ACTIVE VIBRATION CONTROL FOR UNDERWATER SIGNATURE REDUCTION OF A NAVY SHIP

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Dutch navy ships are designed and built to have a low underwater signature. For low frequencies however, tonal vibrations of a gearbox can occur, which might lead to increased acoustic signatures. These vibrations are hard to reduce by passive means. To investigate the possibilities of active vibration control to reduce the underwater signature, a full scale experiment was performed with an active vibration control system on board of a navy ship. For this purpose six special, high efficiency, actuators were built and mounted on the gearbox. A MIMO adaptive feedforward control system was used to reduce the tonal vibrations of the gearbox which were excited by the diesel engine. Vibrations onboard and underwater acoustic pressures were used to monitor the performance of the system during full scale runs on the underwater acoustic range in Bergen, Norway. It can be concluded that the system is able to reduce the vibration and the acoustic signature significantly.

1. Introduction

Dutch navy ships, see Figure 1, are designed and built to have a low underwater signature. Most ships have two propulsion trains, starboard and portside. For each propulsion train, a large gearbox is installed which gives the ability to run on the diesel engine or a gas turbine. Both engines and the gearbox are mounted on springs for vibration isolation. Also a flexible coupling is installed between the diesel engine and the gearbox, see Figure 2. Overall, the performance of the vibration isolation is good. For low frequencies however, in combination with some rpm’s when the diesel engines are running, tonal vibrations of the gearboxes occur, which lead to a possible increase of the acoustic signatures. The frequencies are related to the 3rd engine order and hard to reduce by passive means.
Active vibration control is proposed as a solution for the acoustic signature problem. In this study a feasibility study and first onboard tests have been performed.

2. Active vibration control approach

For active vibration control shakers were used to generate anti-forces to reduce the vibrations. Because the frequency range of the vibration problem is around the resonance frequency of the gearbox on its springs, the approach was chosen to install shakers on the gearbox. The actuator and sensor configurations could be chosen in many ways. To choose proper positions for the actuators and sensors, and to have indications about the required forces, an analysis was performed beforehand. In this analysis a rigid body model of the gearbox was made. The mass and moments of inertia were included, including all springs on which the gearbox is installed and the connections to the gas turbine and diesel engine. Then various actuator positions were chosen which are feasible in practice. Based on a number of sensor positions on which gearbox vibrations were measured, the
possible reductions and the required forces were calculated. A kind of Monte Carlo simulation was performed to find the best positions.

In the end a configuration was chosen which is represented in Figure 3. In total 6 actuators were chosen, represented by $F_1$ to $F_6$. Three actuators were acting in the vertical ($z$) direction and three were acting in the horizontal ($y$) direction. At three positions accelerometers were installed in vertical and horizontal directions.

![Figure 3. Top view of the starboard gearbox.](image)

From the feasibility study it followed that the maximum required force was around 1800 N.

3. Experiments

3.1 Actuators

Special efficient electromechanical actuators had to be designed and developed for this application. The actuators were successfully tested in the laboratory at TNO and installed on the gearbox, see Figure 4. Standard audio amplifiers (LabGruppen fp6400 and fp13000) were used for generating the power needed for the actuators. A water cooling system was made for cooling the actuators.
3.2 Sensors

Six accelerometers (B&K 4514-001) were installed on the gearbox and served as error signals. Ten more accelerometers (Endevco 50) were installed on several positions on the gearbox and served as independent performance sensors. The error signals were integrated such that the velocity was measured. In this way the third order was more pronounced compared with higher orders and therefore easier to follow by the control system.

3.3 Control system

The control system uses a continuous measurement of the rotation speed of the main shaft by means of a tacho sensor, see Figure 5. This tacho sensor generates 16 pulses per revolution of the main shaft. From the rotation frequency of the shaft, the fundamental frequency of the diesel engine and its harmonics were derived. In the current case only the third engine order was important and used for control. The measured frequency, together with a measured vibration signal on the gearbox, was used to generate a signal which was synchronous with the third engine order component of the vibration signals on the gearbox. This reference signal was used by the controller as input for the adaptive control algorithm [1], [2].

The algorithm uses the transfer functions between the actuators and the error sensors. These transfer functions were estimated off line by feeding a noise signal to the actuators and measuring the resulting signals on the error sensors. The control system used six error sensors and six actuators. Only one reference signal was used. The control system minimises the squared sum of all velocity signals.

Figure 4. Actuators installed on the gearbox
3.4 Acoustic range

To monitor the underwater sound levels during control, the experiments were performed on the acoustic range in Bergen, Norway. In this range hydrophones are installed which record the underwater sound produced by the ship. Two hydrophones are applied for these experiments.

3.5 Runs

Various runs are performed at two different speeds: $N_1$ and $N_2$ rpm. Only the starboard propulsion train is running. The portside propulsion train was decoupled because there was no active control system installed on this gearbox.

To check the influence of the portside gearbox, an accelerometer was installed on this gearbox. Various runs have been performed with control system on and off. During these runs the vibrations onboard and the underwater sound were recorded.

4. Results

The results are given in terms of vibrations on the gearbox and the underwater sound spectra. The results are given for two engine speeds.

4.1 $N_1$ rpm

4.1.1 Vibrations

The sensor signals are six error signals (velocities) and ten performance signals (accelerations). The average spectra for each frequency are calculated as the sum of all signal energy divided by the number of signals. So the energetic mean is given.

The average spectrum of the error and performance signals for rotation speed $N_1$ are given in Figure 6. The average reduction on the error sensors at the frequency of interest is 5.6 dB. From the results it is clear that only the 3rd order is controlled. The other frequencies are unaffected. The average reduction on the performance signals is 5.5 dB. This result was obtained at the same time as the hydrophone results given section 4.1.2. During this passage the controller was only marginally stable. The spectra just before the passage are given in Figure 7. The reductions are 13.8 dB on the error sensors and 12.2 dB on the monitor sensors. The actuator levels were in the nominal range.
Figure 6. Average vibration spectrum at \( N_1 \) rpm during passage over the hydrophones. Left: error sensors (reduction 5.6 dB at 3\(^\text{rd}\) order), Right: performance sensors (reduction: 5.5 dB at 3\(^\text{rd}\) order).

Figure 7. Average vibration spectrum at \( N_1 \) rpm just before passage over the hydrophones. Left: error sensors (reduction 13.8 dB at 3\(^\text{rd}\) order), Right: performance sensors (reduction: 12.2 dB at 3\(^\text{rd}\) order).

4.1.2 Underwater sound

The underwater sound spectra at the two hydrophones are given in Figure 8. The reductions are 4.1 and 3.5 dB. This is in good agreement with the reductions measured onboard, given in Figure 6. Underwater sound levels which correspond with the onboard vibration spectra just before the passage over the hydrophones (Figure 7) are unfortunately not available.
4.2 \( N_2 \) rpm

4.2.1 Vibrations

The average spectrum of the error and monitor signals for rotation speed \( N_2 \) are given in Figure 9. The average reduction on the error sensors is 10.9 dB. The average reduction on the monitor signals is 8.2 dB. This result is obtained at the same time as the hydrophone results given section 4.2.2. The actuator levels were higher than the actuators were originally designed for.

4.2.2 Underwater sound

The underwater sound spectra at the two hydrophones are given in Figure 10. The reductions are 8.4 and 14.7 dB respectively.
5. Discussion and Conclusions

It can be concluded that the active control system is able to reduce the underwater acoustic signature significantly. To learn more from the system, for instance at heavy sea, and to improve its performance, more experiments have to be performed.

The reduction measured onboard give good indications for the reductions underwater. This means that for the problem frequency indeed the gearbox is the dominant source for the underwater sound.

A redesign has to be made for the actuators. The current actuators are not optimised for a long lifecycle and the maximum forces have to be increased.

It was seen that there is a strong coupling between the starboard and portside gearboxes. This coupling and the effect for the control setup has to be studied in more detail.

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REFERENCES
