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8) ABSTRACT
The mortality threshold for juvenile herring exposed to sonar signals is 180-190 dB (re 1μPa), and for other species even higher. This report analyses the potential impact of sonar transmissions on recruitment to important economical and ecological fish stocks in Norwegian waters, based on a worst-case scenario approach and a real Anti Submarine Warfare (ASW) exercise.

The analysis has shown that sonar intense exercises in a herring spawning area will affect less than 0.3‰ of the total stock of juvenile fish. This constitutes less than 1% of the natural daily mortality. The effect of the sonar on juvenile herring, is thus considered to be insignificant. For other species of fish, the effect is expected to be even less. Consequently, there is no need for drastic limitations on the use of active sonar in Norwegian waters, based on the direct physiological impact on juvenile fish. However, for herring, CW-transmissions (Continuous Wave) at frequencies within the frequency band corresponding to the swim bladder resonance escalate the impact significantly. Although the impact is still small (1‰) compared to daily natural mortality (5%), moderate restrictions on the use of CW-signals at specific frequencies, areas and time periods related to the presence of high densities of juvenile herring should be considered.
Further studies are necessary to investigate possible behavioural effects of sonar signals on herring.

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CONTENT

THE POTENTIAL IMPACT OF 1-8 kHz ACTIVE SONAR ON STOCKS OF JUVENILE FISH DURING SONAR EXERCISES

1 EXECUTIVE SUMMARY

Fish larvae and juveniles might be particularly vulnerable to impact from intense acoustic sources because they have a limited ability to escape from unpleasant stimuli, and might also be in a physiologically vulnerable stage of development. Furthermore the gas filled swim bladder of fish larvae and juveniles has resonance frequencies within the 1-8 kHz frequency band. A recent study executed at the Norwegian College of Fisheries Science in collaboration with the Norwegian Defence Research Establishment has found that the threshold for significant mortality of juvenile herring exposed to sonar signals was 180-190 dB (re 1μPa). For CW signals at frequencies corresponding to swim bladder resonance frequencies this threshold was near 180 dB whereas the threshold for frequency modulated (FM) signals or CW signals outside resonance was found to be 10 dB higher.

This report analyses the potential impact of sonar transmissions on recruitment to important economical and ecological fish stocks in Norwegian waters during sonar intense exercises. It is based on the study referred to above, a worst-case scenario approach and frigate maneuvering from real ASW exercise. During the hypothetical exercise two frigates perform a submarine search in the middle of the spawning area of an ecological and economical important stock of fish, in the most intensive spawning period. Both frigates use Active Towed Array Sonar (ATAS) and Hull Mounted Sonar (HMS), transmitting alternately at maximum power and duty cycle.

The analysis shows that normal peacetime sonar exercises has no significant effects on juvenile fish at a population level. Consequently, there is no need for drastic limitations on the use of active sonars in Norwegian waters based on the direct physiological impact on fish. However, for herring, CW-transmission at frequencies within the frequency band corresponding to the resonance frequency of the swim bladder, will escalate the impact significantly. Even though the impact is still small compared to the natural mortality, moderate restrictions on the use of CW-signals at specific frequencies, areas and time periods related to the presence of high densities of juvenile herring should be considered (see table 6.1). Suggested restrictions on CW-transmission are to change the frequency of transmission, reduce source level or reduce signal duration. Restrictions are not considered necessary for the use of helicopter operated dipping sonars or sonobuoys due to low source levels and small volumes exposed during exercises. Furthermore, restrictions on the use of FM-signals during normal sonar exercises and restrictions related to the presence of species of fish other than herring, are considered unnecessary based on the direct physiological impact. However, further studies are necessary to investigate possible behavioral effects of sonar signals on herring.

2 INTRODUCTION

From 2006, the Royal Norwegian Navy will phase in new frigates with sonar systems operating in the frequency band from 1 to 8 kHz. Fish larvae and juveniles might be particularly vulnerable to impact from intense acoustic sources, because they have a limited ability to escape from unpleasant influences, and might also be in a physiologically vulnerable stage of development. Studies on the impact of seismic airguns have shown that damage only occurs at distances of less than 5 meters from the airgun (Dalen *et al.* 1996, Booman *et al* 1996), and that seismic explorations have no effect on fish larvae and juveniles at a population level (Sætre & Ona 1996). However, compared to airgun-cracks, sonar pings have different pressure and frequency characteristics, and the impact of the different signals can therefore not necessarily be extrapolated based on knowledge of the impact of the other. Of special interest is the fact that the gas filled swim bladder of fish larvae and juveniles has resonance frequencies within the 1-8 kHz frequency range (Løvik & Hovem 1979, McLennan & Simmonds 1992, Jørgensen *et al.* 2005). The Norwegian College of Fisheries Science at the University of Tromsø, in collaboration with The Norwegian Defence Research Establishment, therefore investigated the effects of sonar signals on the survival and development of fish larvae and juveniles (Jørgensen *et al.* 2005). Immature fish at different developmental stages and of different species were exposed to relevant sonar signals at sound pressure levels from 160-190 dB (re 1 μPa). Generally, no tissue damage that can be linked to the sonar signals was found in any of the groups, and post exposure development was normal (Jørgensen *et al.* 2005). Furthermore, no direct or long-term mortality was found in any group, except for a 20-30% mortality in herring (*Clupea harengus*) when exposed to CW signals at 180-190 dB (Jørgensen *et al.* 2005).

This report analysis the potential impact of sonar transmission from the Nansen-class frigates on recruitment to important economical and ecological fish stocks in Norwegian waters, based on a worst-case scenario approach and a real anti-submarine warfare (ASW) exercise, involving the Oslo-class frigates. This investigation is part of a more extensive study, executed by the Norwegian Defence Research Establishment, on the effects of sonar transmission on fish and marine mammals in Norwegian waters (Sevaldsen & Kvadsheim 2004).

3 THE SCENARIO

Although military sonars may transmit intense acoustic signals into the ocean, the acoustic source is highly mobile, and under normal peacetime exercises the duration of such transmissions within a geographical area is limited. The current analysis of the potential impact of the Nansen-class frigates on stocks of juvenile fish is based on the following worst-case scenario: Two frigates perform an ASW-exercise in the middle of the spawning area of an ecological and economical important stock of fish, in the most intensive spawning period. Both vessels use all available sonar systems transmitting alternately at maximum power and duty cycle.

4 ANALYSIS OF IMPACT

The analysis of the impact of the exercise described above is based on a similar analysis of the impact of a full-scale 3D seismic survey (Sætre & Ona 1996). Technical information regarding the sonars and tactical information regarding sonar operations is primarily found in Hollekim (2003). The ratio of a class of fish being affected by the exercise relative to the whole class (*M*), is given by the equation;

$$M = P_1 \cdot P_2 \cdot P_3 \tag{1}$$

where P_1 is the ratio between the volume affected by the sonar pings (V_{aff}) and a risk volume (V_{risk}), defined by the range of the exercise area and the vertical zones around the sonar which are potentially affected (fig.4.1), P_2 is the ratio of overlap between the vertical range of V_{risk} (impact zone) and the vertical distribution of the fish larvae and juveniles (fish zone) (fig 4.1), and P_3 is the proportion of the fish class expected to be within the exercise area.

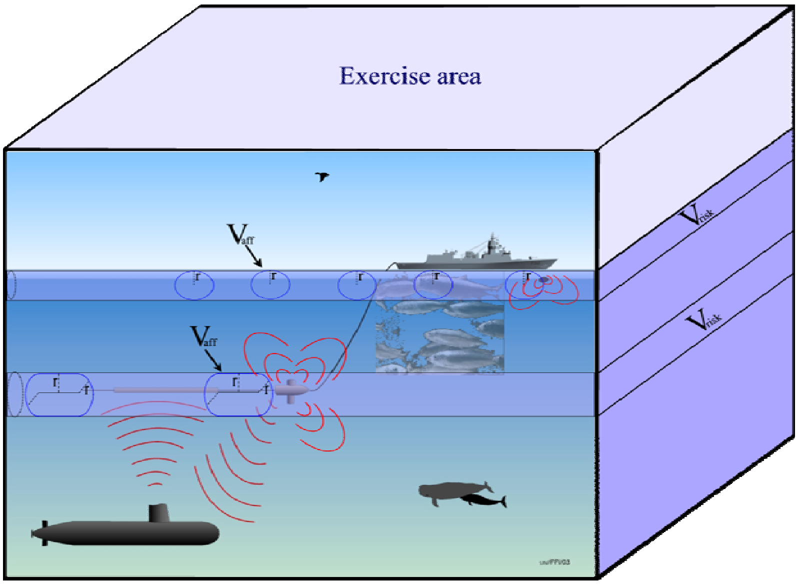

Figure 4.1 *The frigates operate two sonars. A hull mounted sonar (HMS) transmitting at 5-8 kHz at 5 m depth, and an active towed array sonar (ATAS) transmitting at 1-2 kHz operated at 50 m depth or deeper. A risk volume (V_{risk}) is associated with both sonars, and an affected volume (V_{aff}) is associated with each ping. Fish appearing within the affected volume are assumed to be damaged or killed.*

4.1 P_1 – Ratio of affected volume and risk volume

The risk volume is that part of the entire exercise volume where damage may occur because a transmitting sonar transducer passes through it. The size of the risk volume is given by the equation;

$$V_{risk} = A \cdot 2 \cdot r \tag{2}$$

where *A* is the exercise area and r is the range from the sonar source where damage will occur during transmission (impact range). If the impact range (r) is larger than the depth at which the sonar transducer operates (i.e. the risk volume extends above the surface), the risk volume (V_{risk}) is cut off at the surface. The total affected volume (V_{aff}) is calculated as the affected volume for one ping, which is assumed to be cigar shaped (fig. 4.1), multiplied with the number of pings (p), according to the equation;

$$V_{aff} = p \cdot (\pi \cdot r^2 \cdot v \cdot S + \frac{4 \cdot \pi \cdot r^3}{3}) \quad (3)$$

where v is the cruising speed of the frigate and S is the duration of the ping. If the impact range (r) is larger than the depth at which the sonar transducer operates, it is assumed that the part of the affected volume (V_{aff}) which would extend above the surface is reflected downwards back into the risk volume (V_{risk}). However, V_{aff} cannot exceed V_{risk}. The number of pings (p) is given by the equation;

$$p = \frac{D}{I} \quad (4)$$

where D is the duration of the exercise and I is the signal interval. The signal duration (S) is selected by the sonar-operator and will depend on which distance from the ship the operator wants to explore. In this analysis it is assumed that the hull mounted sonars are operated with signal durations of 250 ms and signal intervals of 10 s (duty cycle 2.5%), and the towed array sonar with signal durations of 4 s and signal intervals of 20 s (duty cycle 20%).

The impact range around a sonar transducer where damage occurs (r) will depend on the source level of the sonar, and the threshold of impact. For both HMS and ATAS the source level is assumed to be somewhere between 200 and 225 dB (re 1μPa @ 1m), when transmitting omni-directionally. In the study of Jørgensen *et al.* (2005), the maximum mortality of juvenile herring (*Clupea harengus*) was 30% when exposed to 180 dB (re 1μPa) continuous wave (CW) signals, at a frequency very close to the expected resonance frequency of the swim bladder, as estimated from the empirical model of Løvik and Hovem (1979). However, when exposed to similar signals at 174 dB, the mortality was insignificant, indicating that the threshold of impact is close to 180 dB. When exposed to signals outside the frequency range expected to excite the swim bladder, significant mortality was only observed when the juvenile fishes were exposed to 20 CW-pulses (1 s duration) at 190 dB, while 4 pulses gave no mortality. Thus, for CW-signals the threshold of impact in herring is assumed to be close to 190 dB, except if the frequency of the signal corresponds closely to the resonance frequency of the swim bladder of the exposed fish, in which case the threshold is assumed to be 180 dB. Cod (*Gadus morhua*) was also exposed to CW-signals corresponding to the expected resonance frequency of the swim bladder, but contrary to herring no mortality was observed even at 186 dB sound pressure level. Further more, no mortality was found in cod, saithe (*Pollachius virens*) and spotted wolfish (*Anarhichas minor*) when exposed to signals outside the resonance frequency (spotted wolfish has no swim bladder) at levels up to 190 dB. Since 190 dB was the maximum exposure level tested, the threshold for 100% mortality is unknown. No mortality was observed when juvenile fish were exposed to frequency modulated (FM) sweeps at 180 dB, even if the signals swept through the resonance frequency of the swim bladder. The threshold of impact for FM-signals is therefore assumed to correspond to the threshold for CW signals outside the resonance frequency band of the swim bladder (190 dB). Thus, the threshold of impact seems to vary with species, frequency and signal type. However, in this worst-case scenario analysis 180 dB is assumed to be the threshold of impact for CW signals and 190 dB the threshold of impact for FM-signals. Above this threshold, 100% mortality occur.

Assuming spherical spreading, the distance from the sonar source where damage will occur (impact range (r)) is calculated by from equation 5;

Source level – Threshold of impact = 20log(r) (5)

As the impact range (r) increases with source level, the extent of the risk volume (V_{risk}) and the affected volume (V_{aff}) will be constricted by the surface, as already stated. In addition a maximum value of P_1 is reached when horizontal overlap between the affected volumes from one ping to the next ping from the same sonar start to occur. Eventually, a maximum total impact (*M*) of the sonar exercise is reached when there is also vertical overlap between the affected volume of the HMS and the ATAS, in which case the entire fish zone is covered by the affected volume.

4.2 P_2 – Overlap between the impact zone and the fish zone

P_1 (eq. 1) is that part of the risk volume where damage actually will occur, but the juvenile fish will be vertically distributed so that only a part of the fish within the exercise area will overlap with the risk volume. According to eq. 5 the impact range (r) for both sonars will be 178 m, assuming maximum source level (225 dB) and 180 dB threshold of impact, and 56 m if threshold of impact is 190 dB. The HMS is positioned at 5 m depth and the ATAS is assumed to be towed at 50 m depth. Assuming 180 dB threshold of impact, the vertical zone affected (impact zone) will be from the surface to 183 m depth, and from the surface to 228 m depth, for the two sonar systems, respectively. If the threshold of impact is assumed to be 190 dB, the impact zone will be from the surface to 61 m depth and from the surface to 106 m depth, for the two sonar systems, respectively. However, if the source level is reduced to 200 dB, the impact zone will be reduced to cover 0-15 m for the HMS and 40-60 m for the ATAS, if the threshold of impact is 180 dB, and 2-8 m for the HMS and 47-53 m for the ATAS, if the threshold of impact is 190 dB. The vertical distribution of fish larvae and juvenile fishes will vary with species, stage of development and light conditions, but they will generally be concentrated above 30 m depth (Sætre & Ona 1996). Consequently, if the source level is 225 dB the impact zones of both sonar systems will fully cover the fish zone (P_2=1). However, if the source level is 200 dB, the impact zone of the HMS covers only 20% of the fish zone (P_2=0.2) if the threshold of damage is 190 dB, and 50% if the threshold of damage is 180dB, while the impact zone of the ATAS does not reach up to the fish zone at all (P_2=0) (see table 5.1).

4.3 P_3 – Proportion of fish stock within exercise area

Multiplying P_1 and P_2 will give the proportion of juvenile fish within the exercise area actually affected. However, the production of fish larvae is spread out in time and space. In addition, wind and ocean current will disperse the larvae rapidly. Thus, only a small proportion of the entire stock will be within the exercise area at any given time. According to Sætre & Ona (1996) the spawning area of cod, herring and capelin (*Mallotus villosus*) is at least 1000 km^2, and the daily hatching rate is 3% of the total production of larvae. The expansion rate of the distribution area of the larvae will vary with species and local metrological and oceanographical conditions, but will be at least 1000 km^2/day (Sætre & Ona 1996). Thus, a maximum of 3% of the stock of larvae will be within the spawning area at any given time.

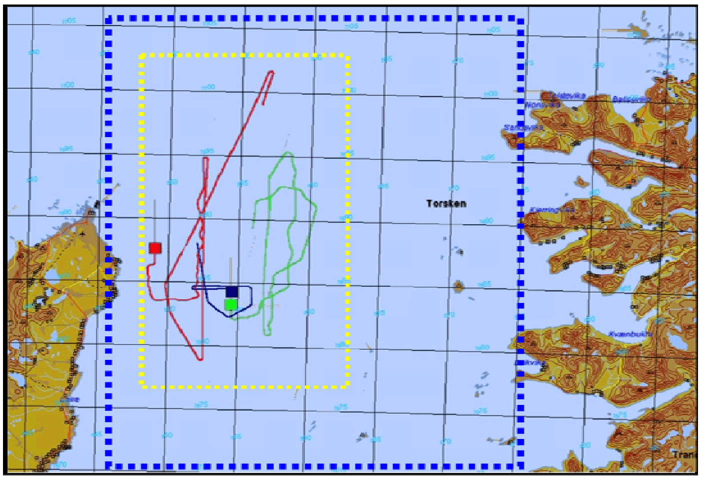

__Figure 4.2__ Two frigates (red and green line) performing a submarine (blue line) search during FLOTEX 2003. Hatched blue square indicates size of hypothetical spawning area (1000 km^2) and hatched yellow square the size of the exercise area (375 km^2). The duration of the exercise was 148 min, combined distance covered was 100 km, and average cruising speed was 13 knots. The figure is generated by FFI project SIMSON (2004).

The size of the exercise area is defined by the outer limit of the area where sonar transmission takes place. We have used a real ASW-exercise that corresponds well with the scenario in the analysis. During FLOTEX 2003, two frigates of the Oslo-class performed an ASW-exercise in Andfjorden (fig 4.2). The size of the exercise area was 375 km^2 and thus, constitute 38% of the spawning area. Consequently only 1.1% of the total stock of fish larvae would be within the exercise area during the exercise (P_3=0.011).

5 RESULTS

Table 5.1 summarizes the relevant inputs to the analysis of the potential impact of sonar transmission on juvenile fish in a spawning area in the middle of the spawning period.

In the analysis, it is assumed that two vessels transmit alternately with their HMS and ATAS. The threshold of impact is assumed to be 180 dB (re 1 μPa @ 1m) for CW signals and 190 dB for FM signals. The source level of the sonars is assumed to be between 200 and 225 dB. Thus, the analysis is run assuming source levels of 200-225 dB and thresholds of impact of 180 or 190 dB (fig. 5.1).

Parameter	Eq.	**Hull mounted sonar (HMS)**	**Towed array sonar (ATAS)**
Source level (SL)	5	200-225 dB (re 1μPa @ 1m)	200-225 dB (re 1μPa @ 1m)
Threshold of impact CW	5	180 dB (re 1μPa)	180 dB (re 1μPa)
Threshold of impact FM	5	190 dB (re 1μPa)	190 dB (re 1μPa)
Impact range (r) CW, SL=225dB	2,3,5	178 m	178 m
Impact range (r) CW, SL=200dB	2,3,5	10 m	10 m
Impact range (r) FM, SL=225dB	2,3,5	56 m	56 m
Impact range (r) FM, SL=200dB	2,3,5	3 m	3 m
Vertical impact zone CW, SL=225dB		0-183 m	0-228 m
Vertical impact zone CW, SL=200dB		0-15 m	40-60 m
Vertical impact zone FM, SL=225dB		0-61 m	0-106 m
Vertical impact zone FM, SL=200dB		2-8 m	47-53 m
Vertical distribution of fish (fish zone)		0-30 m	0-30 m
Number of pings (p)	3,4	1775	888
Signal duration (S)	3,4	0.250 s	4 s
Signal interval (I)	4	10 s	20 s
Duration of exercise (D)	4	148 min	148 min
Cruising speed (v)	3,4	13 knots	13 knots
Distance covered (L)	4	100 km	100 km
Exercise area (A)	2	375 km^2	375 km^2
Spawning area		1000 km^2	1000 km^2

Table 5.1 ***Summary of relevant input parameters in the analysis of the impact of sonar-intense ASW-exercises on stocks of juvenile fishes.***

If the source level of the sonars is assumed to be 225 dB, which corresponds to the presumed maximum source level, and the threshold of impact is assumed to be 190 dB, which corresponds to the estimated threshold for FM signals on herring, 0.3‰ of the total stock of juvenile fish will be affected by the HMS and 0.2‰ by the ATAS (fig. 5.1). However, since the volume affected by the HMS and that affected by the ATAS overlap, the combined effect of the two sonar systems is only 0.3‰ (fig. 5.1). If the threshold of impact is assumed to be 180 dB, which corresponds to the estimated threshold for CW signals at frequencies close to the resonance frequency of the swim bladder of herring, while the source level is 225 dB, 1.0‰ of the total stock of juvenile herring will be affected by this exercise (Fig. 5.1). In this case the impact zone of both sonars fully covers the fish zone, so that the impact of individual sonars is also 1‰ (Fig. 5.1). If the source level is reduced to 200 dB, the affected volume becomes very small and covers only a small portion of the fish zone. Consequently, the impact of the sonars will be almost zero (fig. 5.1). In fact, the impact zone of the ATAS does not reach up to the fish zone before the difference between the source level of the sonar and the threshold of impact exceeds 27 dB. If operated at source levels below this, the ATAS will have no impact on the juvenile fish (fig. 5.1).

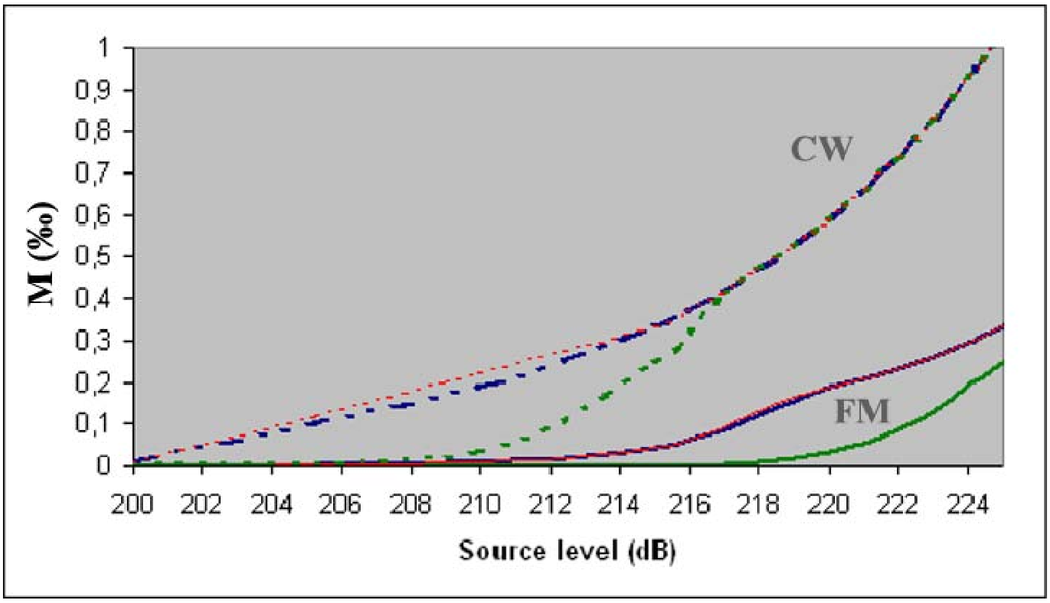

***Figure 5.1** Proportion (M in ‰) of juvenile herring affected by ASW-exercise relative to the whole class of juvenile herring as a function of sonar source level. The scenario involves two frigates, both operating hull mounted sonar (HMS, blue lines) and towed array sonar (ATAS, green lines) simultaneously in a spawning area. The threshold of impact is assumed to be 180 dB (broken lines), which corresponds to the estimated threshold for CW signals at frequencies close to the resonance frequency of the swim bladder, or 190 dB (solid lines), which corresponds to the estimated threshold for FM-signals. Red lines represent the sum of both sonar systems.*

6 DISCUSSION

The most important fish populations in Norwegian waters spawn in coastal areas. Under normal conditions, there is no tactical benefit of using CW-sonar signals in coastal waters. On the contrary, the use of FM-signals reduces reverberation from bathymetric structures, which is a major problem in coastal areas. The most commonly used sonar signal during ASW-exercises, at least in costal areas, would therefore be FM-signals, even though CW-signals might be used occasionally. The threshold of impact for FM-signals is assumed to be 190 dB. For CW-signals it is assumed to be 180 dB, but this threshold only applies to herring and only if the transmitted frequency is within the frequency band corresponding to the resonance frequency of the swim bladder (Jørgensen *et al.* 2005). The width of this frequency band would typically be 1-2 kHz (McCartney & Stubbs 1971, Sand & Hawkins 1973, Løvik & Hovem 1979). When herring was exposed to CW-signals outside of this frequency band, the threshold of impact was 190 dB (Jørgensen *et al.* 2005). The most realistic estimate of the threshold of impact of ASW-exercises on herring is therefore 190 dB, and even higher than this for other species (Jørgensen *et al* 2005). Thus, this worst-case analysis has shown that an ASW-exercises involving two frigates operating their HMS and ATAS simultaneously in a herring spawning area, at a source levels of 225 dB, will affect less than 0.3‰ of the total stock of juvenile herring. Natural daily mortality for larvae and juveniles of herring and other common fish species such as cod and capelin are 5-15%, which is gradually reduced to 1-3% by the time they reach the 0-group phase about 6 months later (Sætre & Ona 1986). However, by this time they are probably also less sensitive towards external influences, such as acoustic exposure. Thus, the impact on juvenile herring inflicted by the sonar will constitute less than 1% of the daily natural mortality (fig. 6.1), and is therefore considered to be insignificant.

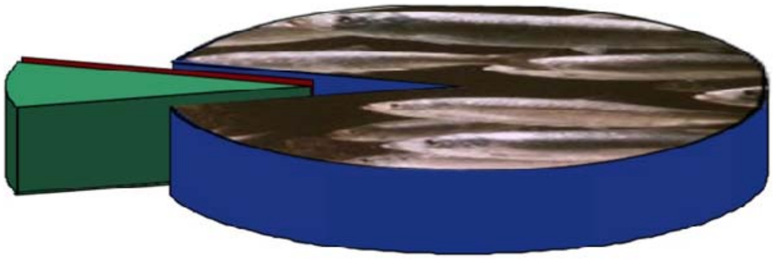

***Figure 6.1** "Fish pie" indicating part of stock of juvenile herring (entire pie) affected by ASW-exercise (red slice=0.3‰), and daily natural mortality (green slice=10%). The source levels of the sonars are assumed to be 225 dB and the threshold of impact 190 dB, which corresponds to the assumed threshold for FM-signals.*

The effect of sonars on juvenile fish of other species such as cod, saithe and wolfish, is probably even less than for herring, because the threshold of impact is higher (Jørgensen *et al.* 2005). The physiological effect of sonars on adult fish is expected to be less than for juvenile fish because adult fish is in a more robust stage of development, the swim bladder resonance frequencies will be outside the 1-8 kHz frequency band and adult fish is expected to move away from unpleasant stimulus. Consequently, there is no reason to inflict strict regulations on normal use of active 1-8 kHz active sonars, even within spawning areas, based on the physiological effect sonar signals have on fish. This conclusion is in accordance with the conclusion of Sætre & Ona (1986), who found that a 3D seismic survey might affect about 0.3‰ of a juvenile fish stocks, and that this has no significant effect at a population level. However, clupeid fishes, such as herring, is expected to be able to hear sonar signals at frequencies up to 5 kHz (Enger 1967), and Jørgensen *et al* (2005) did observe stress reactions in herring when exposed to low frequency sonar signals at 1.5 kHz (ATAS type). This stress reaction was not seen in cod, saithe and spotted wolfish, but they are also expected to be unable to hear these signals (Chapman & Hawkins 1973, Sand & Enger 1973). The effect of sonar signals on the behavior of herring therefore needs to be investigated further.

The current analysis has shown that the impact of CW-transmission will be in the order of 3 times the impact of FM-transmission (fig. 5.1). However, this CW-effect occurs in herring only if the transmitted frequency is within the resonance frequency band of the swim bladder of the exposed fish. Even though the effect of CW-transmission is fairly small at a population level (1‰ at 225 dB source level (fig 5.1)), it is suggested that the use of CW-signals is to some extent restricted in areas densely populated with juvenile herring. Since the critical frequency band is predictable based on the size of the fish and the empirical models of Løvik & Hovem (1979) and McLennan & Simmonds (1992), this restriction can be limited to defined areas and frequency bands where you expect to find high densities of juvenile herring of the critical size, as indicated in table 6.1. Effective mitigation measures against the destructive effect of CW-signals are to use shorter duration signals (e.g. <250 ms), or to reduce source levels (e.g. <215 dB). Both measures are expected to bring the impact of CW-transmission down to the FM-level.

According to the current analysis, the impact of HMS is greater than the impact of ATAS (fig. 5.1). Turning off the ATAS, when operating at full power (225 dB), will for example not reduce the total impact on the juvenile fish stock at all, because the HMS fully covers the fish zone. Turning of the HMS, on the other hand will reduce the impact by 25%. This difference is explained by the difference in signal interval between the HMS and the ATAS. At reduced source levels, this difference is partly also explained by the fact that the impact zone of the HMS has a greater vertical overlap with the fish zone than the ATAS.

Herring length	Restricted frequency band	Restricted period	Restricted area
2.5-3 cm	3-6 kHz	April-May	Coastline Møre-Troms
3-4 cm	2-5 kHz	June-July	Coastline Lofoten-northward
5-6 cm	1.5-3 kHz	August-September	Finmark-Barents Sea
6-10 cm	1-3 kHz	October-December	Finmark-Barents Sea

Table 6.1 Suggested restrictions on the use of CW-sonar signals in areas densely inhabitated by juvenile herring. The restricted frequency band is defined based on the expected resonance frequencies of the swim bladder of the juvenile herring, as estimated from the length of the fish using the empirical model of Løvik & Hovem (1979) ± 1 kHz bandwidth (McCartney & Stubbs 1971). Restricted period and area is subsequently defined based on growth rates (Jørgensen *et al.* 2005) and spatial distribution of juvenile herring versus time (Føyn *et al.* 2002).

6.1 The robustness of the analysis

We have chosen to analyze a real ASW-exercise because this type of exercise, where surface vessels are searching for and subsequently tracking a submarine, is a very sonar-intense exercise performed within a highly restricted geographical area such as a spawning area. The analyzed exercise is considered to be a typical free-play ASW-exercise, where two vessels are working in pair.

Generally, the two factors influencing the outcome of the analysis most is the number of pings (p) and the impact range (r). In turn p depends on the duration of the exercise (D) and the signal interval (I) (eq. 4), and r depends on the threshold of impact and the source level of transmission (eq. 5). The fraction of the population of juvenile fish affected by the sonars (M) is proportional to the number of pings and roughly proportional to the square of the impact range. However, if the sonars are operated at or close to full power (source level above 220 dB) there will be a horizontal overlap between the pings of the HMS, and a complete vertical overlap between the impact zone of the HMS and the fish zone. In this situation, it is only the areal coverage of the spawning area that determines the total impact. Increasing the number of pings by reducing the signal interval, will, for instance, not change the total impact. M will now change in proportion with the distance covered by the transmitting vessels and the impact range. In turn this will depend of the duration of the exercise, the speed of the vessels, the transmitting source level and the threshold of impact.

If the threshold of impact is 10 dB below the assumed thresholds, the affect of the same exercise would be escalated 3 times (fig.5.1), due to the increased impact range. However, since the threshold of impact is the threshold for 30% mortality, not 100% as assumed in the analysis, and since the sonar systems on the Nansen-class frigates are not expected to transmit at source levels above 225 dB, the impact range is probably overestimated in this analysis. Increasing the speed of the vessel or the duration of the exercise will both increase the distance covered by the transmitting vessels and thereby their areal coverage and M correspondingly, if sonar transmission is continuous. Theoretically, the impact on the juvenile fish stock could increase by 50% if the speed of the vessels were increased to a maximum. However, this is unlikely to happened when operating within a restricted area like this spawning area, because it will create more noise for the sonar antennas. Also, during peacetime operations there is a natural limitation of hours on such exercises. If the upper limit of acceptance on impact level on the population is assumed to be 3%, the duration of sonar transmission has to continue for 10 days in order to reach this level. The length of sonar exercises usually is in the order of hours and seldom lasts longer than 2 days.

In this analysis, the number of transmitters is set to be four, two vessels both operating a HMS and an ATAS. In addition to this the Nansen-class frigates will be equipped with a helicopter, operating an active dipping sonar (3.5-4.5 kHz) and active sonobuoys (6.5-9.5 kHz). However, dipping sonars and sonobuoys are generally less powerful than HMS and ATAS and are usually operated below 50 m, indicating that $P_2 \approx 0$. In addition, these sonars are fairly stationary, indicating that also $P_1 \approx 0$. Consequently, compared to the hull mounted sonar and towed array sonar the impact of dipping sonars and sonobuoys can be ignored. The number of vessels involved in an ASW-exercise might off course exceed two. However, there are natural limits on how many active sonar sources that can be used simultaneously within a restricted area (the spawning area), because the signals create reverberations which eventually will reduce the chance of detecting the reflected signals from a target. Future sonar technology will probably allow bistatic or multistatic operations between different sonar systems and between vessels, and even though this might increase the number of vessels involved in an ASW-exercise within an area, it will reduce the number of active sonar transmissions necessary.

In summary, we therefore conclude that it is more likely that this analysis overestimates than underestimate the impact of sonar-intense exercises on stocks of juvenile fish, and that the main conclusion, that such exercises has insignificant effects, is not influenced by possible inaccuracies in the analysis.

7 CONCLUSIONS AND OPERATIONAL RECOMMENDATIONS

This analysis has shown that normal peace-time sonar exercises has no significant effects on juvenile fish at a population level. Consequently, there is no need for drastic limitations on the use of active sonars in Norwegian waters. However, herring and probably also sprat (“brisling” in Norwegian) (*Sprattus sprattus*) seem to be more sensitive towards sonar signals than other species. This is probably explained by the presence of air filled cavities, which is connected to the swim bladder, in close proximity to the hearing organs of these fish species (Blaxter *et al.* 1981). This structure allows direct transmission of pressure fluctuations in the swim bladder to the hearing organ, and in combination with the unique receptor pattern found in the herring ear (Popper & Platt 1979), explains the unique sense of hearing found in herring (Enger 1967). CW-signals seem to have a greater impact on herring than FM-signals, but only at specific frequencies, which vary with the size of the fish present in the area. As a precautionary measure, restrictions on the use of CW-signals at specific frequencies, areas and time periods (defined in table 6.1) related to the presence of high densities of juvenile herring should be considered. Suggested restrictions on CW-transmission are to change the frequency, reduce source level to 215 dB or reduce signal duration to 250 ms. These restrictions are not considered necessary for helicopter operated dipping sonars or sonobuoys. Furthermore, restrictions on the use of FM-signals during normal sonar exercises and restrictions related to the presence of other species of juvenile fish or adult fish are considered unnecessary based on the expected direct physiological effect of sonars. However, further studies are necessary to investigate possible behavioral effects of sonar signals on herring.

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List of abbreviations

A	Exercise area.
ASW	Anti Submarine Warfare
ATAS	Active Towed Array Sonar
CW	Continous wave
D	Duration of exercise.
FM	Frequency modulated
HMS	Hull mounted sonar
I	Signal interval.
L	Distance covered by transmitting vessels.
M	Total impact of sonar exercise of stock of juvenile fish (‰).
p	Number of pings.
P_1	Ratio V_{aff} /V_{risk}
P_2	Ratio of overlap between the vertical impact zone of the sonar and the fish zone.
P_3	Proportion of fish stock within exercise area.
r	Impact range, range from sonar transducer where damage occur during transmission.
S	Signal duration.
SL	Source level of sonar transducers.
v	Speed of transmitting vessels.
V_{aff}	Volume affected by the sonar pings.
V_{risk}	The proportion of the entire exercise volume where damage might occur because a sonar transducer passes through it.