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Control of Sound Radiation from a Vibrating Surface using Locally Acting Acoustic Sensors and Sources

M.E. Johnson and S.J. Elliott

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UNIVERSITY OF SOUTHAMPTON

INSTITUTE OF SOUND AND VIBRATION RESEARCH

SIGNAL PROCESSING & CONTROL GROUP

Control of Sound Radiation from a Vibrating Surface using Locally Acting Acoustic Sensors and Sources

by

M.E. Johnson and S.J. Elliott

ISVR Technical Memorandum No. 818

June 1997

Authorised for issue by
Prof S J Elliott
Group Chairman

Contents

1 Introduction

This report considers the possibility of controlling the sound radiation from a vibrating surface using an acoustic control source placed close to the surface. One of the potential applications of such a system would be a number of locally acting control sources operating over the entire surface of an aircraft cabin to reduce low frequency broadband noise, i.e. boundary layer noise, radiating into the cabin.

2 A monopole primary source

Figure 1 shows a simple monopole source placed on a baffle with a secondary monopole source placed a distance r from the surface of the baffle. The secondary source shown can be considered to have an image source of similar source strength on the opposite side of the baffle. If a suitable feedforward signal were available to drive the control system then the secondary source could be used to minimize the sum of the squared pressures at a number of microphones in the far-field (free-field conditions are assumed here). The minimization of the sum of the squared pressures over a hemisphere in the far field is equivalent to minimizing the sound power radiation from the source.

The attenuation in total power output when total power output is minimized is shown in figure 2. This shows that large reductions in sound power radiation are only possible when $kr < 2$. Optimal reductions in the sound power radiation from a monopole source in a free-field using a number of sources has been investigated by Nelson *et al.* [1]. Due to the image source, the configuration shown in figure 1 is equivalent to the minimization of the sound power radiation from a monopole operating in a free-field using two secondary sources placed on opposite sides of the primary source at a distance r. Therefore, the results presented here are the same as those presented by Nelson *et al.* [1] for cancellation using two sources.

To understand the mechanism of control it is useful to look at the pressure fields created by the system before and after optimal control. Figure 3 shows a contour plot of the modulus of the pressure field of the primary monopole source (figure 1) before control and after control. The main mechanism of control is to alter the radiation behaviour of the system to be of a predominantly quadrupole type. The resulting source is not exactly a quadrupole but for the purposes of this work, this is a useful approximation [2, 1].

Figure 4 shows another representation of the modulus of the pressure field after control when the secondary source is optimally adjusted. There is a trough of minimum pressure which runs between the primary and secondary sources and continues into the far-field. As will be discussed further on in this report, this feature has important implications for a practical control strategy using an acoustic error sensor.

2.1 Distributed primary source

If the primary source in modelled as a one dimensional source (i.e. a beam) of length $2.5r$, as shown if figure 5, then the maximum attenuations possible using a single monopole

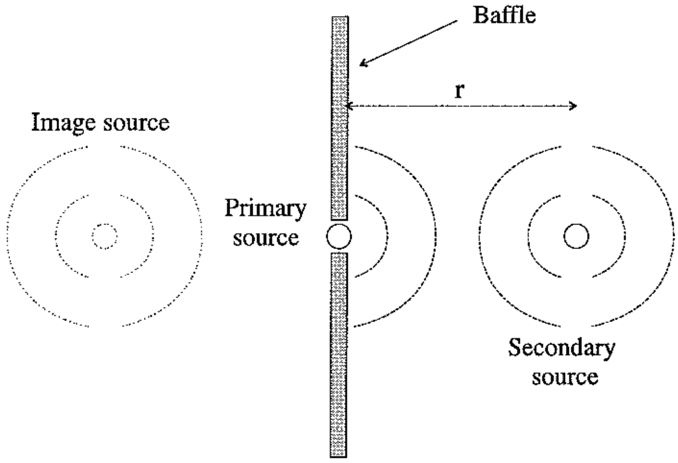

Figure 1: The location of the primary and secondary sources in an active control system designed to reduce the sound radiation from the primary source.

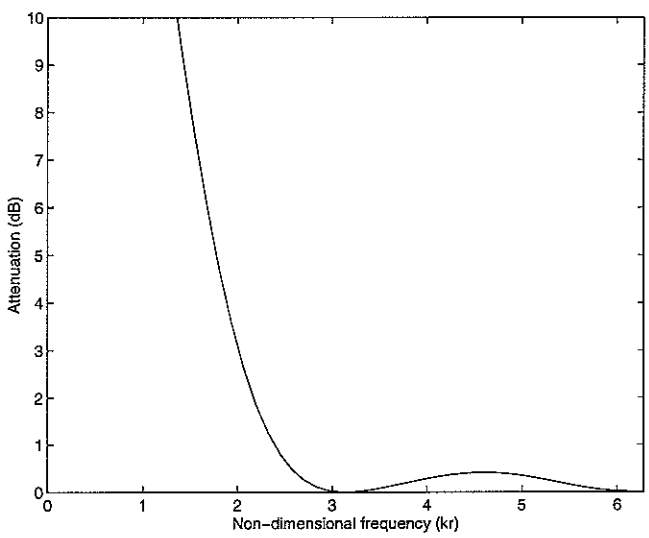

Figure 2: The attenuation in total sound power after sound power minimization using the source configuration shown in figure 1 as a function of kr.

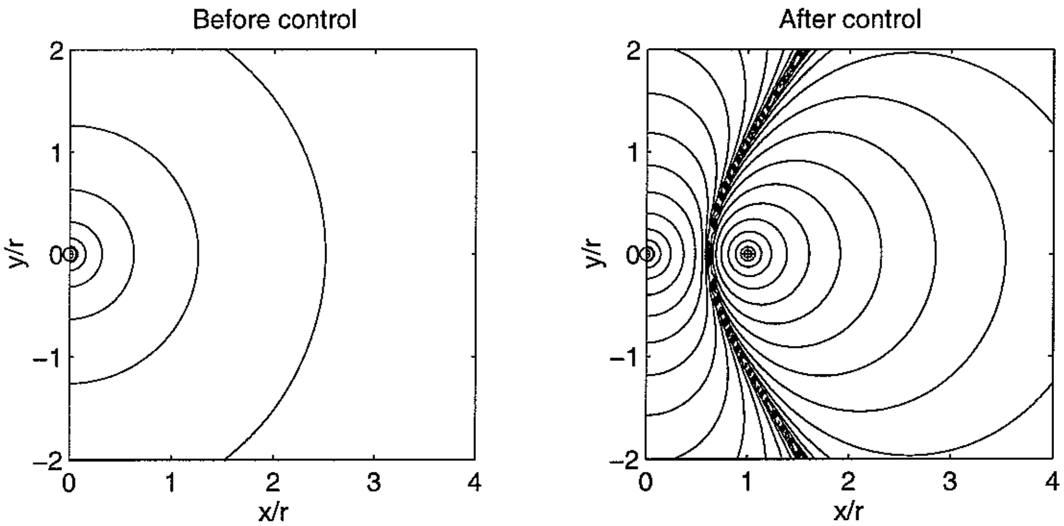

Figure 3: A contour plot ($6dB$ contours) of the modulus of the pressure field before (left-hang graph) control and after (right-hand graph) control when the secondary source (+) is set to minimize the total sound radiation from the primary source (o) and where $kr = 0.1$.

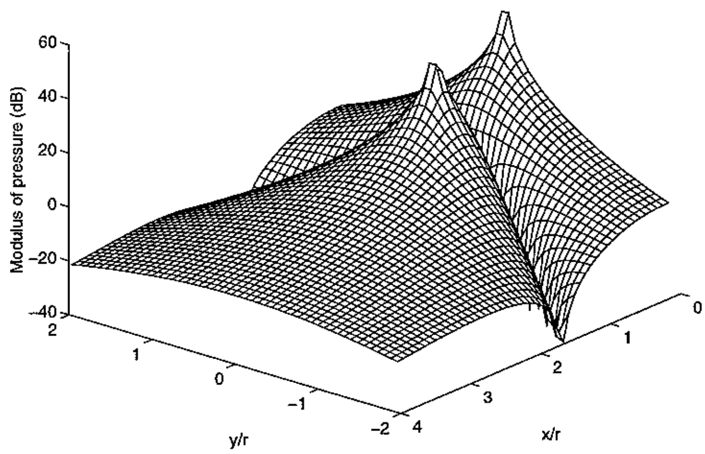

Figure 4: A mesh plot of the modulus of the pressure field when the secondary source is minimizing the total sound radiation from the primary source and where $kr = 0.1$.

secondary source are shown in figure 6 for the case in which the primary source is modelled as a piston, and also for the cases when the primary velocity distribution corresponds to the first and third modes of a simply supported beam. The primary source is modelled using a number of discrete monopole sources (twenty for these examples) whose source strengths can be varied to approximate different types of sources i.e. a piston or beam mode. The reductions in sound power shown in figure 6 take a similar form to those for a monopole primary source with good attenuations possible when $kr < 1.5$. There is some variation in the attenuation possible for the three cases considered since the distance between the primary and the secondary is no longer simply r but some distributed value i.e. the first zero in the attenuation curve is smaller than π. The radiation from the third mode of a simply supported beam (dot-dashed line) is mainly from its ends, since the middle section is self cancelling (a dipole). For this reason the effective primary-secondary distance of the third mode is the longest of the three cases considered with the first mode (dashed line) having the shortest primary-secondary distance. The effective primary-secondary distances for these cases are all longer than for the case of the monopole primary (figure 2). In principle the largest value this distance can take is the distance of the secondary from the ends of the primary which is $r\sqrt{1 + 1.25^2} = 1.6r$ which would make the first zero in the attenuation curve occur at $kr = 1.96$.

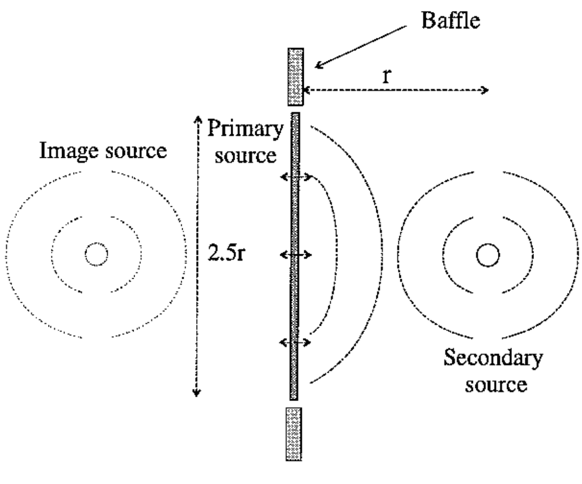

Figure 5: The location of the primary and secondary sources in an active control system designed to reduce the sound radiation from the primary source which is a distributed one dimensional source of length $2.5r$.

2.2 Cancellation of pressure as a control strategy

The modulus of the sound pressure field after control at two frequencies, $kr = 0.1$ and $kr = 1$, and for two primary sources, the first and third modes of a simply supported beam, are shown in figure 7. The sound fields in all four of these cases show similar characteristics. In all of the cases there is a deep trough which runs between the primary and secondary source and continues off into the far-field. By cancelling the pressure at

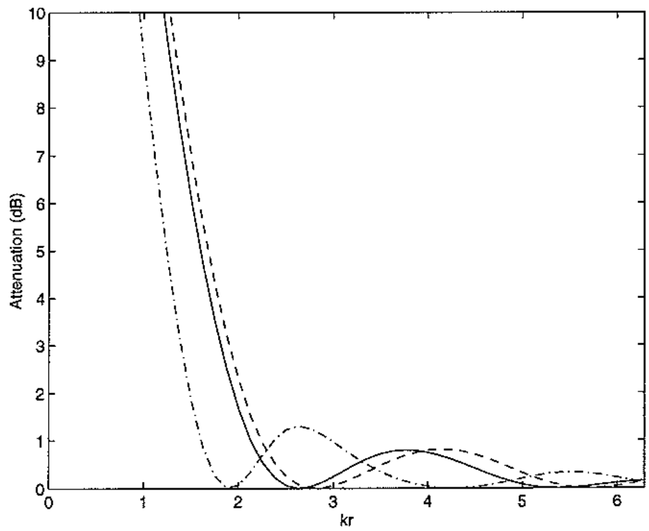

Figure 6: The attenuation in total sound power after sound power minimization using the source configuration shown in figure 5 as a function of kr. The primary source acts as a piston (solid), or with a velocity distribution equal to that of the first mode (dashed) and the third mode (dot-dashed) of a simply supported beam.

a microphone placed in this trough we would expect the resulting residual pressure field to be similar to the residual field created by an optimally adjusted secondary source and therefore achieve good reductions in radiated sound power. To test this strategy the sound pressure at a single microphone was cancelled and the resulting attenuations in sound power radiation calculated. Figure 8 shows the position of three microphones which were tested using the pressure cancellation strategy. Two of these positions (2 and 3) were chosen because they lay close to the pressure trough. Position 1 however was chosen to be close to the secondary source since this position minimized any time delay between the secondary source and the microphone as this would potentially increase the performance of a feedback control system.

The attenuations in total sound power as a result of adjusting the secondary source to cancel the pressure at each of these microphone positions are shown in figure 9, as a function of kr, for a primary source which is assumed to be the first mode of a simply supported beam. This figure shows that placing the microphone in the pressure trough, shown in figure 4, produces large attenuations at low frequencies, microphone 3 being the best position, and placing the microphone very close to the secondary, microphone 1, produces very poor attenuation.

2.3 A one-dimensional primary source with a dipole component

If the structural wavelengths on the beam are short enough such that the beam exhibits modal behaviour then the even modes (dipole type behaviour) are likely to be significantly excited. All of the above analysis is carried out on a beam with zero dipole behaviour

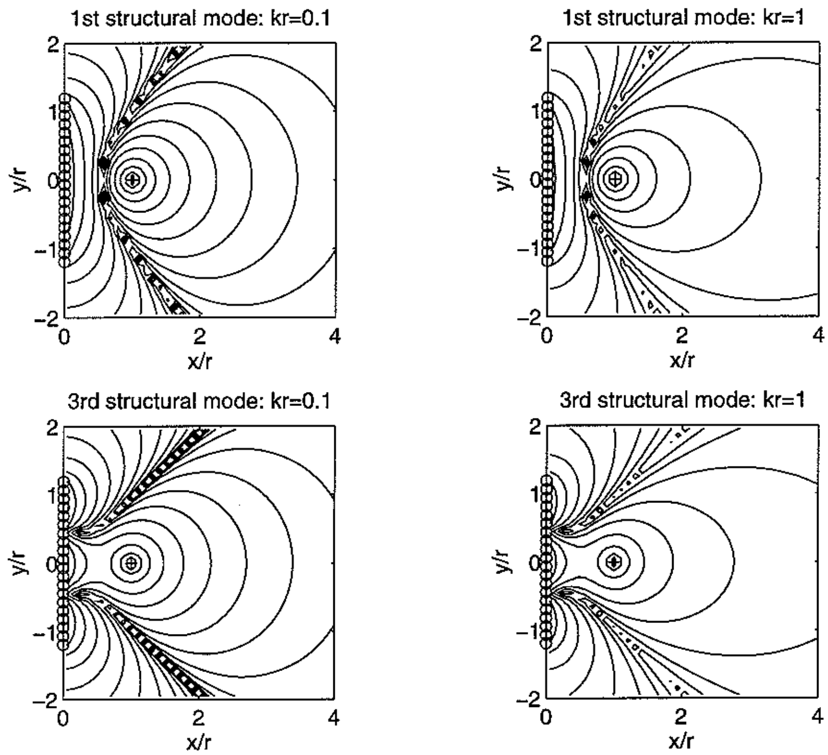

Figure 7: Four contour plots ($6dB$ contours) of the modulus of the pressure fields after control when the primary source is a first structural mode and a third structural mode and where $kr = 0.1$ and $kr = 1$.

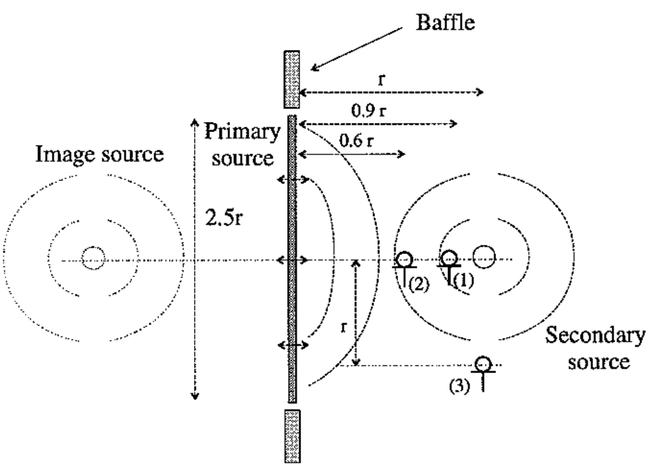

Figure 8: The positions of the three microphones used to cancel the sound pressure.

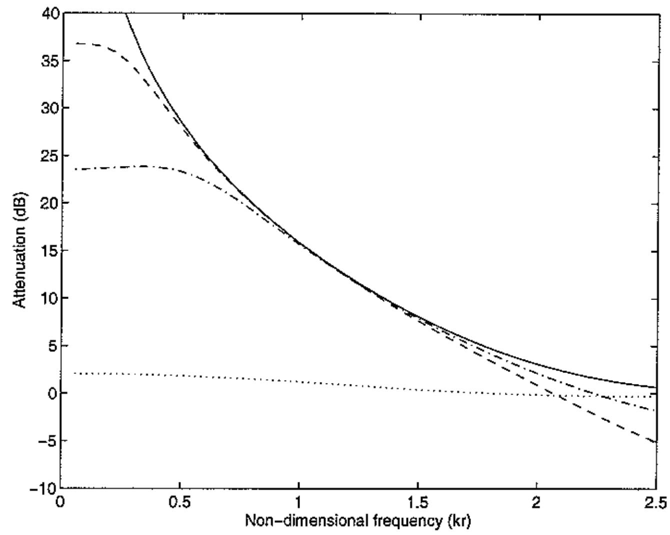

Figure 9: The reduction in sound power radiation due to optimally reducing the sound power radiation (solid) and cancelling the pressure at mic 1 (dotted), 2 (dot-dash) and 3 (dashed) when the primary source is modelled as the first mode of a simply supported beam.

and therefore by cancelling the monopole type behaviour the resulting radiation has a quadrupole form (more exactly a third order radiation mode). In any real system with relatively short structural wavelengths the attenuation will be limited by the dipole behaviour (more exactly the second order radiation modes) of the structure.

The solid line in figure 10 shows the optimal attenuation in radiated sound power when a single secondary source is used to control the radiation from a beam whose surface velocity is equivalent to a simply supported beam whose first and second modes are excited to a similar extent. The reductions achieved by cancelling the pressure at microphone location 2 (figure 8) are given by the dashed line in figure 10. The reductions in this case are not as large as those shown in figure 9 but are nevertheless substantial. By using a microphone placed at location 3 the level of attenuation is found to vary significantly depending on the particular form of the primary source. This can be explained by looking at the pressure field after optimal control (figure 11). The residual pressure field is more dipole-like and the trough in the pressure field is larger on one side of the secondary source than on the other. Cancelling the pressure at a microphone placed at position 3 will produce a different level of attenuation than cancelling the pressure at a microphone placed at a position exactly on the opposite side of the secondary source to position 3. The attenuations achieved when using microphone location 2 are less likely to be affected by changes in the primary source since dipole sources will tend to produce little pressure in this symmetric position.

If the primary source acts purely as a dipole source i.e. an even mode of a beam, then no control is possible using a single centrally placed secondary source [4]. However, it is assumed that the radiation efficiency of a dipole type source at low frequencies is sufficiently small to make the radiation, as compared to monopole type sources, insignificant.

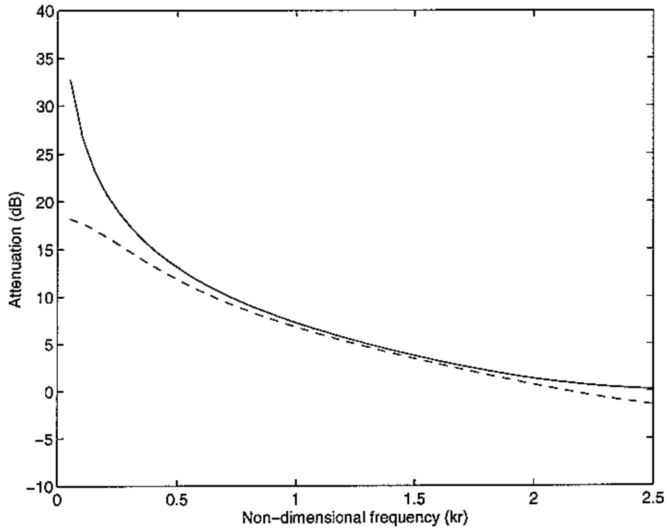

Figure 10: The reduction in sound power radiation due to optimally reducing the sound power radiation (solid) and cancelling the pressure at mic 2 (dashed) where the primary source is modelled as a combination of the first and second modes of a simply supported beam.

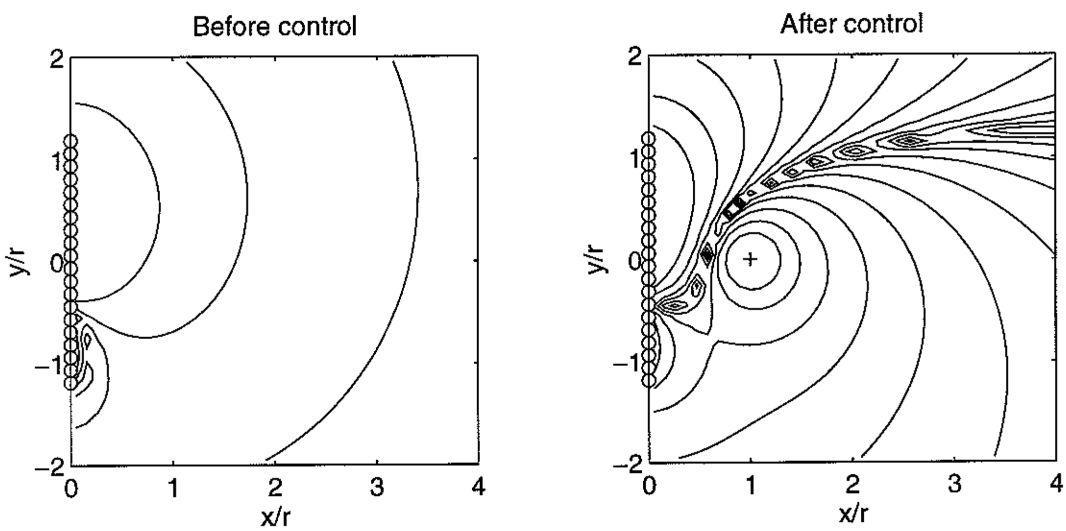

Figure 11: A contour plot ($6dB$ contours) of the modulus of the pressure field when the secondary source is minimizing the total sound radiation from a primary source which is modelled as a combination of the first and second modes of a simply supported beam. $kr = 0.1$

2.4 Control of radiation from a plate.

The control of radiation of sound from a two-dimensional primary source is a more realistic application for this active control technique. The reductions in the sound power radiation using a single monopole secondary source, where the primary source is a rectangular plate of dimensions $2.5r$ by $2.3r$, are shown as the solid line in figure 12. The primary source in this case is modelled as the first mode of a simply supported plate. As with the case of radiation from a beam, large reductions in sound power are achievable when $kr < 1.5$. The source is modelled using an array of monopole sources (eight by eight in this case) whose relative amplitudes can be varied to approximate different types of sources. Figure 13 shows a contour plot of the modulus of the acoustic pressure after optimal control, in a plane perpendicular to the surface of the plate and running through the secondary source. The secondary source is again placed a distance r perpendicular to the plate's centre and the primary source is modelled as the first mode of a simply supported plate. There is, as for the case of radiation from a beam, a trough in the pressure field after control which runs between the two sources and off into the far-field. For this example however the trough runs closer to the primary source than for the case of a beam. By cancelling the pressure at a microphone located between the secondary source and the primary source at a distance of $0.46r$ normal to the centre of the plate, large reductions in radiated sound power can be achieved and are shown as the dashed line in figure 12.

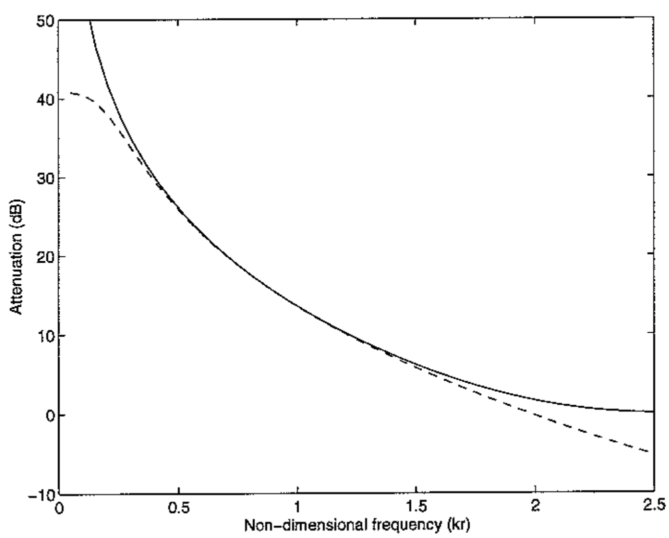

Figure 12: The reduction in sound power radiation due to optimally reducing the sound power radiation (solid) and cancelling the pressure at a microphone placed in the centre of the plate and $0.46r$ from the surface (dashed) where the primary source is modelled as the first mode of a simply supported plate.

If the primary source exhibits complex vibrational behaviour, for example higher order structural modes, then the attenuations using a microphone placed between the primary and secondary are not as large. When the primary source is modelled as the (3,1) mode

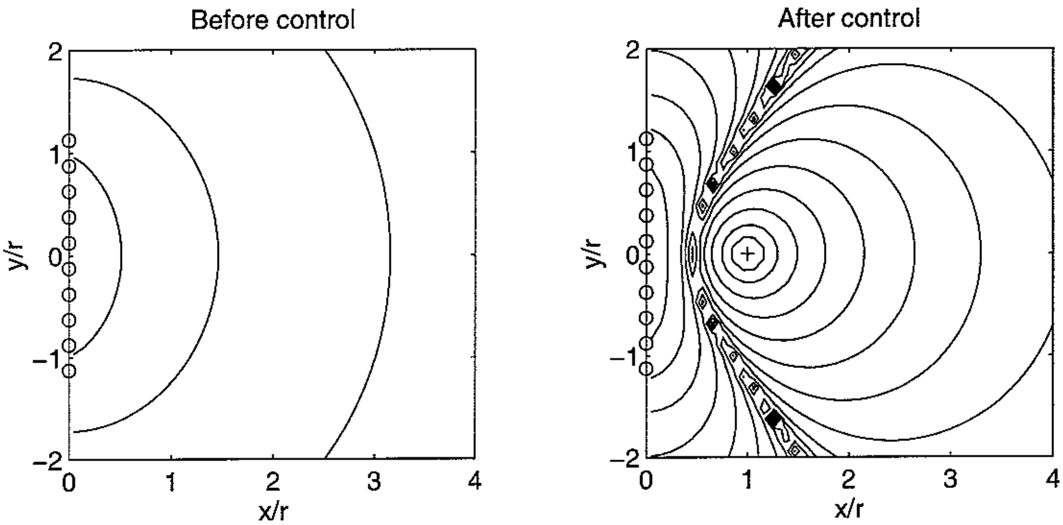

Figure 13: A contour plot ($6dB$ contours) of the modulus of the pressure field when the secondary source (+) is minimizing the total sound radiation from the primary source (o), which is modelled as the first mode of a simply supported plate, and where $kr = 0.1$. The plot represents a plane perpendicular to the plate at $z = 0$.

of a simply supported plate and the pressure is cancelled at the same position as in the above example then only $3dB$ attenuation is possible at low frequencies. However, by placing the error sensor to the side of the secondary source (as for position 3 in figure 8) then as much as $30dB$ attenuation can be achieved at low frequencies. Centrally placed microphones, i.e. between the primary and the secondary source, have the advantage of being reasonably robust to any dipole-like behaviour of the primary but do not perform as well for other types of primary source.

For a $1.3mm$ thick aluminium plate, such as an aircraft fuselage [3], the structural wavelength at $1kHz$ is approximately $0.11m$ which implies that at this frequency a panel of about $0.5m$ by $0.25m$ between the frames and stringers will exhibit complex vibration behaviour. If the stringers in the aircraft are very stiff and the external excitation is correlated over a large area then it is possible that the 'even modes' of individual sections will not be significantly excited but it is difficult to make this assumption at this point.

To determine the performance of the strategy of pressure cancellation in a more realistic situation, the primary source is modelled as a simply supported baffled aluminium plate of dimensions $0.25m$ by $0.23m$ by $1.3mm$. The plate is excited by an incoming plane wave at a polar angle of 45^o and an azimuth angle of 45^o to the x-axis. The method of calculation and the plate setup used is the same as that presented in an earlier paper by the authors [5] which follows the procedure outlined in a paper by Wang and Fuller [6]. The damping ratio is taken to be 0.025. Figure 14 shows the sound transmission ratios before control (solid line), after optimal control using a point source secondary placed $0.1m$ away from the centre of the plate (dashed line) and after cancelling the pressure at a point $0.046m$ away from the centre of the plate using a similarly positioned secondary source (dash-dot line). This plot shows that although the performance of the strategy of pressure cancellation is not very good in controlling the radiation from the (3,1) and (1,3) modes ($520Hz$ and $590Hz$), the overall performance is very encouraging with significant attenuations achieved up to about $800Hz$. The strategy of pressure cancellation also achieves similar results to the optimal strategy over most of the frequency range.

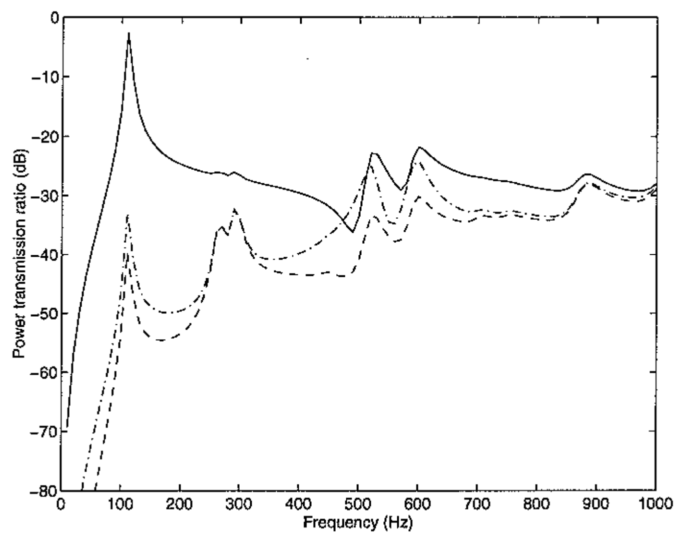

Figure 14: The power transmission ratio for a simply supported plate before control (solid), after minimization of sound power radiation using a point monopole secondary source (dashed) and after cancelling the pressure at a single point in the near field (dash-dot).

2.5 Modelling the secondary source as a rigid sphere with an active segment

Thus far in this report the secondary source has been modelled as a monopole. This section introduces a more realistic secondary source which is a rigid sphere with an active segment. The diffraction from a rigid sphere and the radiation from a rigid sphere with an active segment can be achieved using the *equivalent source technique* [7] which uses sources inside the sphere which are driven to satisfy the boundary conditions at the surface of the sphere. The case of a rigid sphere with an active segment has been done, for other simulation purposes, by Garcia-Bonito using spherical harmonic sources placed at the center of the sphere [8]. Figure 15 shows the modulus of the pressure (when $kr = 0.1$) in the near-field of a rectangular piston source of dimensions $2.5r$ by $2.3r$ with and without the presence of a rigid sphere of radius $0.4r$. Since the frequency is low the presence of the sphere does not greatly affect the pressure field.

Figure 16 shows the resulting pressure fields when the source is adjusted to minimize the total radiated sound power. Two examples are given where the active segment is facing

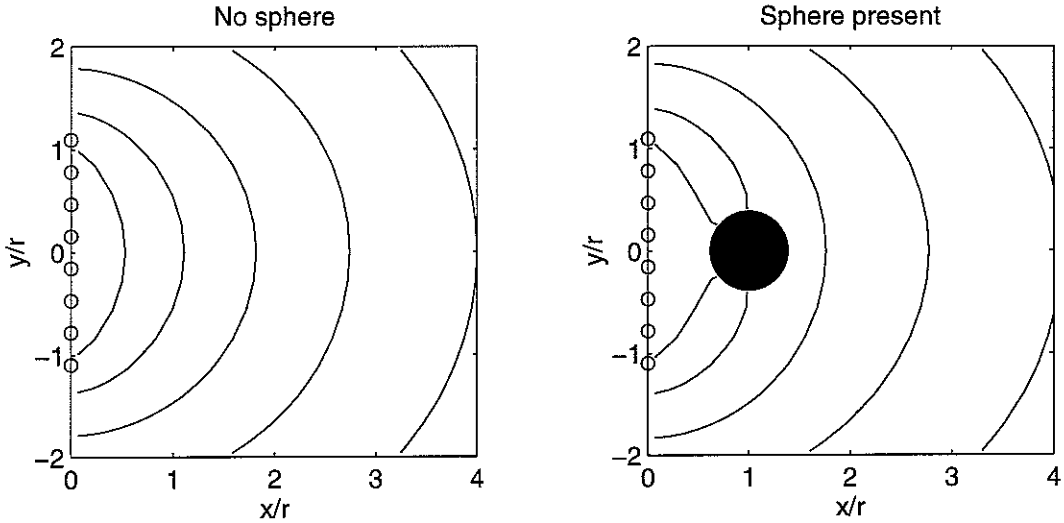

Figure 15: A contour plot ($3dB$ contours) of the modulus of the pressure in the near-field of a plate vibrating as a piston with and without a rigid sphere present. $kr = 0.1$ where r is the distance from the center of the sphere to the plate.

inward and then outward. In both examples a pressure trough is created and for the case of the active segment facing outward the trough runs into the sides of the sphere. The attenuation possible using these two configurations is shown in figure 17. It appears that by using more realistic sources the levels of attenuation can be significant even at relatively high frequencies i.e. $5dB$ at $kr = 4$ for the case of an inward facing secondary source. It is expected that the outward facing source would not achieve as good attenuation since, in effect, its active segment is further from the vibrating surface and therefore the 'kr' values are slightly biased.

For the case of the sphere with an outward facing active segment cancelling the pressure at a microphone placed in the position of the pressure trough near the side of the sphere ($x = 0.95r$ and $y = 0.4r$) achieves large reductions in radiated sound power at low frequencies. This is shown in figure 18 where a $21dB$ reductions in radiated power is achieved at low frequencies using this method.

3 Conclusions

The sound radiation from a vibrating surface can be successfully controlled at low frequencies (source size and primary secondary separation small compared to an acoustic wavelength) using a single acoustic control source. It was found that the pressure field after control, when the control source was optimally adjusted to minimize sound radiation, had a trough which ran between the primary and secondary sources in which the pressure was driven close to zero. In a practical system, where the volume velocity of the structure is difficult to measure directly, pressure transducers may instead be used as error sensors.

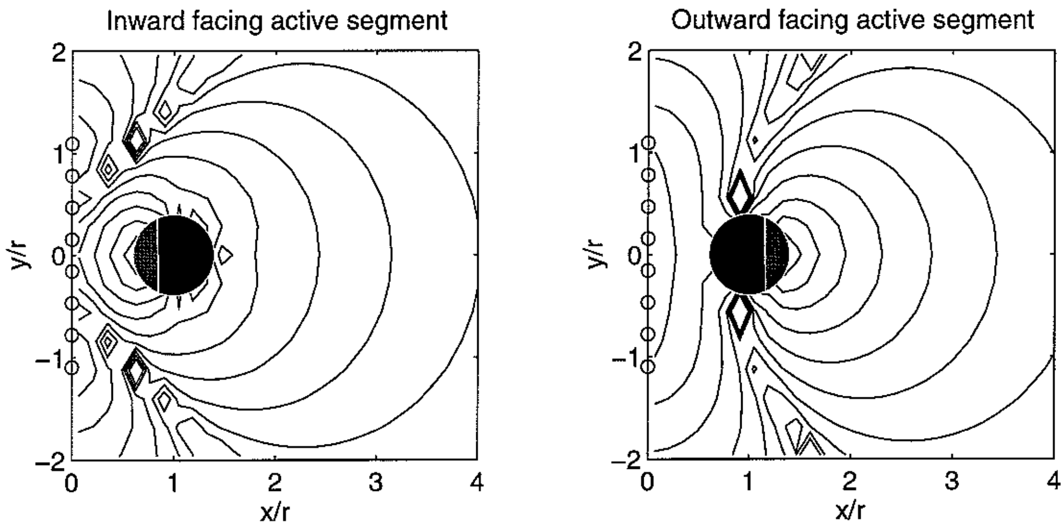

Figure 16: A contour plot ($6dB$ contours) of the modulus of the pressure when the secondary source is adjusted to minimize total radiated sound power when the active segment is facing inward (left-hand graph) and outward (right-hand graph): $kr = 0.1$

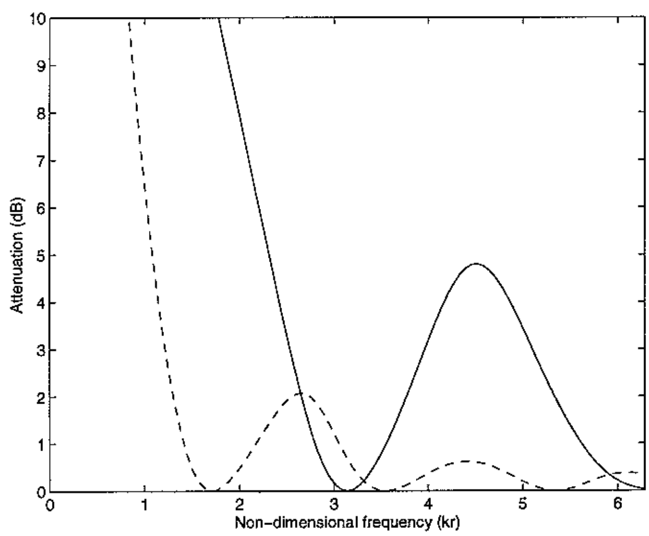

Figure 17: The attenuation achieved when using the inward facing (solid line) and outward facing (dashed line) sources when they are adjusted to minimize the total radiated sound power. The primary source is considered to be a rectangular piston of dimensions $2.5r$ by $2.3r$.

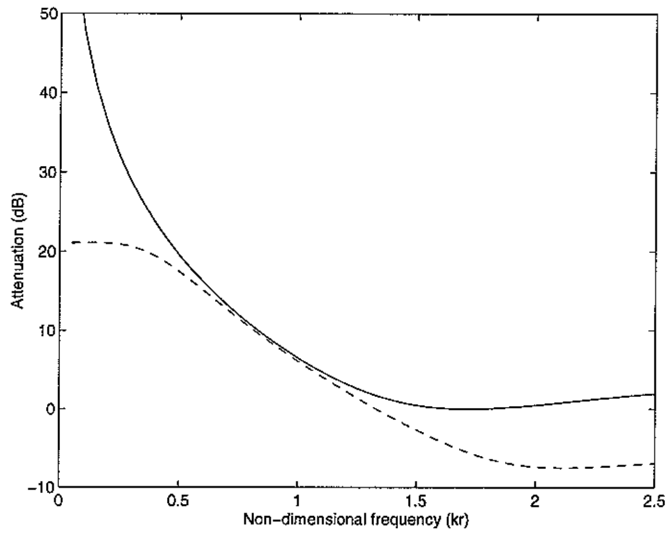

Figure 18: The attenuation achieved when using the outward facing source when the source is adjusted to minimize the total radiated sound power (solid line) and to cancel the pressure at the side of the sphere i.e. $x = 0.95r$ and $y = 0.4r$. The primary source is considered to be a rectangular piston of dimensions $2.5r$ by $2.3r$.

If the pressure sensor (microphone) was placed in a location which corresponded to a trough in an optimally adjusted case then the minimization of the output of the pressure sensor would produce similar results to the optimal case. It was found that placing the pressure sensor directly between the primary and secondary sources produced a more robust performance when the primary excitation was altered. For the case of a primary source of dimension $2.5r$ by $2.3r$ where r is the distance between the primary and the secondary source, a good position (in the near-field) for the error microphone appeared to be $0.46r$ normal to the centre the primary source. By modelling the secondary source as a rigid sphere with an active segment it has been shown that the mechanisms of control do not alter greatly from the case of an idealized point monopole. If the active segment is facing outward then the pressure trough runs into the side of the sphere and by cancelling the pressure at this position good attenuations in radiated sound power can be achieved.

The pressure cancellation control strategy was used to control the sound radiation from a primary source modelled as a simply supported plate excited by an incoming plane wave. This strategy is shown to achieve good attenuation up to $800Hz$ which corresponds to a kl value of 3.5 where l is the largest dimension of the plate and that these results compare favorable with the reductions achieved using an optimal strategy of sound power minimization. This supports earlier work where the sound radiation from a plate was controlled using structural actuators and it was also shown that good attenuations were only possible up to a kl value of 3.5 [5]. The advantage of the pressure cancellation technique is that the actuators are cheap and simple. Structural acoustic control, although requiring more complex transducers has the ability to control the radiation efficiency *and* the resonant behaviour of the structure whereas acoustic control can only affect the radiation efficiency of the primary source.

In practice the optimal position for the pressure cancellation microphone may have to be found experimentally and is dependent to some extent on the nature of the primary source and the secondary source. Without more detailed information about the physical system it is difficult to make a clear assessment of the exact location of the optimal pressure cancellation point.

If a feedback control system is used to cancel the pressure at the error microphone then the performance will be adversely affected by any delays in the system. This implies that the microphone should be placed as close to the secondary source as possible, although this may not be the best position for pressure cancellation. A feedforward control strategy could be adopted using a structural reference sensor or an acoustic sensor placed close to the surface of the primary with an acoustic error sensor placed in the "trough". However, such a strategy will inevitably require the use of a more complex control system and processor.

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