MODELLING ANALYSIS OF ECHO SIGNATURE AND TARGET STRENGTH OF A REALISTICALLY MODELLED SHIP WAKE FOR A GENERIC FORWARD LOOKING ACTIVE SONAR

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Abstract: *The acoustic modelling in TNO's ALMOST (=Acoustic Loss Model for Operational Studies and Tasks) uses a bubble migration model as realistic input for wake modelling. The modelled bubble cloud represents the actual ship wake. Ship hull, propeller and bow wave are the main generators of bubbles in the wake. The bubble volume originates from the wake velocity field, combined with properties and physical processes of air bubbles in water. The bubble volume is assumed to be insonified by a generic active forward looking sonar. The resulting back-scattered sound is modelled with the recently developed ALMOST-REATES module (=Range Estimator for Active sonar and Target Echo Strength). It takes into account bubble scattering spectra and positions, and other important factors for the echo signal, like propagation loss from sonar transmitter and back to sonar receiver, beam forming, and signal processing. The new method is a further development of the ALMOST-REACT module (=Range Estimator for ACTive sonar): The active sonar equation is programmed here based on echo arrival times, computing sonar performance for point targets. The new method uses specified bubble positions, provided by the ship wake bubble migration model, to compute first the Impulse Response function. With the given spectrum of the active sonar pulse, the echo time series is modelled by simulating active sonar processing. Detection performance and an effective Target Strength for the scenario are deduced from this echo time series. The actual sonar processor is simulated, usually equipped with matched filter or straightforward energy detector. To run the model on a standard PC, the number of bubble positions is limited, while also the run time must be acceptable. The consequences of this limitation are reduced by applying some statistics in the modelling. Some results of echo structures and sonar performance are shown in a realistic active sonar scenario.*

Keywords: *ship wake modelling, acoustic sonar performance, acoustic signature, Target Strength*

1. INTRODUCTION

Recently wake reflection modelling was started as a further development of the already existing ALMOST model (=Acoustic Loss Model for Operational Studies and Tasks) [1]. For a pulse sent by active sonar, the reflection from the bubble clouds inside the ship wake is modelled, based on bubble positions and size distribution. The new computation module is called REATES (=Range Estimator for Active sonar and Target Echo Strength). It computes the expected echo time series in a coherent way which allows further sonar processing like matched filtering. The input wake geometry for the acoustic modelling, is generated by a wake model implemented at TNO [2], [3], [4], supplying an array of bubble positions and sizes as a function of range behind the ship. This wake model basically computes the velocity field in the wake, and combines this with the dynamics for the individual bubble where upward force, pressure and drag play a role. Originally the wake model was only based on air entrapping sources near each of the propellers and the ship hull. Recently air sources due to the bow waves left and right of the ship have been implemented, thus yielding a more realistic wake geometry compared with measurements [5].

In the REATES time series modelling, multipath propagation for a realistic sonar scenario, from ALMOST, is taken into account. Further a realistic active sonar is modelled using the sonar directivity patterns from the REACT module (=Range Estimator for ACTive sonar) for active sonar performance predictions. Here the active sonar equation is modelled for simple point targets of given Target Strength. The method uses travel times for the echoes via the various propagation paths, computed as eigen-rays [6]. Echo level and reverberation are modelled versus time, presented as active sonar range for practical reasons. The new simulator is a straightforward extension of this existing modelling, but here for targets described by a number of scatterers. Examples are reflecting targets like ships assuming a suitably dense representation by scattering pixels. A cloud of air bubbles also forms a reflecting target, for instance occurring in ship wakes. The bubbles show a resonance effect [6], [7], to be modelled including phase, in the new method.

In the next part the basics of the echo modelling will be described [8], as well as the air bubble resonance phenomenon. Then the wake geometry is taken into account, as well as the directivity of the active sonar. The wake aspect angle, which is the angle between wake axis and sonar beam, turns out to be an important operational parameter.

Further behind the ship, forming the older part of the wake, the mean bubble size is smaller than closer to the ship. Echo modelling results for a variety of sonar frequencies, computed for different ranges after the ship will illustrate this effect.

2. THEORY AND MODELLING

Inside the wake there is an air bubble cloud, which consists of air bubbles at a number of positions, but with different bubble radius at each position. In order to model this cloud as a reflecting target using active sonar, the cloud will be approximated with a number of sub divisions for this cloud. Each sub division in the cloud only consists of bubbles with a radius between two rather close limits. So in the computation for the sub division the radius distribution can be well approximated as constant. A sufficient number of such sub divisions are taken together to model the actual cloud.

Air bubbles show a resonance effect in their transfer function, as follows:

$$H_{bubble}(\omega) = \frac{P_{scattered}}{P_{incident}} = \frac{R}{r} \cdot \frac{1}{\omega_{res}^2 / \omega^2 - 1 + i\delta} \quad (1)$$

$$\omega_{res} = \frac{1}{R}\sqrt{\frac{3\alpha P_{g0}}{\rho} - 2\frac{\sigma}{\rho R}} \quad (2)$$

$$\delta = \frac{\omega R}{c} + \frac{4\eta}{\omega \rho R^2} + H_{thermal} \quad (3)$$

With:

δ =damping, 2nd+3rd term $\approx .1$ [ratio]

$R =$ bubble radius [m]

$\omega =$ radial frequency [Hz]

$\omega_{res} = \omega$ at resonance [Hz]

$r =$ range to bubble [m]

$c =$ sound speed [$m.s^{-1}$]

$\eta =$ shear viscosity of the water [$kg.m^{-1}.s^{-1}$]

$\rho =$ density of the water [$kg.m^{-3}$]

$H_{thermal} =$ heat conductivity loss term [ratio]

$\alpha =$ polytropic constant ($1 < \alpha < C_p / C_v = 1.4$) [ratio]

$\sigma =$ surface tension of bubble [$N.m^{-1}$]

$P_{g0} =$ hydrostatic pressure in bubble ($= \rho g D_b + P_0$) [$N.m^{-2}$]

$g = 9.81$ [$m.s^{-2}$]

$D_b =$ bubble depth below surface [m]

$P_0 =$ atmospheric pressure, say about 10^5 [$N.m^{-2}$]

Apart from the radiation (1st) term in (3), the other terms are difficult to evaluate.

First the Target Impulse Response function (TIR) is evaluated for supposed simple "white" delta scatterers at the bubble positions, but already including all different combinations of propagation paths to and from this cloud target. Moreover these propagation paths will each possess different grazing angles, causing specific shifts in arrival time. Also the directivity of the sonar beams for transmission and reception is included in TIR, which is subsequently transformed to the frequency domain in an efficient way applying an FFT. Combining this result with the bubble transfer function we have:

$$s(t) = \int_{\omega=-\infty}^{\infty} \sum_{n=1}^{N} H_{bubble}(\omega) \cdot C_n \cdot e^{-i\omega(t - r_n / c)} \, d\omega \quad (4)$$

With:

$$\omega \cdot r_n / c = \vec{R}_n \cdot \vec{k}_{1,src} + \vec{R}_n \cdot \vec{k}_{1,rec} \tag{5}$$

$\vec{R}_n =$ position vector of pixel ***n***

$\vec{k}_{1,src}, \vec{k}_{1,rec} =$ wave vector for paths towards sonar transmitter respectively receiver.

$C_n =$ Source Level minus propagation loss

Because of the resonance behaviour of air bubbles, only those bubbles are taken into account in the model which are more or less near resonance for the given sonar pulse. In this way an effective bubble cloud is made by selection from the original one, for the sonar pulse in question. So all other bubbles with radii outside the required bubble range interval are ignored further on. In the obtained bubble radius interval, a number of 31 sub divisions is chosen, each with its specific mean bubble radius. By further supposing the bubble positions in these sub divisions identical but slightly randomly shifted as a whole in order to avoid artefacts, the final frequency response is determined by summation over the responses from all subdivisions. The random shifts of the sub division clouds only result in an extra complex phase factor in this summation.

Multiplying this result with the transmitted pulse spectrum, the modelled echo signal, in the frequency domain is fit for any kind of processing, like for instance matched filtering. The detector is modelled using the Hilbert transform to obtain the envelop signal. Also SAS processing can be applied to the time series using different sonar positions.

The sonar detection scenario is presented in Fig.1, where a sonar system is pinging from aside towards a ship wake. Because of the horizontal beam width of the sonar, the bubble object insonified by this beam will be quite large, dependent on “wake target” range and also “wake target” aspect angle. The number of bubbles as well as the TIR function would also become very large in such cases. Therefore only a part of the bubble cloud is selected for the TIR function. After modelling of this echo, time shifted copies are added including retardations dependent on the arrivals from the remaining insonified wake. Some statistical phase shifts and compensations for different propagation losses are added before coherent summation for the response from the entire insonified part of the wake.

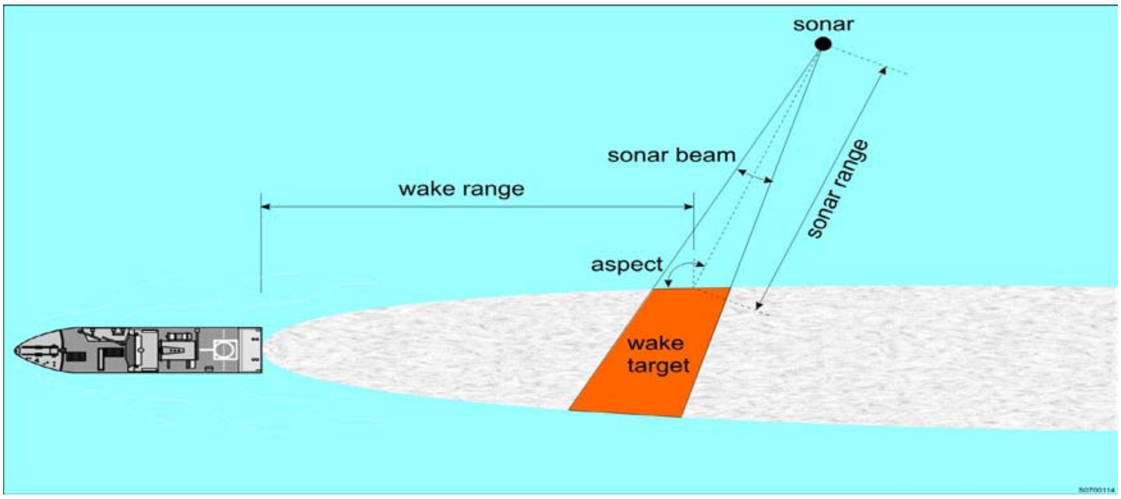

Fig.1 Sonar detection scenario with wake

In the following the above scenario is modelled in REATES, where the ship wake is modelled by the wake model [2] computing the velocity field behind the ship, combined with the bubble dynamics, [3], [4]. This wake modelling has been extended with wake originating from the bow waves left and right of the ship (not shown in Fig.1), resulting in a horizontally much broader wake structure, as observed in measurements [5].

3. PARAMETRIC STUDY USING THE WAKE ECHO MODEL

Inside the wake, the volume contains air bubbles with a bubble radius distribution which is dependent on the range after the ship, further called "wake range". Cross sections of the modelled wake at wake ranges 100 and 400 m are shown in Fig.2. In the left and the right areas in these figures, the wake from the bow waves left and right are shown, with the central part originating from the two propellers and the hull. At 400 m smaller bubble radii are shown than at 100 m.

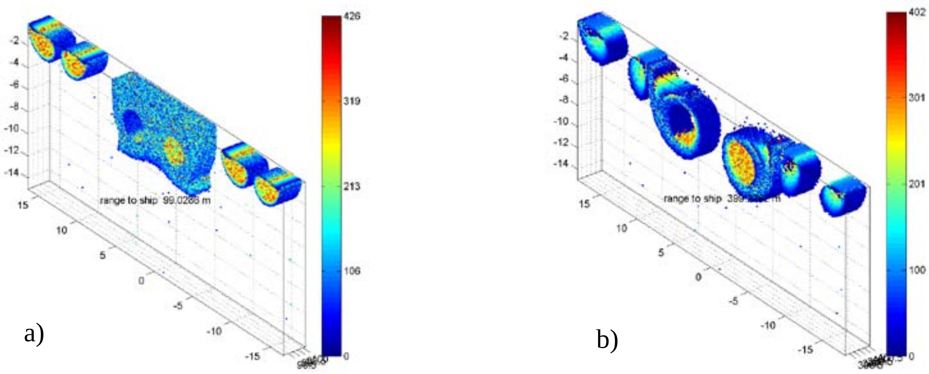

Fig.2: Cross section of wake a) at 100 m wake range (behind ship) b) at 400 m.

Running REATES for both above mentioned wake ranges, at some different frequencies, for the scenario of Fig.1, we get the results in Fig.3 to Fig.5. The horizontal axis represents active sonar range which is virtually the time scale just like the sonar display. The vertical axis shows the received level in dB re 1 μPa (taking 0 dB gain for the matched filter). The black curves are the envelop echo signal versus time, after matched filtering. The cyan curves are the background level, modelled as realistically processed envelop signals, applying the echo modelling method described above, but here for the rough bottom as a target. This bottom roughness is taken from literature [9]. A maximum filter output is shown in the plots, for signal as well as for background, in order to better indicate detection probability of the "wake target".

Particularly the echo for 10 kHz is much lower at 400 m than for 100 m. An explanation here is that the resonating bubbles are relatively large here, while larger bubbles will vanish faster than smaller ones. So there will be considerably less bubbles of large size at 400 m wake range. This effect is also checked in the output of the wake model, being the input for REATES.

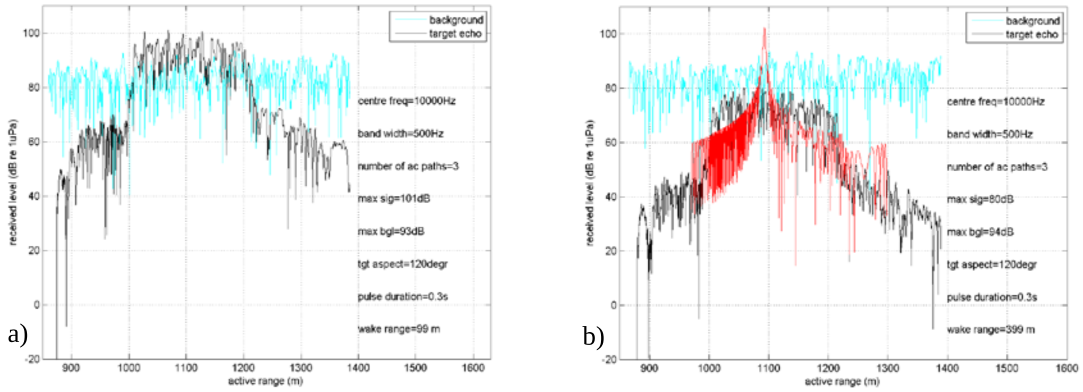

Fig.3: modelled echo structure of wake at 10 kHz a) at wake range 100 m b) at 400; in red a 0 dB point target.

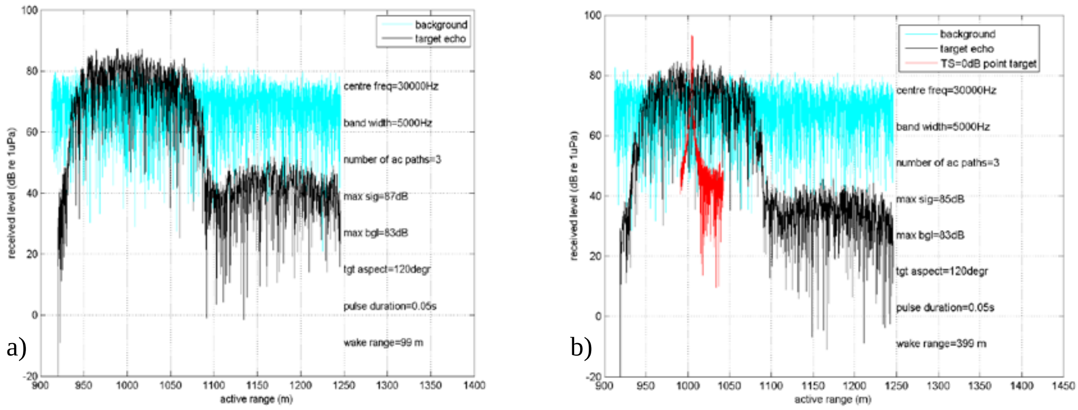

Fig.4: modelled echo structure of wake at 30 kHz a) at wake range 100 m b) at 400; in red a 0 dB point target.

In Fig.4a, also the response for a point target with Target Strength 0 dB (referred to 1 m) is plotted. A maximum filter, which is often applied for detection purposes, shows 93 dB for the point target of 0 dB Target Strength, and 85 dB for the wake echo. The dB's in the above received levels are relative to 1 µPa, assuming that the matched filter gain is set 0 dB. So at this specific target range of 1000 m and aspect angle 120 degree, the echo indicates an effective Target Strength of -8 dB (=85-93) at this wake range of 400 m and 30000 Hz frequency.

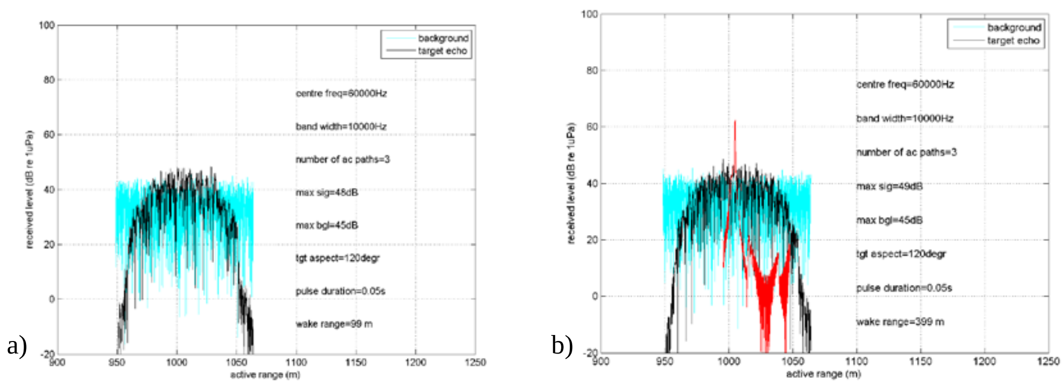

Fig.5: modelled echo structure of wake at 60 kHz a) at wake range 100 m b) at 400; in red a 0 dB point target.

In Table 1 the various TS values for the above examples are shown.

Wake range	*frequency*	*10k Hz*	*30 kHz*	*60 kHz*
100 m		-1	-6	-14
400 m		-22	-8	-13

Table 1 Target Strength of wake echo (dB re 1 m) for some special cases.

4. CONCLUSIONS

A new wake echo modelling method has been developed. Its input is a realistic wake consisting of air bubbles of different sizes, generated by a separate model. The model generates realistic wake structures, in agreement with measurements. Besides air entrapped near the ships hull and propellers, also air entrapped near the bow waves left and right of the ship has now been implemented. The model computes a realistic target echo structure applying a fully coherent modelling method, yielding echo time series and envelope. The method, being a further development of the ALMOST/REACT modelling of propagation and active sonar performance, takes into account full sonar processing, beam directivity patterns, environmental propagation effects, as well as specific scenario geometries for the wake detection using a forward looking medium or high frequency active sonar. The model can be used for parametric studies. The wake echo level appears to vary considerably with parameters like the distance to the ship, the aspect angle and the centre frequency of the transmitted pulse. The echo level can be quantified using an effective Target Strength. The cases for which the effective TS values have been derived show medium to low TS values.

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