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IDENTIFICATION OF RESONANCE STRUCTURES IN ECHO SIGNALS FROM SIMPLE CYLINDRICAL OBJECTS

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8) ABSTRACT

This note presents results from analysis of data from a series of measurements where a set of cylinders have been insonified at relatively short range by a low frequency broadband sonar source. Purpose of the analysis was to identify resonance structures in reflected sonar signals, and to estimate cylinder properties like diameter, filling material, wall thickness and wall material based on the resonance features. The analysis software used has been developed at SACLANTCEN under projects aimed at improving classification of buried mines and mines in high clutter areas.
Our objective with the testing was to gain experience with resonance structure analysis by making tests and collecting data in a similar way as has previously been done at SACLANTCEN, and analysing the recorded echo signals using SACLANTCEN's software. The analysis software which also includes models of simple cylindrical objects, had been transferred to FFI early 1998 as part of a Joint Research Project (the JRP on Dectetion and Classification of Mines). The tests combined both air-filled and water-filled cylinders, and included tubes of diameters from 89 to 500 mm insonified at normal incidence and tilted at a small angle with the normal.
Our results for the larger diameter cylinders are quite in line with what has been found at SACLANTCEN. Tilted incidence also produced results comparable to results obtained at normal incidence in several cases.
Regarding analysis of small diameter tube data the software would not always provide results.
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IDENTIFICATION OF RESONANCE STRUCTURES IN ECHO SIGNALS FROM SIMPLE CYLINDRICAL OBJECTS

1 INTRODUCTION

1.1 General

It is well known that a submerged object insonified by an active sonar signal modulates the echo signals that are reflected or scattered from the object. It is not well known what factors affect this modulation process, and if or how it is possible to extract information about the object based on observations of the modulated echo signals. Depending on the structural complexity of the insonified object several modulating processes may exist. Among these processes resonances in the mechanical structure are of the more promising effects. Several workers in this field have reported that mechanical resonances can be excited in underwater objects by active sonar insonification, and that such resonances are indeed observable in the received echo signals, see (2, 3, 4, 5, 6 & 7),
The work reported in this note was intended as a first step in direction of a comprehensive study of echo signal modulation in general and resonance structures in active sonar echoes in particular. We wanted to study the possibilities of exploiting such structures in active sonar classification and false alarm reduction. Basically this task applies both to ASW and mine-hunting. However, a natural starting point for studies in echo structure analysis has been modelling and measurements on simple objects like cylinders or spheres. We selected cylinders of mine dimensions or smaller for our initial measurements which means that our work may not bedirectly applicable to existing ASW systems.

A very important task in mine-hunting operations is reduction of the many false alarms encountered particularly when hunting for bottom mines in high clutter areas. Our aim has been to find ways to classify mines or mine-like objects in such areas. We want to be able to distinguish man-made objects from natural ones like stones or rocks, and, among man made objects, to distinguish mine-like objects from other objects. Structural resonances excited in a target and modulation of sonar echoes by these resonances are interesting clues to object classification if this modulation can be identified at the receiver.

This note documents what has been done and achieved in this first step.

1.2 About the measurements

Measurements were conducted in Horten 25th November 1998 using simple cylindrical targets at short range. At that particular date a TOPAS parametric echo sounder type PS 040 needed for the measurements was made available to us by KDA/Stjørdal under the UNISON project. Our objective with the testing was to gain experience with resonance structure analysis by repeating measurements previously conducted at SACLANTCEN, and analysing the recorded echo signals using software developed at SACLANTCEN. This software had been transferred to FFI early in 1998 as part of a Joint Research Project (the JRP on Dectetion and Classification of Mines).

The tests combined both air-filled and water-filled cylinders, and included tubes of diameters 89 to 500 mm at normal incidence and tilted at a small angle with the normal.

Figure 1.1 sketches the measurement barge with parametric transducer and arrangement for measuring the acoustic response of the cylindrical objects. In table 1.1 are listed the objects measured with their dimensions: Length, outer radius, wall thickness etc. The incident/reference signal is shown in figure 2.1. It is a 10 kHz Ricker pulse recorded by means of a hydrophone placed in the position of the targets after the targets had been removed.

The objects used as targets were 2 equal sets of 4 tubes each, one set air-filled, one set open, i.e. water-filled, see table 1.1 below. These were the targets available when the opportunity to make the initial tests appeared.
We made tests at normal incidence (3° down from the normal), and tilted at 11.5°. The tilting was done electronically with the transducer lifted to a higher level so that the location of the tilted beam footprint on the measured object remained approximately unchanged, see figure 1.1.

The parametric sonar secondary beam opening angle has been estimated to 4° in the prevailing measurement situation at a range of $r = 10.4$ m.

Objects measured:

Object	Length	Radius	Wall thickness	Relative wall thickness
Cylinder 1	2 m	a = 250 mm	t = 6.3 mm	t /a = 2.5 %
Cylinder 2	3 m	a = 136.5 mm	t = 6.3 mm	t/a = 4.6 %
Cylinder 3	3 m	a = 70 mm	t = 4.0 mm	t/a = 5.7 %
Cylinder 4	3 m	a = 44.5 mm	t = 3.2 mm	t/a = 7.2 %

Two sets of these 4 cylinders were used, one set water-filled (WF),
the other set air-fille (AF).
All cylinders were measured at normal incidence approximately (3°),
and tilted (11.5°).

Table 1.1 List of cylindrical objects

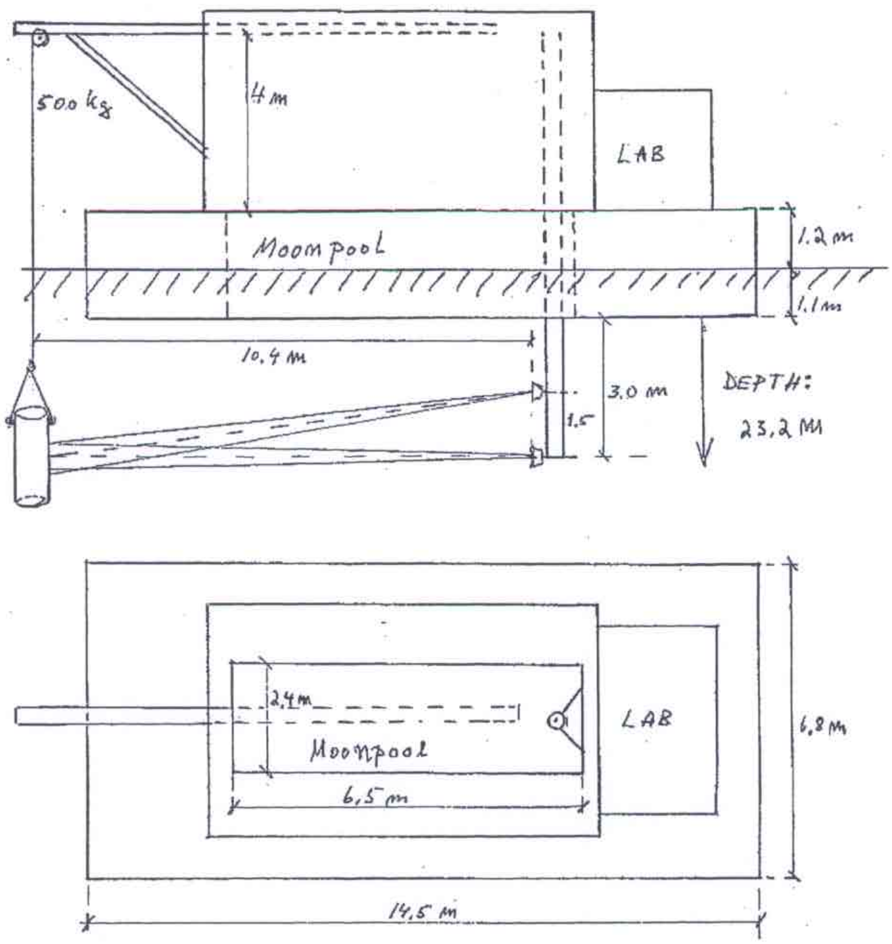

Figure 1.1 Measurement barge with arrangement for transducer and targets

2 ANALYSIS OF RECORDED DATA

2.1 General

We conducted these measurements and analysis to acquaint ourselves with echo structure analysis and resonance classification of simple objects in general, and with use of the analysis software developed at SACLANTCEN in particular. The Mine Target Echo Analysis software is described below.

SACLANTCEN has been working in this field for some time doing both modelling and measurements for verification of model predictions. FFI joined SACLANTCEN and other NATO country institutes in a Joint Research Project (JRP) on Mine Detection and Classification in 1997. Our contributions to the JRP have been rather limited due to limited funds and changing priorities. However, SACLANTCEN has transferred to FFI their Mine Target Echo Analysis software developed before and during the JRP.

Our measurements and analysis of echo signals from various types of cylinders could be useful also for the JRP and SACLANTCEN. We repeated some of the tests previously done at SACLANTCEN and added new ones like smaller diameter tubes, higher relative tube wall thickness and tilted as well as normal incidence. The analysis results, which are in line with what has previously been found at SACLANTCEN, should strengthen their conclusions. And the results, which fall outside what has been observed previously, may spur additional work and increase our understanding of the phenomena studied.

Both mine-like (50 cm diameter) tubes and smaller tubes which were relatively thicker than tested previously, were used, and all tubes were measured both at normal incidence approximately (3°) and tilted (11.5°). Secondary beam-width of the TOPAS parametric sonar at the recorded range of 10.4 m was estimated by the transducer manufacturer to 4°. All tube types were tested both air-filled and water-filled during the one-day test period.

Echo signals from the tubes were recorded and stored on disk. Table 2.1 connects the file numbers to the actual measurements. The numbering is according to the sequence of tests done. A file number identifies cylinder type (tube), if it was air-filled or water-filled, testing at normal incidence or tilted, frequency band used in the analysis and echo or ping number.

The last column of table 2.1 contains some of the results of the analysis. We will revert to these results in the next section 3.0 Discussion of the results. At this stage it is sufficient to state that this column shows which signals have been found by the analysis software to fulfil the confirmation criteria for the hypotheses water-filed or air-filled cylindrical object or not.

Each file recorded consisted of 200 pings/echoes. For the analysis the 10 first echo signals were converted to a format readable from Matlab. All 10 records were then checked by inspecting visually the power spectra of the echo signals received from the objects under test. Two of these echo signals were then selected, one echo considered typical for the ensemble, the other with more spectral features (minima) in the transfer function. It does not appear that the analysis results were significantly different for the 2 types of selected echo signals.

2.2 The Mine Target Echo Analysis software

The programs were all written in Matlab.
Different programs were supplied for air-filled objects and water-filled ones.
The software consisted of 4 basic programs and a number of functions/subroutines called by the basic programs.

The basic programs were

1. dec_ar
2. AF_est
3. parest3v
4. thnshest

1) dec_ar

This program is used both for air-filled and water-filled objects. It computes the best (according to the Akaike's criterion AIC) AR (Auto Regressive)-based spectral estimation of the object's Transfer Function, TF, see (1).
Inputs to the program are the reference signal incident on the object and the echo signal from the object. The echo signal is deconvolved with the reference signal and Fourier-transformed to produce an estimate of the object's TF.

Other inputs are frequency range for the deconvolution operation, resonance cut-off frequency and the desired range minimum and maximum values of possible AR polynomial orders for the TF.
Most of the echoes were analysed using frequency bands 1 & 2.
- Frq.band 1: 500 - 36500 Hz, cut-off frequency = 35500 Hz,
- Frq.band 2: 500 – 25000 Hz, cut-off frequency = 22000 Hz,
(One signal only, file 10 from tube 1 was also analysed using Frq.band 0:
- Frq.band 0: 500 - 48000 Hz, cut-off frequency = 46000 Hz.
Only the lowest frequencies, frq.band 2, were used for tilted incidence.

From figure 2.1 can be seen that that spectrum level of the input reference signal is
20 dB down at 20 kHz, (max frequency used in comparisons with models, frq.band 2.)
40 dB down at 35 kHz, (max frequency used in comparisons with models, frq.band 1.)
60 dB down at 45 kHz
Nominal primary frequency, f_p = 40 kHz .
To make sure that the primary signals were not included in the analysis, frequency bands 1 and 2 were selected.

As is evident from the above the *dec_ar* program contains an AR (Auto Regressive) model representation of the data. The AR model is introduced because it will produce a more accurate spectral representation of a set of data points than the Fourier transform does when the problem is to resolve closely spaced spectral components. This is precisely the case here. The incident broadband signal is of very short duration, and also the reflected echo signals from the target are of short duration which prevents high resolution Fourier-transforms.
Outputs from the program are: A listing of the calculated AR resonances and a plot of the Transfer Function with the AR resonances superimposed as vertical lines, see figure 3.1.

2) Air-filled cylinders (using programs dec_ar and AF_est)
The analysis starts from basic theoretical considerations derived from Resonance Scattering Theory (RST) under conditions of far-field backscattering from circular cylindrical targets of infinite length excited by plane waves at normal incidence. Under the measurements reported here, finite length cylinders were used, but only a small part of the cylinder was insonified by the parametric transducer (see figure 1.1).

The *AF_est* program provides estimates of outer and inner radius of the cylinder tested and its shell speed parameter c^* based on the following input parameters:
- resonance frequencies estimated by the common analysis program *dec_ar*.
- sea water sound speed
- max frequency of analysis
- range of possible values of outer radius a
- range of possible values of the shell speed parameter c^*
The shell speed parameter (membrane velocity) c* (C^{star}) is defined as

$$c^* \approx c_s \sqrt{\frac{2}{1-\nu}}\ , \quad \nu = \text{the Poisson ratio,}\ \nu = \frac{c_p^2 - 2c_s^2}{2\left(c_p^2 - c_s^2\right)}$$

c_p = pressure velocity of shell material
c_s = shear speed of shell material

A multi-hypothesis test procedure is used to compare the resonances associated with the proposed solutions with the estimated resonances found in the measured data.
The model used in this process is a normal mode model based on RST as mentioned above.

The first output from program *AF_est* is a statement saying
"Hypothesis of air-filled thin-walled shell with roughly circular cross-section CONFIRMED!" (or "NOT confirmed!").
The *AF_est* program supplied interesting results for the two larger tubes. However, when it came to smaller diameter tubes this program failed to provide results both for tilted and normal incidence. It would not end calculations within reasonable time.

3) Water-filled cylinders (using programs dec_ar and parest3v and thnshest)
The resonance frequencies estimated by the common analysis program *dec_ar* are used as inputs to the programs made for analysis of water-filled cylinders, *parest3v* and *thnshest,* to perform a multi-hypothesis automatic resonance classification. The method starts from the assumption that the scatterer is a circular, thin-walled cylindrical shell insonified from broadside. It is also assumed that the inner fluid is a liquid. The models used in this process are normal mode scattering models derived from Resonance Scattering Theory (RST) and Plane Plate Theory (PPT), see (2) and (3). Referring to (3) a set of wave families likely to be present in resonance scattering has been identified. These waves are
- S Lamb-type
- S_{out} = Scholte-Stoneley waves on the outer cylinder/water interface
- S_{in} = Scholte-Stoneley waves on the inner cylinder/liquid interface
- r_l internal reflections
Adopting a set of approximate equations, which have been found to supply acceptable results, the location of all resonance frequencies depends only on 4 parameters,

- a = outer radius of the cylinder
- b = inner radius of the cylinder
- c_{in} = sound speed of the internal liquid
- c* = the shell speed parameter (or membrane wave speed).

Inputs to the program *parest3v* are
- Resonance frequencies estimated by *dec_ar*
- Max frequency of the analysis
- water sound speed
A range of possible values for each target parameter is selected:
- outer radius *a*
- relative wall thickness *h*
- sound speed of internal liquid, c_{in}
The program *parest3v* models all combinations of the possible input values of *a*, *h* and c_{in}, calculates the corresponding resonance frequencies and then compares each of these possible solutions with the estimated resonances from the measured object.
Outputs from the program are
A statement saying: "Hypothesis of fluid-filled shell with roughly circular cross-section CONFIRMED! " (or "NOT confirmed!")
Then the program supplies data for the cylinder with the set of parameters which best fits the resonances estimated from the measured data (by minimising a distance-based cost function): Mean values and spreading around the mean of outer and inner radius, wall thickness and speed of sound in the inner liquid.
Program *parest3v* seems to be the "best" program for estimating target parameters because it always produces results.

Inputs to program *thnshest* are a range of possible values of the membrane velocity *c** plus a subset of the input parameters to *parest3v*. Output from program are new value of outer radius *a* which may be different from the one from *parest3v*, an estimate of the membrane velocity *c**

and spreading values for both estimates. The spreading value for *a* is always much larger than the spreading calculated by *parest3v.*
Program *thnshest* does not always produce results, it stops or "hangs" and must be terminated in many cases with data from tilted incidence and/or smaller tube diameters. However, it is this program which estimates the shell speed parameter/membrane velocity c^* (c^{star}) .

In the analysis and results presented we have chosen to utilise the outer diameter values and spreading as provided by program *parest3v.* The reason for this choice is mainly the fact that program *parest3v* always produced results whereas program *thnshest* several times failed to do so. Parameters used in the analysis of the recorded data are shown in table 2.2 below.

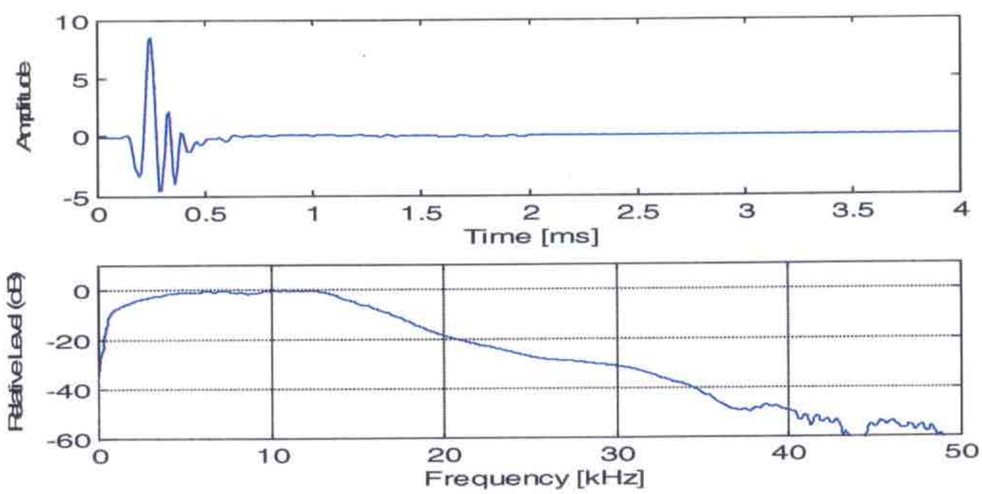

Figure 2.1 *Reference signal*

File no	Tube	Air/ Water	Normal/ Tilted	Frq.	Echoes Analysed	Confirmed/ programs	
File1	1	WF	Norm.Incid.(3°)	0,1,2	6 & 10	C	P&T
File3	1	WF	Tilted (11.5°)	2	4	C	P&T
File5	1	WF	Tilted (˜< 10°)	2	1	C	P&T
File7	1	AF	NI (3°)	1,2	3 & 6	C	A_e
File9	1	AF	Tilted (11.5°)	2	3 & 10	C	A_e
File 11	2	AF	NI (3°)	1,2	3	C	A_e
File13	2	AF	Tilted (11.5°)	2	2	C	A_e
"	2	AF	- " -	2	9	NO RES.	
File15	2	WF	NI (3°)	1,2	1 & 6	C	P&T
File17	2	WF	Tilted (11.5°)	2	5 & 9	C	P&T
File20	3	AF	NI (3°)	1,2	6	NO RES.	
"	3	AF	- " -	1	9	NO RES.	
"	3	AF	- " -	2	9	NO RES.	
File22	3	AF	Tilted (11.5°)	2	1	NO RES.	
"	3	AF	- " -	2	8	NO RES.	
File24	3	WF	Tilted (11.5°)	2	6 & 8	C	P
File26	3	WF	NI (3°)	1	2 & 7	C	P&T
"	3	WF	- " -	2	2 & 7	C	P
File28	4	AF	NI (3°)	1,2	8	NO RES.	
"	4	AF	- " -	1,2	6	NO RES.	
File30	4	AF	Tilted (11.5°)	2	7 & 10	NO RES.	
File32	4	WF	Tilted (11.5°)	2	4	C	P
"	4	WF	- " -	2	8	NC	P
File34	4	WF	NI (3°)	1,2	2 & 6	C	P

Table 2.1 *Files and measurements*
(See sect. 3.0 Discussion of results for explanation of coding in last column)

File	WF/ AF	Tilt	Ping no	Frequency (Hz)	a-range	h-range	Cin-range	Cstar-range
File 1	WF	NI	10	500-45000	0.2:0.001:0.3	.02:.001:.05	1480:1:1500	5000:100:7000
- " -	"	"	10	500-35000	0.2:0.005:0.3	-- " --	1480:1:1495	-- " --
- " -	"	"	10	500-20000	-- " --	-- " --	-- " --	4000:100:7000
- " -	"	"	6	500-35000	.22:.002:.28	-- " --	1480:1:1500	4000:100:6500
- " -	"	"	6	500-20000	-- " --	-- " --	-- " --	-- " --
File 3	WF	11.5°	4	500-20000	.23:.002:.3	.016:.001:.032	1480:2:1500	4000:100:6000
File 5	WF	<10°	1	500-20000	0.2:0.002:0.3	-- " --	-- " --	-- " --
File 7	AF	NI	3	500-35000	.22:.002:.28			4000:100:6500
- " -	"	"	6	500-35000	.24:.001:.3			4000:50:6000
- " -	"	"	3 & 6	500-20000	-- " --			-- " --
File 9	AF	11.5°	3 & 10	500-20000	0.2:0.002:0.3			4000:100:6000
File 11	AF	NI	1	500-35000	0.1:0.001:0.18			4000:50:6000
- " -	"	"	1	500-20000	-- " --			-- " --
File13	AF	11.5°	2	500-20000	.11:.001:.17			4000:50:6000
- " -	"	"	9	- " -	.11:.002:.17	.02:.001:.09	1480:2:1500	
File 15	WF	NI	6	500-35000	.12:.002:.2	0.02:0.002:0.1	-- " --	4500:50:6000
- " -	"	"	1	-- " --	.12:.001:.19	0.02:0.001:0.1	1480:1:1500	4000:50:6500
- " -	"	"	6	500-20000	-- " --	.02:.001:.09	-- " --	-- " --
- " -	"	"	1	-- " --	0.1:0.001:0.18	0.02:0.001:0.1	-- " --	-- " --
File 17	WF	11.5°	5	500-20000	.11:.002:.17	.02:.001:.09	1480:2:1500	4000:50:6000
- " -	"	"	9	-- " --	.11:.002:.18	-- " --	-- " --	
File20	AF	Norm	6 & 9	500-20000	.05:.002:.1	.03:.002:.12	1480:2:1500	-
- " -	"	"	- " -	500-35000	- " -	- " -	- " -	-
File22	AF	11.5°	1 & 8	500-20000	.05:.001:.09	.03:.001:.12	1480:2:1500	-
File24 (P)	WF	11.5°	6	500-20000	.05:.001:.09	.03:.002:.12	1480:2:1500	-
- " -	"	"	8	- " -	- " -	.03:.001:.12	- " -	-
File26 (P)	WF	Norm	2 & 7	500-20000	.05:.002:.1	.03:.002:.12	1480:2:1500	-
- " - (T)	"	"	7	500-35000	.06:.002:.11	- " -	- " -	4000:100:6000
- " - (T)	"	"	2	- " -	.07:.002:.12	- " -	- " -	
File28	AF	Norm	6 & 8	500-20000	.03:.002:.1	.03:.002:.12	1480:2:1500	
- " -	"	"	- " -	500-35000	- " -	- " -	- " -	
File30	AF	11.5°	7 & 10	500-20000	.025:.001:.07	.03:.002:.12	1480:2:1500	
File32 (P)	WF	11.5°	4 & 8	500-20000	.025:.001:.07	.03:.002:.12	1480:2:1500	
File34 (P)	WF	Norm	2 & 6	500-20000	.03:.002:.09	.04:.005:.14	1480:2:1500	
- " -	"	"	- " -	500-35000	- " -	.03:.005:.12	- " -	

Table 2.2 Parameters used in the analysis (for dec_ar, AF_est and parest3v).

3 DISCUSSION OF THE RESULTS

Figure 3.1 shows one example of the results produced by program *dec_ar*. Tube 1 of diameter 50 cm, water-filled and measured at normal incidence is shown. The frequency band used for the analysis is band 1, (0 - 35500 Hz) with max frequency for the resonance frequencies set to 35000 Hz. As can be seen there are many more resonance estimates from the AR-based spectral estimation than from the Fourier-based TF. Some of the frequency estimates are common, others are not. This is a general feature in this analysis

The programs made for multi-hypothesis testing of the measured objects, *AF_est, parest3v* & *thnshest,* are comparing the resonances that have been calculated based on measurements with model predictions of such resonances from a range of object sizes. Results of the analysis and comparisons in the form of estimates of cylinder dimensions etc. are presented in tables 3.1, 3.2, 3.3, 3.4 and 3.5 below. For each cylinder or tube average results are shown for the different situations tested: Water-filled versus air-filled, and normal incidence versus tilted incidence. The results shown in the tables mentioned are discussed below.

Going back to table 2.1 and the results presented there, the coding has been as follows:

AF:	Air-Filled (cylinder)
WF:	Water-Filled (cylinder)
C:	CONFIRMED i.e. the hypothesis Water-Filled cylinder or Air-Filled cylinder is confirmed
NC:	The hypothesis is NOT CONFIRMED The case is WF, and the WF hypothesis is not confirmed (one case only).
NO RES.:	The case is AF, program *AF_est* produced NO RESULT.
A_e:	*AF_est*, program for analysing AF-data, produced results
P&T:	Both WF analysis programs *parest3v* and *thnshest* worked
P:	In this WF case program *parest3v* only produced results and program *thnshest* did not.
NI (3°):	Normal Incidence (which means 3° off the true normal)

From Table 2.1 we observe the following:

Water-filled cylinders: The analysis worked and produced results in all cases except for one, the thinnest tube at tilted incidence for which the WF-hypothesis was not confirmed.
Program *thnshest* did not work in some cases for the two thinner tubes which means that we did not get any estimate of the shell speed parameter in those cases.
Air-filled cylinders (the two thickest ones): Ok except for one case (tilted incidence) where the analysis program *AF_est* did not produce results.
Air-filled cylinders (the two thinner ones): Program *AF_est* did not produce results in any of the cases.

Large diameter cylinders/thin shell and smaller diameter cylinders with not so thin shells:
We observe that the WF software is less sensitive to tube diameter and thickness of shell than the AF software (or stronger and more detectable resonances are set up in WF cylinders than in AF cylinders

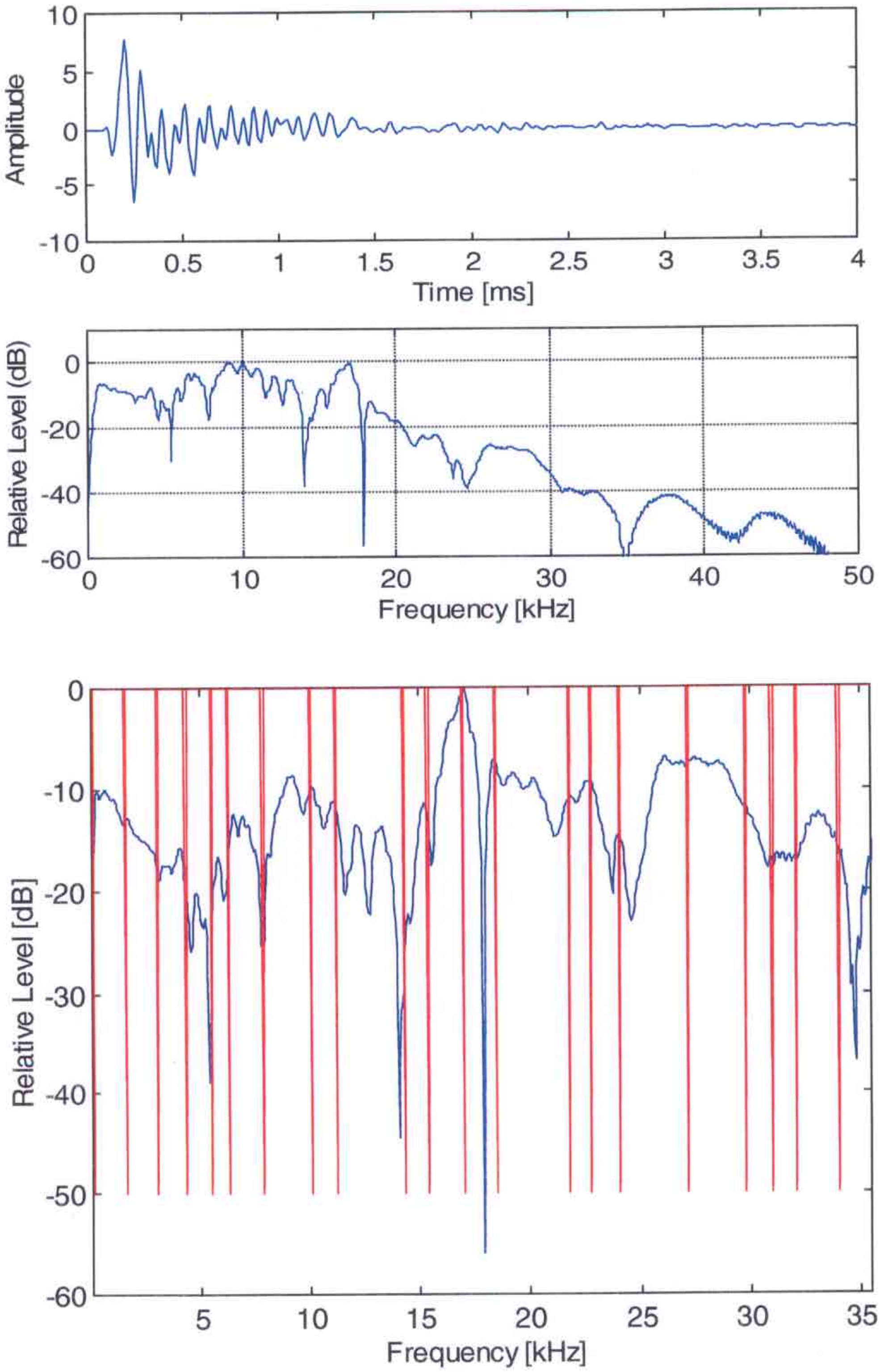

Figure 3.1 *Output from program dec_ar: Echo signal time function, power spectrum and Transfer Function with AR-based resonances (Tube 1, water-filled, frq.band 1, normal incidence)*

The results observed for the smaller tubes may not be surprising. In development of the RST (Resonance Scattering Theory) model software the cylinders have been assumed to be infinitely long, the incident signal a plane wave and a thin sheet approximation has been applied in the model. Relative thickness of the thinner tubes is greater than for the larger diameter tubes, 7.2 % for the thinnest compared with 2.5 % for the largest tube, see table 1.

Normal and tilted incidence:
Measurements at tilted incidence (11.5°) produced a much lower signal level than at normal incidence. Beamwidth of the incident signal was estimated by the supplier of the TOPAS source to be 4°. If this estimate is correct there would be no specular return path from tube to receiver. Usable signal bandwidth for the received echo signals were up to 20000 Hz, ie. the echo signals would generally disappear into the noise at frequencies above 20000 Hz. Therefore frequency band 2 (500-20000 Hz) had to be used in the analysis. Even at the low S/N ratios encountered analysis of these echo signals supplied interesting results not very different from those at normal incidence in many cases. The WF software identified resonances and tube parameters in most cases whereas the AF software succeeded only for the two largest tubes.

3.1 Object parameters estimated from the recorded data

Tables 3.1, 3.2, 3.3 & 3.4 are showing averaged results for the 4 cylinders respectively. The most important result are confirmation or non-confirmation of the hypotheses water-filled or air-filled cylinder versus other object. A qualitative evaluation of the estimates is offered below.

Table 3.1: Cylinder 1 - t /a = 2.5 %
All hypotheses CONFIRMED.
Outer radius: Good, better than 14 % error, AF better than WF
Wall thickness: Not so good, AF/Normal more than 100 % above, Tilted better than normal,
Shell speed parameter c*: Good estimates (on the average), AF mean very close and better than WF mean.

Table 3.2: Cylinder 2 - t/a = 4.6 %
All hypotheses except for one (AF/Tilted) were CONFIRMED.
Outer radius: Reasonably good, better than 25 % error, AF slightly better than WF
Wall thickness: Accuracy approximately as for cylinder 1, tilted and normal near equivalent
Shell speed parameter. c*: Good estmates (on the average).

Table 3.3: Cylinder 3 - t/a = 5.7 %
All AF cases NO RESULTS
All WF cases CONFIRMED, but program *thnshest* did not work in all cases.
Outer radius: Reasonably good, better than 34 %, worst case for WF/Normal
Wall thickness: Reasonably good estimates
Shell speed parameter: Good estimates (on the average).

Table 3.4: Cylinder 4 -t/a = 7.2 %
All AF cases NO RESULTS
WF/Normal CONFIRMED, WF/Tilted: 1 CONFIRMED, 1 NOT CONFIRMED.
Outer radius: Poor estimates except for the Tilted case which is reasonably good
Wall thickness: Good estimates
Shell speed parameter: No estimates provided because non of the programs *AF_est* or *thnshest* worked.

In table 3.5 all estimates are combined such that the effects of all variables can be seen in one table

- Cylinder type (4 different cylinders, see table 1)
- Water-filled or Air-filled
- Normal or Tilted incidence
- Frequency band selected for the analysis, LF: 500-20000 Hz, HF: 500-35000Hz

The only new information available from this table is that there seems to be no significant difference in the results between the 2 frequency bands employed in the analysis, LF : 500-20000 Hz, and HF: 500-35000 Hz.

It is clear from the results presented in tables 3.1 to 3.5 that the program *parest3v* for analysing WF-cases is more robust than the AF program *AF_est*, since it always produces results. The WF program *thnshest* is similar to the AF-program *AF_est* in that it fails to provide results for the smaller diameter tubes and tilted incidence. The way these 2 programs fail are by not stopping within a reasonably (long) period of time.
In more detail:

i) For water-filled cylinders the first analysis program *parest3v* would always produce results and stop, whereas the second program for analysing WF-objects, *thnshest*, in some cases would not stop within a reasonable time period. This happened for the thinner tubes and tilted incidence, and also for the thinnest tube at normal incidence. The thin-sheet assumption is doubtful for the thinnest tubes..

ii) In the water-filled cases where both programs (*parest3v* and *thnshest*) worked, the program would always say: Hypothesis Confirmed! In only one case (for the thinnest tube at tilted incidence) the analysis program *parest3v* stated: Hypothesis NOT CONFIRMED. The reason for this outcome may be that the thin sheet assumption is doubtful for the tube diameters and thicknesses encountered.

iii) The analysis program *AF_est* for air-filled cylinders behaved in more or less the same way as the program *thnshest* for the water-filled cases. The program provided no results for the two thinner tubes neither at normal incidence nor tilted.
The programs *AF_est* and *thnshest* are not so robust as the *parest3v*-program.

Analysis results:

Cylinder 1, length 2 m

Dimensions	Radius a (mm)	Thickness t (mm)	Shell speed parameter	Hypothesis (C/ NC/NR)
Nominal	250	6.3	C* = 5435 m/s	
Estimates	a ± σ	t ± σ	Cm ± σ	
WF, Normal Incidence (3°) (Average of 5)	273 ± 2.4	10.5 ± 3.2	5700 ± 1065	C (Frq.bnd 0,1,2 echo 6,10)
AF, Normal incidence (3°) (Average of 4)	265	13.9	5400	C (Frq.band 1, 2 echo 3, 6)
WF, Tilted (11.5°) (Average of 2)	287 ± 4.7	8.6 ± 5.0	4900 ± 710	C (Frq.band 2 echo 1, 4)
AF, Tilted (11.5°) (Average of 2)	233	9.5	5450	C (Frq.band 2 echo 3, 10)

C: Hypothesis CONFIRMED
NC: Hypothesis NOT CONFIRMED
NR: NO RESULTS
(When program AF_est does not work, i.e. it will not stop within reasonable time)
When in WF-cases no shell parameter speed C* is listed, this means that program *thnshest* did not supply any result.

Table 3.1 Cylinder 1

Cylinder 2, length 3 m

Dimensions	Radius a (mm)	Thickness t (mm)	Shell speed parameter	Hypothesis (C/ NC/NR)
Nominal	136.5	6.3	C* = 5435 m/s	
Estimates	a ± σ	t ± σ	Cm ± σ	
WF, Normal Incidence (3°) (Average of 4)	171 ± 1.3	13.1 ± 2.0	5388 ± 980	C (Frq.band 1, 2 echo 1, 6)
AF, Normal incidence (3°) (Average of 2)	163	13.5	5350	C (Frq.band 1, 2 echo 3)
WF, Tilted (11.5°) (Average of 2)	171 ± 1.8	9.0 ± 1.8	5325 ± 1150	C (Frq.band 2 echo 5, 9)
AF, Tilted (11.5°)	134	14.1	5550	Echo 2: C Echo 9: NR (Frq.band 2)

C: Hypothesis CONFIRMED
NC: Hypothesis NOT CONFIRMED
NR: NO RESULTS
(When program AF_est does not work, i.e. it will not stop within reasonable time)
When in WF-cases no shell parameter speed C* is listed, this means that program *thnshest* did not supply any result.

Table 3.2 Cylinder 2

Cylinder 3, length 3 m

Dimensions	Radius a (mm)	Thickness t (mm)	Shell speed parameter	Hypothesis (C/ NC/NR)
Nominal	70	4.0	C* = 5435 m/s	
Estimates	a ± σ	t ± σ	Cm ± σ	
WF, Normal Incidence (3°) (Average of 4)	94 ± 1.3	5.0 ± 1.5	5350 ± 1238	C (Frq.band 1, 2 echo 2, 7)
AF, Normal incidence (3°) (Average of 3)	-	-	-	NR (freq.band 1,2 echoes 6, 9)
WF, Tilted (11.5°) (Average of 2)	75 ± 1.1	4.3 ± 1.1	-	C (Frq.band 2, echo 6, 8)
AF, Tilted (11.5°)	-	-	-	NR (Frq.band 2 echoes 1, 8)

C: Hypothesis CONFIRMED
NC: Hypothesis NOT CONFIRMED
NR: NO RESULTS
(When program AF_est does not work, i.e. it will not stop within reasonable time)
When in WF-cases no shell parameter speed C* is listed, this means that program *thnshest* did not supply any result.

Table 3.3 Cylinder 3

Cylinder 4, length 3 m

Dimensions	Radius a (mm)	Thickness t (mm)	Shell speed parameter	Hypothesis (C/ NC/NR)
Nominal	44.5	3.2	C* = 5435 m/s	
Estimates	a ± σ	t ± σ	Cm ± σ	
WF, Normal Incidence (3°) (Average of 4)	76 ± 1.5	3.2 ± 1.8	-	C (Frq.band 1, 2 Echo 2, 6)
AF, Normal incidence (3°) (Average of 2)	-	-	-	NR (Frq.band 1, 2 echoes 6, 8)
WF, Tilted (11.5°)	29 ± 0.7	2.4 ± 0.7	-	Echo 4: C Echo 8: NC (Frq.band 2)
AF, Tilted (11.5°) (Average of 2)	-	-	-	NR (Frq.band 2, echo 7, 10)

C: Hypothesis CONFIRMED
NC: Hypothesis NOT CONFIRMED
NR: NO RESULTS
(When program AF_est does not work, i.e. it will not stop within reasonable time)
When in WF-cases no shell parameter speed C* is listed, this means that program *thnshest* did not supply any result.

Table 3.4 Cylinder 4

# records	Cylinder no.	WF/AF	NI/Tilted	LF/HF	Outer Radius a ± σ	Wall Thickness d ± σ	C* (m/s) c* ± σ	Hypothesis C/NC
2	1 (250/6.3)	WF	NI	LF	263 ± 2.5	11.8 ± 3.4	5900±1743	C
2				HF	274 ± 3.2	11.7 ± 4.1	5750±894	C
2	1	WF	Tilted	LF	287 ± 4.7	8.6 ± 5.0	4900±710	C
2	1	AF	NI	LF	264 ± 1.0	13.9 ± 0.8	4925±	C
2				HF	266 ± 0.8	13.7 ± 0.5	4625±	C
2	1	AF	Tilted	LF	233 ± 1.0	9.43 ± 1.0	5450±	C
2	2	WF	NI	LF	180 ± 1.5	11.0 ± 2.1	5200±790	C
2				HF	162 ± 1.2	15.2 ± 1.9	5575±1169	C
2	2	WF	Tilted	LF	171 ± 1.9	9.1 ± 1.9	5325±1154	C
1	2	AF	NI	LF	160 ± 0.5	13.5 ±	5200 ±	C
1				HF	166 ±	13.5 ±	5500 ±	C
2	2	AF	Tilted	LF	134 ±	14.1 ±	5550 ±	C, NR
2	3	WF	NI	LF	94 ± 1.3	4.7 ± 1.3	--	C
2				HF	94 ± 1.3	5.3 ± 1.6	5350±1238	C
2	3	WF	Tilted	LF	62 ± 1.1	4.3 ± 0.7	--	C
2	3	AF	NI	LF			--	NR
2				HF			--	NR
2	3	AF	Tilted	LF			--	NR
2	4	WF	NI	LF	73 ± 1.6	3.5 ± 2.1	--	C
2				HF	79 ± 1.3	3.0 ± 1.5	--	C
2	4	WF	Tilted	LF	29 ± 0.7	2.4 ± 0.7	--	C, NC
2	4	AF	NI	LF	-	-	--	NR
2				HF	-	-	--	NR
2	4	AF	Tilted	LF	-	-	--	NR

Table 3.5 *Estimates of radius, thickness and shell speed parameter.*
Parameters: Cylinder type, Water/Air-filled, Normal or Tilted, Low/High Freq.
*Estimates: Outer radius, **a**, wall thickness, **d**, shell speed parameter, **c***.*
(LF: 500-20000 Hz, HF: 500-35000 Hz, C for steel: 5435 m/s)*

4 CONCLUSION

SACLANTCEN's Mine Target Echo Analysis software has been used to analyse active sonar echo test signals from a set of cylindrical objects. Basically we have found that the analysis software works as expected. The hypotheses regarding object form and air-filled or water-filled interior have been confirmed in most cases, particularly for the larger tubes. Estimates of outer diameters and shell speed parameters are reasonably accurate, whereas cylinder wall thickness estimates for the larger cylinders have been more than twice the true dimension. Thickness estimates for the thinner cylinders are reasonably accurate.

Our tests have had the following variables:
- 4 different cylinders of diameters 500, 273, 140 and 89 mm, length 2, 3, 3 and 3 m respectively
- Water-filled and air-filled cylinders (all tubes)
- Normal (3°) and tilted (11.5°) incidence

We have made the following observations:
<u>Water-filled versus air-filled cylinders:</u>
The software developed for the water-filled cases is less sensitive to tube diameter and thickness of shell than the software developed for air-filled cases (or stronger and more detectable resonances are set up in WF cylinders). The hypotheses of water-filled cylinders were confirmed in all cases except one - the thinnest tube at tilted incidence.
The hypotheses of air-filled cylinders were confirmed for the two cylinders of largest diameter in all cases except one (the smaller one at tilted incidence). None of the two smallest cylinder cases were confirmed.
<u>Large diameter versus small diameter cylinders</u>
The software is better adapted to the larger diameter cylinders than the smaller diameter ones. This is particularly true for the AF-software which did not produce results in any of the two thinner cylinder cases. In the WF-cases the score was much better. However, the analysis program which estimates cylinder shell speed, produced results in only one of the thinner tube cases.
<u>Normal and tilted incidence</u>:
Measurements at tilted incidence produced a much lower signal level than at normal incidence. Usable signal bandwidth in such cases turned out to be not more than 20000 Hz, ie. the echo signals would generally disappear into the noise at frequencies above 20000 Hz.. Even at such low S/N ratios analysis of these echo signals supplied interesting results not very different from those at normal incidence in many cases. The WF software identified resonances and tube parameters in most cases whereas the AF software succeeded only for the two largest tubes.

In developing the Resonance Scattering Theory (RST) model software used in the Mine Target Echo Analysis system the cylinders have been assumed to be infinitely long, the incident signals to be plane waves and a thin sheet approximation has also been applied in the model. The programs have been made for mine-like objects, ie. for cylinders with diameter around 21" (53 cm). Diameter of the two smaller or thinner tubes are 14 cm and 8.9 cm. Relative thickness of the thinner tubes is greater than for the larger diameter tubes, 7.2 % for the thinnest tube compared with 2.5 % for the largest tube (see table 1.1) which is likely to violate the thin sheet assumption. Therefore the peculiarities observed in the results for the smaller tubes may not be surprising.

Based on the model assumptions our tilted incidence results were better than expected. In an infinitely long cylinder the observed resonances would only be weakly excited (if at all) by sonar pulses at tilted incidence. And with a beam width estimated at 4° for the tilt angle of 11.5° only energy scattered from the tube mid section would reach the TOPAS receiver. It is of course possible that errors have corrupted our measurements causing wrong results. The estimated beam pattern at such short ranges (10.4 m) may be wrong as may the plane wave assumption be, i.e. there may have been insonification of the cylinder ends when we believed that only part of the mid section was hit by the beam, causing reflections from the cylinder ends. It is also likely that the short length of the cylinders violates the assumption of infinite length,. and that signals interacting with the cylinder ends will enhance resonances in the cylinders excited by signals outside normal incidence.
The results of our data analysis of cylinder insonification at tilted incidence indicate an increased possibility of detecting cylindrical objects underwater based on structural resonances in the object, compared with estimates based on an assumption of infinitely long cylinders. The results reported should be studied in more detail, preferably in cooperation with SACLANTCEN.

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APPENDIX

A ABBREVIATIONS

AR	Auto Regressive
ASW	Anti Submarine Warfare
AF	Air-Filled (cylinder)
WF	Water-Filled Cylinder)
C	Hypothesis CONFIRMED
NC	Hypothesis NOT CONFIRMED
NO RES.	NO RESULT (no output from analysis program)
JRP	Joint Research Project
KDA	Kongsberg Defence & Aerospace
PPT	Plane Plate Theory
P&T	Both programs *parest3v* and *thnshest* worked
P	In this WF case only program *parest3v* worked
RST	Resonance Scattering Theory
SACLANTCEN	SACLANT Underwater Research Centre
SACLANT	Supreme Allied Commander atLANTic
S/N	Signal-to Noise (ratio)
TF	Transfer Function
TOPAS	Topographic Parametric Sonar
UNISON	Undewater Information and Sonar Technology (project)

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