{(Bl)^2}{Z_E}\right)(S_D+S_P)^2+j\omega\left(M_{MD}S_P^2+M_{MP}S_D^2\right)}{j\omega\left(M_{MD}S_P-M_{MP}S_D\right)}\right]. \tag{13}$$

Significantly, if this input voltage is applied, both the transmitting diaphragm *and* suspension velocities become zero ($u_{T,3} = 0$ and $u_{S,3} = 0$), the transmission loss tends to infinity ($TL_3 \to \infty$), and the source side reflection coefficient becomes one ($R_3 = 1$). Two quantities that are of additional interest include the velocities of the primary actuator diaphragm and the panel supporting the actuator frame:

$$u_{D,3} = \frac{2p_i S_P(S_D+S_P)}{j\omega\left(M_{MD}S_P-M_{MP}S_D\right)} \tag{14}$$

$$u_{P,3} = -\frac{2p_i S_D (S_D + S_P)}{j\omega (M_{MD} S_P - M_{MP} S_D)} \tag{15}$$

From these expressions it is clear that the total volume velocity of the two vibrating surfaces becomes zero ($u_{D,3}S_D + u_{P,3}S_P = 0$) in the controlled state. This condition explains the source side reflection coefficient that becomes one. With zero total volume velocity driving the (one-dimensional) cavity, it is also clear how both the transmitting diaphragm and surrounding suspension velocities are driven to zero. The configuration thus enables efficient global control of these transmitting surface velocities, yielding very high transmission loss.

CONCLUSIONS

The active control of sound transmission through partitions has been an important part of active noise control research for over a decade. To further the efforts of active sound transmission control (ASTC), researchers must be attentive to several matters. Important research considerations and criteria for an attractive ASTC strategy have been suggested in this report. In general, there is a need to develop practical ASTC methods that both simplify actuation and error sensing schemes, and provide very high transmission loss over a broad frequency range. Strategies that are applicable to a wide variety of source and receiving spaces, and that achieve significant sound transmission reductions over the entire receiving space (including the near-field) are also desirable. One promising approach proposed in recent years for ASTC has been to segment partitions into stiff, discretely actuated subpanels.

In this work, a theoretical investigation has been undertaken to evaluate the effectiveness of actuator and partition segment configurations for ASTC, with the control objective of minimizing the normal velocity amplitude of transmitting subpanels. Analysis of these configurations was realized using electro-mechano-acoustical circuits. Certain simplifying assumptions were required to make these circuits manageable, but the models clearly demonstrate important characteristics and trends of segment/actuator configurations. In addition, results from the analysis are well-suited for comparison with classical normal-incidence transmission loss formulations.

The investigation has revealed the inability of certain single diaphragm configurations to simultaneously control vibration of transmitting subpanels, their compliant suspensions, and mutual partition interstices. However, it has also provided guidelines to enhance their transmission loss capabilities. Active segmented partitions should incorporate interstices that are very narrow in the plane of the partition and very stiff in the direction normal to the partition. Resilient suspensions that connect stiff diaphragms to interstices should likewise be thin in the plane of the partition and have reasonably large impedances (within prescribed limits that maintain desired resiliency). Several factors, including resilient suspensions, must be carefully considered and implemented to reduce coupling between adjacent actuated segments that could be detrimental to simple adaptive controllers.

A dual diaphragm configuration was introduced that utilizes an important combination of acoustical actuation and mechano-acoustical segmentation. The arrangement is capable of globally and efficiently controlling transmitting surface velocities over a broad frequency range. Fundamental modeling has demonstrated its effectiveness as a tool for use in active partitions intended to produce high transmission loss. Experiments have also been conducted that verify the usability of the configuration and will be the subject of an upcoming publication.

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