Acoustics 2008
Geelong, Victoria, Australia 24 to 26 November 2008

Acoustics and Sustainability:

How should acoustics adapt to meet future demands?

# Investigation of Control Strategies on Hull-radiated Noise and Propeller Velocity

**Xia Pan, Yan Tso, Paul Dylejko, James Forrest and Ross Juniper**

Maritime Platforms Division, Defence Science and Technology Organisation, 506 Lorimer Street, Fishermans Bend, Victoria 3207, Australia

## ABSTRACT

A theoretical analysis of active control of low-frequency radiated noise from a pressure hull due to a fluctuating propeller load is presented. The model consists of a large water-loaded cylinder, where one end is excited by an axial force due to the fluctuating propeller load while the other end is free. The active control system is implemented through a circumferential line moment applied to a ring stiffener, which could be achieved with a T-sectioned circumferential stiffener driven by pairs of PZT stack actuators. These actuators are located under the flange of the stiffener and driven out of phase to produce a control moment. The effect of the feedback of the active control action on the axial displacement of the propeller is investigated. In general, it was found that the control system was capable of reducing more than 85% of the total radiated pressure from the pressure hull at the first three axial ("concertina") modes.

## INTRODUCTION

The work described in this paper is concerned with the active control of radiated noise of a pressure hull subjected to an axial force transmitted from the propeller-shafting system to the hull.

The radiated pressure from a finite cylindrical shell in axisymmetric vibration has been investigated by Tso and Jenkins (2003), Tso *et al.* (2003) and Dylejko (2007). Pan *et al.* (2008) developed a control strategy for a large submerged finite cylinder by using a T-sectioned circumferential stiffener and pairs of PZT stack actuators driven out of phase to produce control moments around the circumference of the cylindrical shell (see Figure 1(a)). As a first approximation, the control action due to the stiffener and the stack actuators was replaced by a circumferential line moment acting around a bulkhead as shown in Figure 1(b). The inclusion of the bulkhead demonstrates how the method of analysis may be applied to shells with structural discontinuities. A simplified model of the pressure hull may then be considered as a structural junction with two cylindrical shells and a circular plate. Pan *et al.* (2008) then demonstrated theoretically that the control moment could reduce the total radiated pressure from the pressure hull.

In the previous studies (Tso *et al.* 2003 and Pan *et al.* 2008) the primary excitation acting on the pressure hull was assumed to be a unit axial force. However, in reality, the axial load from the propeller is transmitted through the shaft, thrust bearing assembly, foundation and then finally to the pressure hull. The axial force at the driving point of the hull is frequency dependent, and can be significant at blade rate and propeller-shafting resonances. A modification to the pressure hull is therefore required to include the propeller shaft, thrust bearing assembly and foundation to account for the effective axial force that is transmitted to the hull.

Dylejko (2007) further developed the propeller-shafting system model used by Goodwin (1960) to include the drive-point impedance of the hull. The pressure hull in this case was modelled as an orthotropic cylindrical shell with rigid end plates.

The current work combines the active control technique (Pan *et al.* 2008) with the propeller-shafting system (Dylejko 2007). In the current paper, the effect of the feedback of the active control action on the axial displacement of the propeller is investigated. With this active control strategy, the combination of the stiffener and the actuators are capable of developing a control moment to reduce the total radiated pressure from the pressure hull due to the fluctuating propeller load at low frequencies.

Only axisymmitric motion of the pressure hull has been considered in this paper, since the axisymmtric modes are the most efficient radiator (Junger and Feit 1986).

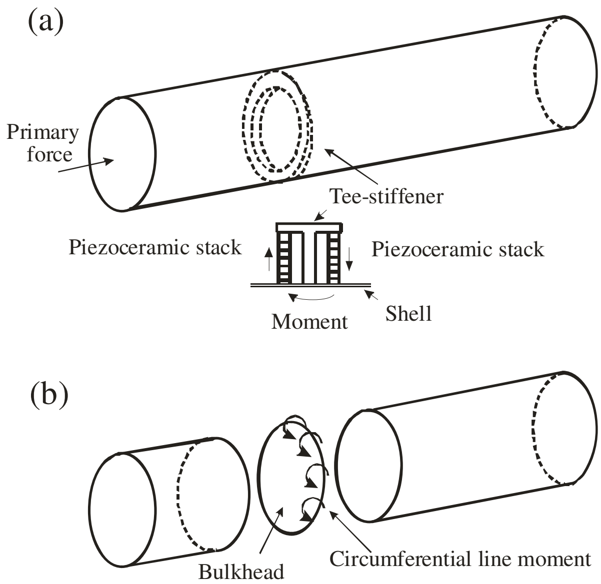


**Figure 1.** (a) Proposed physical model of a pressure hull showing the locations of the primary force and T-stiffener, together with a cross-section of the T-stiffener with actuators; (b) The theoretical model which uses a circumferential line moment applied at a circular-plate bulkhead to represent the action of the T-stiffener and actuators.

The present analysis assumes that the axial force is the dominant cause of underwater radiated noise at low frequencies. The effects of propeller moments and forces in other directions, as well as the effect of hull vibration due to fluid excitation by the propeller (Kinns 2006), are not included in this analysis.

## THEORY

### Pressure hull

An axisymmetric analytical dynamic model of a pressure hull is given by Pan *et al.* (2008) where expressions for the cylindrical shell and end plates are given. These expressions will be used later in this paper to obtain the active control moment to minimize hull radiation.

### Propeller-shafting system (PSS)

A schematic diagram of the PSS model is given in Figure 2. This dynamic model assumes that the propeller and entrained water around the propeller are represented by a lumped mass $m_p$ with viscous damping $c_p$. The propeller shaft, which is modeled as a continuous elastic element, connects the propeller to the thrust block. The thrust bearing, which consists of an oil film separating the thrust pads and bearing plate, is represented by a spring, mass and damper system of stiffness $k_b$, mass $m_b$ and damping coefficient $c_b$. The thrust block is assumed to be attached to the hull via a truncated conical shell. These substructures are modeled by a four-pole parameter representation which consists of a series of 2×2 transmission matrices linking the force and velocity at the propeller to the hull (see Dylejko 2007).

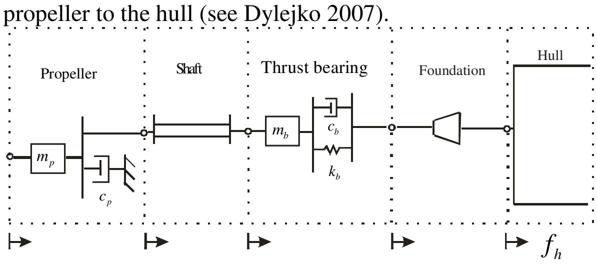


**Figure 2.** Propeller-shafting system model.

The combined response of the complete PSS is given by a 2×2 matrix $\boldsymbol{\beta}^{ps}$ and may be determined by the forward matrix multiplication of the respective four-pole parameters of the different substructures. The expression given by Dylejko (2007) is:

$$\boldsymbol{\beta}^{ps} = \boldsymbol{\alpha}^{p}\boldsymbol{\alpha}^{s}\boldsymbol{\alpha}^{b}\boldsymbol{\alpha}^{f}, \tag{1}$$

where $\boldsymbol{\alpha}^{p}$, $\boldsymbol{\alpha}^{s}$, $\boldsymbol{\alpha}^{b}$ and $\boldsymbol{\alpha}^{f}$ are the transmission matrices of the propeller, shaft, thrust bearing and foundation respectively. The force at the hull resulting from a unit load at the propeller is defined as (Snowdon 1971):

$$f_h = \left( \beta_{11}^{ps} + \frac{\beta_{12}^{ps}}{Z_d^h} \right)^{-1}, \tag{2}$$

where $\beta_{11}^{ps}$ and $\beta_{12}^{ps}$ represent the first and second elements in the first row of the matrix $\boldsymbol{\beta}^{ps}$, and $Z_d^h$ is the driving-point impedance of the hull. The force transmission through the propeller-shafting system $T_f$ is given by:

$$T_f = | f_h |. \tag{3}$$

The propeller velocity resulting from a unit load is given by Dylejko (2007) as:

$$v_p = \left[ \beta_{21}^{ps} + \frac{\beta_{22}^{ps}}{Z_d^h} \right] f_h. \tag{4}$$

### Active control of total sound radiation

The total sound radiation of the pressure hull due to the transmitted axial force and the control moment is given by Pan *et al*. (2008):

$$p_t(R,\theta) = f_h\, p_{u-f}(R,\theta) + m p_{c-m}(R,\theta), \tag{5}$$

where $R$ is the distance from the middle section of the pressure hull to the observer, $\theta$ is the angle between the axis of the pressure hull and the line connecting the middle section of the pressure hull to the observer, $p_{u-f}$ is the radiated pressure due to a unit force, $m$ is the control moment and $p_{c-m}$ is the radiated pressure due to a unit moment. The total pressure is the sum of the radiated pressure from the cylindrical shell and the two end plates.

The PSS may be replaced with a complex force acting on the driving point of the pressure hull. The control moment is applied as a uniform line moment around the circumference of the cylinder.

The optimal control moment may then be obtained by evaluating the derivative of Equation (5) with respect to the control moment and setting the result to zero. This results in the following expression for the optimal control moment:

$$m = -f_h \frac{\int_0^{\pi} p_{u-f}(R,\theta) p_{c-m}(R,\theta)^* \, d\theta}{\int_0^{\pi} | p_{c-m}(R,\theta) |^2 \, d\theta}. \tag{6}$$

For the case of active control, the influence of the control moment on the drive point impedance has to be taken into consideration. The impedance of the hull $Z_d^h$ is calculated on the basis of a unit drive-point force that results in a drive-point velocity caused by both the drive-point force and the control moment $m\,(f_h = 1)$.

After evaluating the complex force $f_h$ using Equation (2), the required control moment may be determined by substituting the force into Equation (6). The total radiation may then be evaluated by Equation (5).

## NUMERICAL RESULTS

The numerical results presented in this section are based on a steel pressure hull of 6.5 m diameter, 45 m length and shell thickness of 0.04 m. Two cases of primary excitations are investigated for comparison. They consist of an axial force of 1 N amplitude applied at the propeller and directly at the end of the pressure hull ($x$ = 0). The location of control moment also plays an important part in the active control system and the effect of two control moment locations are investigated in this paper. The sound pressure level at a distance of 1000 m is used as the error signal for sound radiation control. The cost function to be minimized is the radiated sound power of the pressure hull.

### Control source close to primary excitation

This section considers the effect of using a control moment located at $x = 0.2$ m. The force transmission versus frequency for the uncontrolled and actively controlled cases, are shown in Figure 3. The fundamental PSS resonance is observed at 56.8 Hz. The other peaks are due to hull resonances which will be shown in the next figure.

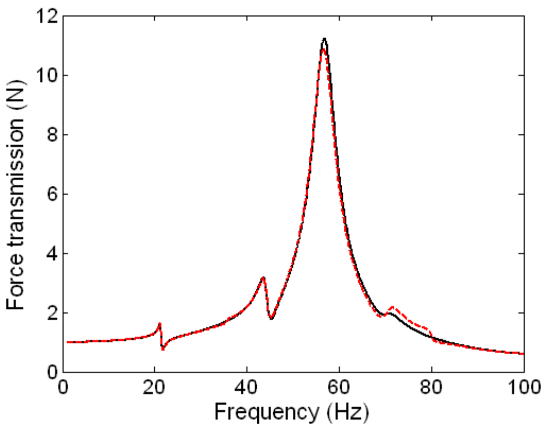


**Figure 3.** Force transmission at the pressure hull resulting from 1 N propeller force and control source located at $x = 0.2$ m. —, uncontrolled; - - -, actively controlled.

For the actively controlled case, the force transmission is similar to the uncontrolled case, except that the transmitted force increases slightly between 70 and 80 Hz. The slight increase may be due to a feedback of the active control action which will be addressed in detail below. At the PSS resonance, the active control system has reduced the axial force. It must be kept in mind that the controlled response may change with different control moment locations.

Figure 4(a) shows the displacement at both ends of the pressure hull $x = 0$ and $x = L$ for a unit load at the driving point $x = 0$. In order to obtain a realistic amplitude near the resonance frequencies of the hull, a structural loss factor of 0.02 is used in the calculations. It can be seen that the first three axial modes are approximately 21.5, 44.9 and 70.5 Hz. Figure 4(b) shows the result of repeating the calculation displayed in Figure 4(a), but for the pressure hull connected to a PSS with a unit propeller load. Comparing Figures 4(a) and (b), it is noted that the PSS has shifted slightly the first three axial modes to 21.4, 44.2 and 70.6 Hz. The peak at 56.7 Hz (see Figure 4(b)) is due to the fundamental PSS resonance.

Figure 5 shows the controlled and uncontrolled maximum far-field radiated sound pressure from the pressure hull due to the two primary excitations. Comparing Figures 5(a) and (b) for the uncontrolled cases, it was found that with the introduction of the PSS, the maximum radiated pressure was reduced at the first axial mode but increased at the second and third axial modes. As expected, Figure 5(b) shows a considerable maximum radiated pressure at the PSS resonance. For the controlled cases, Figures 5(a) and (b) show the control moment reduces the maximum radiated pressure at all the axial modes for both primary excitations. Figure 5(b) indicates the active control action reduces the maximum radiated pressure at the PSS resonance as well.

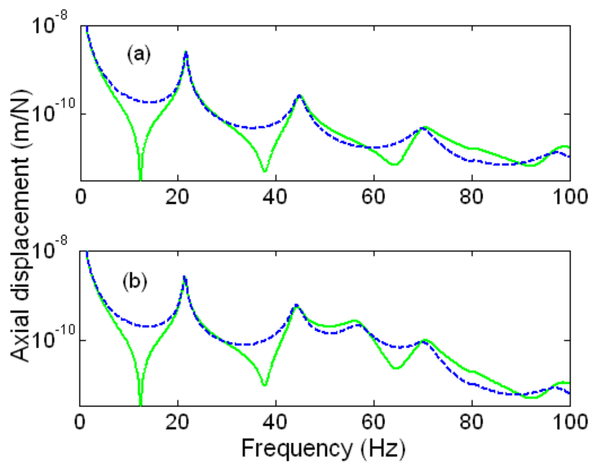


**Figure 4.** Axial response of the pressure hull. (a) due to 1N axial force at the drive-point $x = 0$; (b) due to 1 N propeller load. —, axial displacement at $x = 0$; - - -, axial displacement at $x = L$.

Results shown in Figure 5 indicated that in general, the control moment could reduce the radiated pressure from the cylinder at the axial modes. However, the application of a control moment may affect the dynamic response of the PSS and in particular, the axial velocity of the propeller. This may result in an increase in radiated pressure due to direct radiation from the propeller. In Figure 6, the effect of the control moment on the propeller response is examined.

Figure 6 shows the uncontrolled and actively controlled propeller velocities are generally similar to each other. However, the controlled propeller velocity decreases slightly at the PSS resonance and increases between 70 and 80 Hz similar to the transmitted force (see Figure 3). It should be noted that the term "actively controlled propeller velocity" is referring to the result from active control of hull radiation by the control moment. The control moment is not used to control propeller velocity.

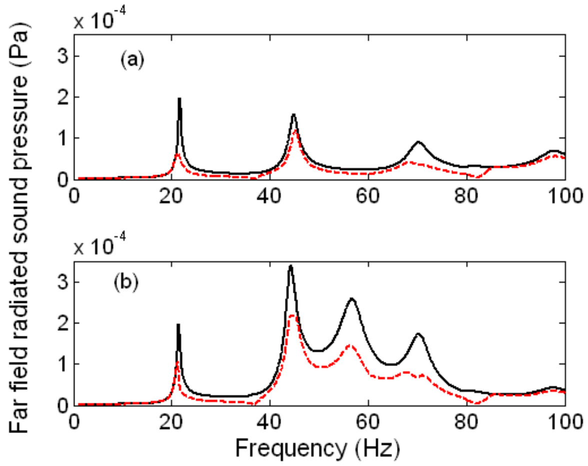


**Figure 5.** Maximum far field radiated sound pressure of the pressure hull with control source located at $x = 0.2$ m. (a) due to 1N axial force at the drive-point $x = 0$; (b) due to 1 N propeller load. —, uncontrolled; - - -, actively controlled.

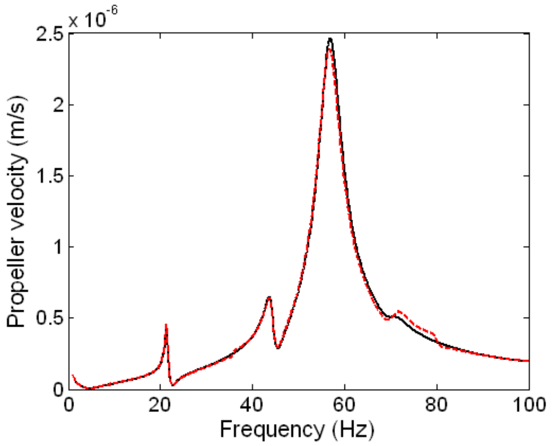


**Figure 6.** Propeller velocity due to 1 N propeller load with control source located at $x = 0.2$ m. —, uncontrolled; - - -, actively controlled.

Figure 7(a) shows the actively controlled and uncontrolled directivity patterns of the pressure hull at the first axial mode. It can be seen that approximately 55% reduction of the total radiated pressure is obtained.

Figures 7(b) an 7(c) show the results of the radiated pressure at the second and third modes respectively. In can be seen that the effect of the control action broadly follows a similar pattern as for the first axial mode, except that the reductions in total radiated pressure in these cases are about 50% at both axial modes.

Figure 7(d) presents the results at the PSS resonance. It can be seen that the reduction in total radiated pressure in this case is reduced slightly with approximately 45% for this pressure hull and PSS configurations.

If more than three pairs of PZT stack actuators were located evenly on the T-sectioned circumferential stiffener, the resulting point moments could be treated as approximately a line moment around the circumference of the hull. Table 1 shows the line moment amplitude required for 1 N of axial propeller load, where the control moment is located at $x = 0.2$ m. The frequencies shown in Table 1 are obtained from the peak locations in Figure 5(b). It can be seen that the amplitude of the control moment decreases with increasing axial mode number for this moment location.

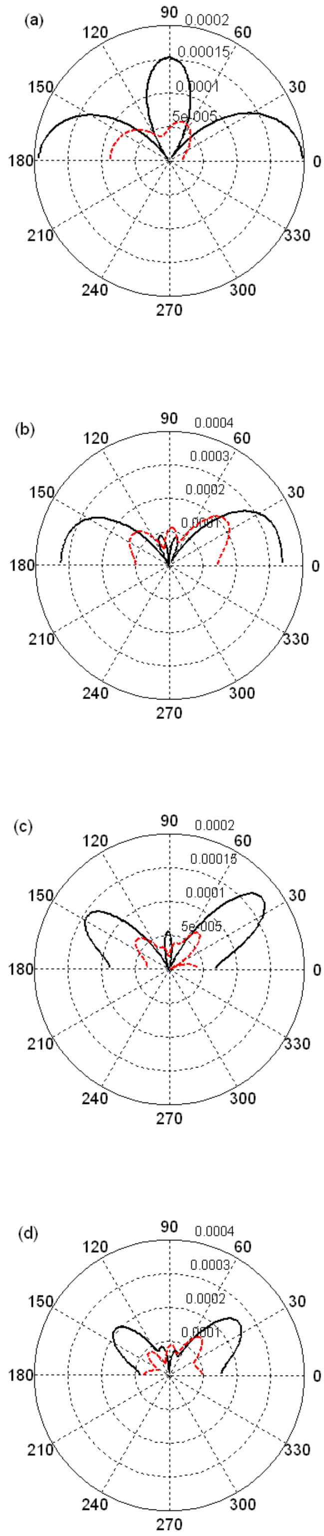


**Figure 7.** Total radiated pressure of the pressure hull for 1 N propeller load and control source located at $x = 0.2$ m. The radiated pressure is plotted in polar coordinates with angle in degrees and radius in Pascals: (a) first axial mode; (b) second axial mode; (c) third axial mode; (d) PSS resonance. —, uncontrolled; - - -, actively controlled.

**Table 1**. Line moment amplitude required for 1N propeller load and control source located at $x = 0.2$ m.

| Resonance | Freq (Hz) | Amplitude (Nm/m) |
|---|---|---|
| First mode | 21.4 | 1.06 |
| Second mode | 44.3 | 0.62 |
| PSS | 56.7 | 0.32 |
| Third mode | 70.3 | 0.08 |

To enable an easy comparison of the effectiveness of the control strategy, the controlled and uncontrolled total radiated pressure of the pressure hull is plotted in dB scale as shown in Figure 8. It can be seen that active control action has achieved average reductions at the first three modes as well as PSS resonance.

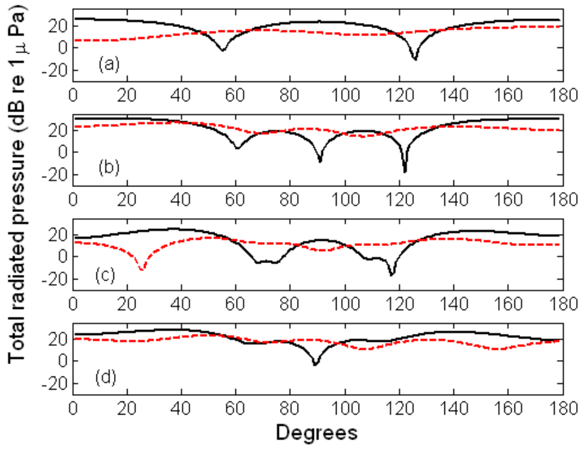


**Figure 8.** Comparison of total radiated pressure of the pressure hull for 1 N propeller load and control source located at $x = 0.2$ m: (a) first axial mode; (b) second axial mode; (c) third axial mode; (d) PSS resonance. ——, uncontrolled; - - -, actively controlled.

## Control source away from primary excitation

This section considers the effect of using a control moment located at $x = 15$ m which is at $L/3$. To conserve space, only results of the radiated pressure will be presented below. Results of the force transmission, end displacements and propeller velocity are similar to those shown in the previous section.

Figure 9 shows the result of repeating the calculation displayed in Figure 5, but for the new control source location. Comparing Figures 9 and 5, it was found that with the new control source location, significant reductions of maximum radiated pressure are achieved at the first three axial modes for each of the primary excitation. However, there is only a small reduction of the maximum radiated pressure at the PSS resonance (see Figures 9(b) and 5(b)).

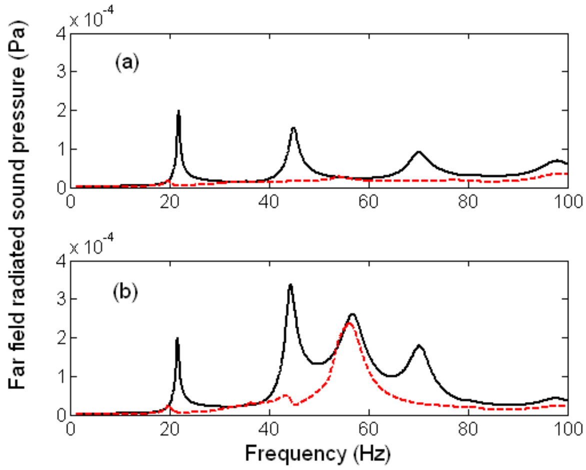


**Figure 9.** Maximum far field radiated sound pressure of the pressure hull with control source located at $x = 15$ m. (a) due to 1 N axial force at the drive-point $x = 0$ m; (b) due to 1 N propeller load. ——, uncontrolled; - - -, actively controlled.

Figures 10 shows the result of repeating the calculation displayed in Figure 7, but for the new control source location. It can be seen that the reductions in total radiated pressure in these cases are more significant with 95% at the first mode, 88% at the second mode and 85% at the third mode. As shown in Figure 9(b), there is no advantage in using a far away control source to reduce the total radiated pressure at the PSS resonance.

Table 2 shows the line moment amplitude required for 1 N axial propeller load, where the control source is located at $x = 15$ m. The frequencies shown in Table 2 are obtained from the peaks in Figure 9(b). In comparison with Table 1, it can be seen that the control moment required in this case is increased at the first and third axial modes and PSS resonance. Note that the small differences in the frequencies shown in Tables 1 and 2 are due to different locations of the ring stiffener.

**Table 2**. Line moment amplitude required for 1 N propeller load and control source located at $x = 15$ m

| Resonance | Freq. (Hz) | Amplitude (Nm/m) |
|---|---|---|
| First mode | 21.5 | 5.39 |
| Second mode | 44.3 | 0.47 |
| PSS | 56.7 | 1.91 |
| Third mode | 70.2 | 0.10 |

Figure 11 presents the results corresponding to Figure 8. It can be seen that the active control moment with the new location results in a large reduction of radiated pressure at each of the first three modes, significantly more than those with the control moment at $x = 0.2$ m. Comparing Figures 11 and 8, it can be seen that the active control is most effective for reducing radiated pressure at the axial modes. For reducing the radiated pressure at the PSS resonance, care must be taken on the control source location.

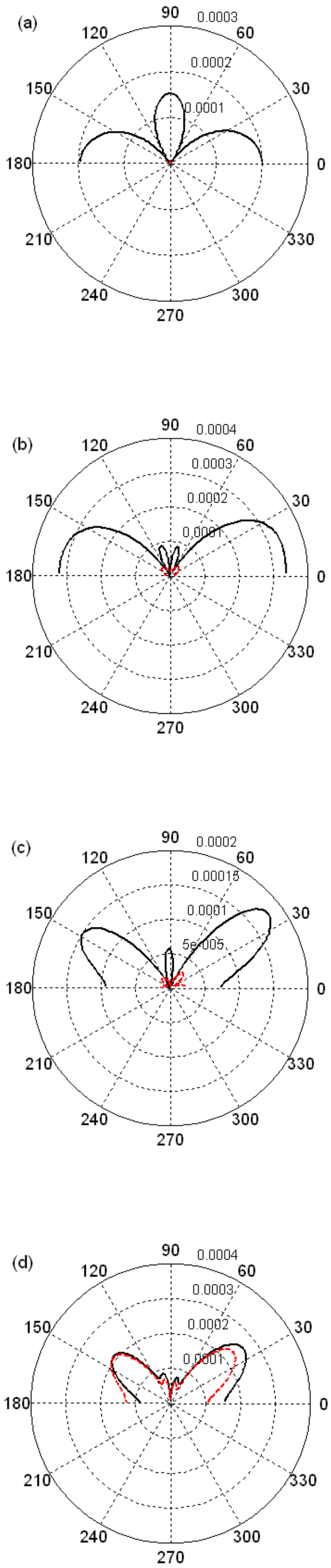


**Figure 10.** Total radiated pressure of the pressure hull for 1 N propeller load and control source located at $x = 15$ m. The radiated pressure is plotted in polar coordinates with angle in degrees and radius in Pascals: (a) first axial mode; (b) second axial mode; (c) third axial mode; (d) PSS resonance. —, uncontrolled; - - -, actively controlled.

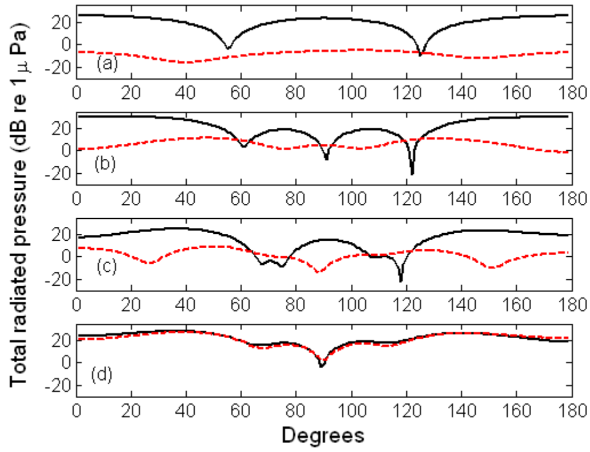


**Figure 11.** Comparison of total radiated pressure of the pressure hull at the axial modes for 1 N propeller load and control source located at $x = 15$ m: (a) first axial mode; (b) second axial mode; (c) third axial mode; (d) PSS resonance. —, uncontrolled; - - -, actively controlled.

### Discussion

The results shown in this paper indicate that the location of the control source is important to ensure maximum achievable reduction at the axial modes as well as the PSS resonance. Only two control source locations were investigated for this paper. Optimal control locations could be found by calculating total radiated pressure with the actuators at small increments, say 10mm, along the pressure hull. Optimal control could then be realized with consideration of maximum reduction of radiated pressure as well as achievable control moment amplitude for each frequency. The results of the total radiated pressure for optimal control moment locations were not presented here due to the required computation time.

## CONCLUSIONS

An active control strategy is developed for the modal control of radiated noise from a pressure hull due to a fluctuating propeller load. The active control is achieved by applying control moments to the pressure hull through a uniform line moment, which could be realized with a T-sectioned circumferential stiffener driven by pairs of PZT stack actuators.

The study indicates that the radiated pressure may be reduced by approximately 85-95% at frequencies of the first three axial modes. It was found that a better reduction was achieved at the PSS resonance if the control source is located close to the primary excitation.

The feedback of the active control action has negligible effect on the axial velocity of the propeller. However, large control moments may be required at the axial modes for a realistic submarine structure. Therefore, reducing the driving-point force at the pressure hull will remain an important area of research. Also, the control moment location is an important condition to ensure effective reduction of the total noise.

## REFERENCES

Dylejko, P.G. 2007, Optimum Resonance Changer for Submerged Vessel Signature Reduction. PhD Thesis, University of New South Wales, Australia.

Goodwin, A.J.H. 1960, The design of a resonance changer to overcome excessive axial vibration of propeller shafting. *Institute of Marine Engineers-Transactions,* **72**, 37- 63.

Junger, M.C. and Feit, D. *Sound structures and their interaction*, Massachusetts: The MIT Press, 1986.

Kessissoglou, N., Tso, Y.K. and Norwood, C. 2003, Active control of a fluid-loaded cylindrical shell, part 2: active modal control. *Proceedings of the Eighth Western Pacific Acoustics Conference, Melbourne, Australia*.

Kinns, R., Thompson, L., Kessissoglou, N., and Tso, Y.K. 2006, Hull vibration forces transmitted via the fluid and the shaft from a submarine propeller. *Proceedings of the 5$^{th}$ International Conference on High Performance Marine Vehicles, Australia*.

Pan, X., Tso, Y. and Juniper, R. 2008 Active control of low frequency hull radiated noise. *Journal of Sound and Vibration* **313,** 29-45.

Snowdon, J. C. 1971, Mechanical four-pole parameters and their application. *Journal of Sound and Vibration* **15,** 307-323.

Tso, Y.K. and Jenkins, C.J. 2003, *Low Frequency Hull Radiation Noise*. Report No. Dstl/TR05660, Defence Science and Technology Laboratory, U.K.

Tso, Y.K., Kessissoglou, N. and Norwood, C. 2003, Active control of a fluid-loaded cylindrical shell, part 1: dynamics of the physical system. *Proceedings of the Eighth Western Pacific Acoustics Conference, Melbourne, Australia*.