BROADBAND LFM SIGNAL SOURCE FOR A MODULE-BASED DIVER DETECTION SONAR

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A new approach to design of the diver detection sonar's sounding pulse source is presented. It is based on modules comprising 8 or 16 elements of the transducer grouped on the transmitting channel. The basic advantage of this solution is that it reduces significantly the number of group transmitters. The required output power and topology of the transmitters were determined through theoretical estimation and measurements in a four terminal network. Measurements were taken of the frequency characteristics in the transducer modules including the compensation system used. It is demonstrated that the source level is most irregular in the transducer under examination when the transducer's voltage has a constant amplitude, i.e. with parallel compensation. It is also demonstrated that by appropriately selecting elements for a series compensation of the transducer, the frequency characteristics becomes more regular and source level is increased at the extreme ends of the working bandwidth. The result is a compensated characteristics on the receiving side.

INTRODUCTION

In recent years the threat of terrorism has led to the launch of a number of initiatives designed to improve the security of marine sites, in particular sea ports, anchorages and offshore facilities. Underwater security relies on active and passive sonars for the detection of divers, small underwater vehicles and submerged diver delivery vehicles. The sonars are manufactured by a number of companies worldwide.

Installed at the Polish Navy Port, the Active Stationary Sonar [1] has been in operation for several years with very good results. It was built by OBR CTM in a project called KRYL. The company is currently working on a new generation modular sonar [2] for the detection of underwater objects in ports and anchorages. Its special feature is that it can be adapted to the geometry of the site it is surveilling (the shape of the pool, configuration of the quays and breakwaters and the type of bottom). The sonar is easy to install, portable or stationary, can be installed on quays, ships and in open bodies of water. It is protected from disturbances and changing conditions of sound propagation. One of the research problems the project is addressing is the development of methods for integrating sonars and modules of acoustic barriers. The objective is to build a cost effective and efficient system of underwater security which can successfully operate in a variety of large-scale sites and ensure that mutual disturbances and reverberation levels are kept to a minimum.

Because sonar parameters must be changed in a wide range (especially the observation sector), a module-based design is required. Modules are primarily used in the transducer, transmitter, receiver and signal processing. The number and type of modules in the sonar depend solely on the parameters of the site and its conditions. Special software is used to connect the modules.

1. SONAR CHARACTERISTICS

The diver detection sonar (DDS) uses a broadband piezzocomposite transducer [3] a product of a US-based company MSI. It has 128 transmit-receive sections placed on the side of a cylindrical casing. Vertical beam pattern has a constant width at 12° because it operates in shallow waters. The horizontal width of the sounding beam and its orientation, however, must be adapted flexibly to the geometry of the area under surveillance.

To build a modular structure of the sonar's source of transmitting pulses, the elementary sections of the transducer are grouped (on the transmitting side) into modules operated by individual group transmitters. With this structure it is easy to configure that part of the array which is excited. The operation of the individual transmitters within the group can be easily controlled by low voltage settings made in the main level system.

The dimensions of the transducer module determine the minimal angle by which the transmit sector width and position can be changed. The sector's highest level of precision is achieved with single section modules. This, however, would require a 128 channel transmitter. While the stroke angle for 8 or 16 element modules is wider, it is still acceptable (22.5° or 45°). This structure is matched by lower numbers of group transmitters (16 or 8) but with a higher output power.

The ease of observation sector changes is not the only factor speaking in favour of the modular design of the sonar's transmitting channel. It was also important to consider whether the following can be corrected depending on the size of the module:

- dispersion of the transmit patterns for the elementary sections of the transducer;
- irregularity of the frequency characteristics in the working bandwidth.

The need for correcting the characteristics became apparent from the results of measurements taken by the manufacturer of the transducer. They showed (Fig.1) significant fluctuation of source level *SL* in the sections with some as high as 8 dB in the middle of the working bandwidth.

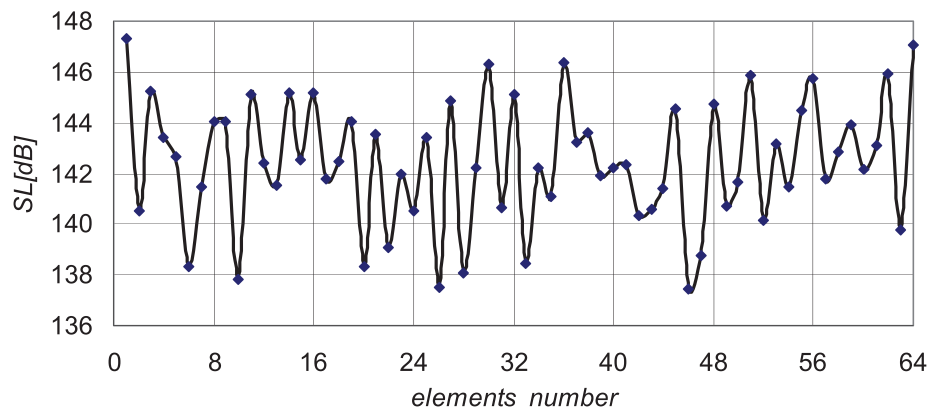


Fig.1. Spread of source level *SL* [dB ref. 1µP/V/1m] for 64 array elements

The dispersion of source level can be corrected separately for each section using single element transmit modules. But this is not necessary because the beam patterns of the transducer's elementary sections are wide and for the practical widths of the scan sector many adjacent sections have to be excited (40 for a 90° sector). This leads to averaging on the acoustic side. As a result, even if non-identical sections are connected in parallel – just like in a multiple elements module - the beam pattern is slightly smoothened out. Its shape and level of ripple resemble that of the theoretical pattern which was obtained for identical elements. This is confirmed by the results of measurements taken by MSI, as seen in Fig.2.

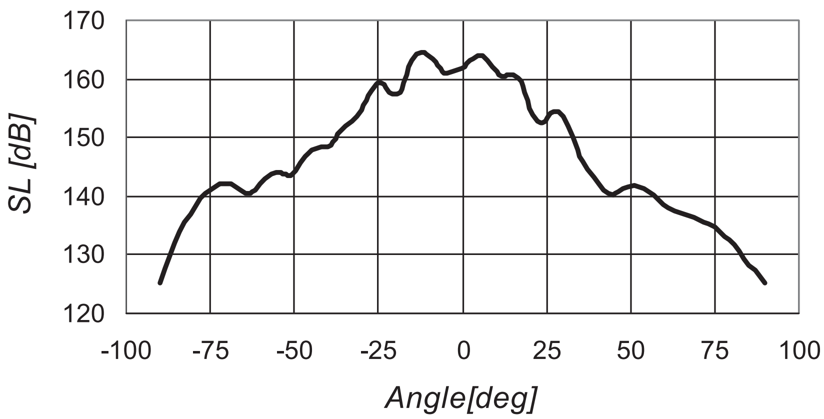


Fig.2. Horizontal transmit beam patterns for a 16 element module of the cylindrical transducer

Figure 3 shows the irregularity of the frequency characteristics. As you can see the drop in *SL* at the edges of the working bandwidth (60÷80kHz) reaches 6 dB. A similar irregularity is seen in the receiving sensitivity which adds up to the drop of 12 dB for the transmit-receive frequency characteristics.

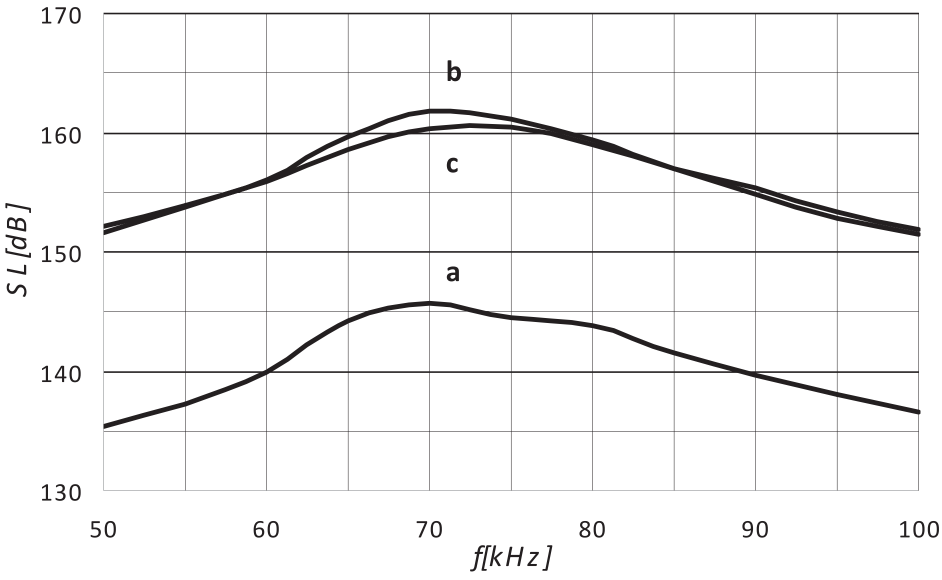


Fig.3. Normalized source level *SL* in the frequency function for a single element (a) and modules with 8 (b) and 16 (c) elements

The decrease in transmit signal level at the ends of the bandwidth can be compensated by controlling the transmitters using a signal whose amplitude will depend on the frequency. The downside of this solution, however, is that the nominal power of the transmitters must be increased significantly (by 12dB) just using linear topology. As a result, it is suitable for single element modules only.

The irregularity of the frequency characteristics can also be corrected with correlation processing by using specially corrected replicas.

As you can see we can build DDS' transmit channel using one of two design alternatives:

• with 128 transmitters to ensure separate access to the transducer's elementary sections;

• with multi-element transmitter modules excited by group transmitters.

This paper presents a concept of a source of sonar transmit pulses using 8 or 16 element modules.

2. SOURCE LEVEL AND ELECTRICAL POWER OF THE TRANSMITTED PULSE

Transmitters of sounding signals are usually power amplifiers. They are excited by the control signals transmitted to their input as a short sinusoidal pulse. The parameters of the signals such as duration, period of repetition and carrier frequency (constant or changing in time for FM) determine the parameters of sounding signals.

The transmitters can be linear, transistor power amplifiers of sinusoidal signals class B or AB. But there are some disadvantages such as limited energy efficiency (maximum of 78% for class B and with full power supply) and limited output power of integrated circuits, having to abstract the heat accompanying the high power losses and not very high working frequencies. The advantages include seamless control of source level by changing the amplitude of the exciting signal and ease of parallel or series compensation of transducer susceptance. For a monochromatic output signal the transmitter will only feed active power to the compensated load. For FM signals compensation will not be perfect in the entire working bandwidth.

Pulse transmitters are a separate group and use D class amplifiers. They feature high energy efficiency usually exceeding 95% which means that we can build small modules with a very high output power (in the order of several kW) with no extra cooling required. They can be supplied from high voltage sources (in the order of 500V). This helps reduce the level of energy, the size of the buffering capacitors and reduce the size of the transmitter even further. Pulse transmitters are inexpensive and reliable and well protected from overload. Their other advantage is that they can operate easily in high frequencies.

The basic disadvantages of pulse transmitters of sounding signals include:

- limited potential for controlling output power which means that in fact only the changes in supply voltage are used;
- presence of higher harmonic components in the rectangular shape of voltage at transmitter output (voltage source) which in fact limits the choice of compensation and only series compensation can be used; parallel compensation would require a complex resonance topology or filtration of fundamental harmonic component from the output signal.

The overview of the basic properties of linear and pulse transmitters shows that the output power is the decisive criterion when choosing the topology of a group transmitter. To estimate it we can use the relationship between *SL* and electrical power P_e of output pulses [4]:

$$SL \cong 10\log(P_e/ P_1) + 10\log\eta + DI + 170.7, \qquad (1.1)$$

where P_1 =1W is the unit electrical power, η is the efficiency of electroacoustic transformation and *DI* is the directivity index of the antenna.

In the sonar in question source level SL = 205 dB re 1μPa at 1m and directivity index $DI \approx$ 10dB. If we assume that $\eta \approx 50\%$, we can calculate:

$$P_e \approx 470\text{W}.$$

Based on the value of P_e we can estimate the powers of electrical pulses at the outputs of group transmitters: 30W for the 8 element module and 60W for the 16 element module.

The required transmitter output power was verified experimentally in a measurement pool. Simultaneous measurements were taken of P_e and its corresponding source level *SL*. The measurements were made with two different transmitters: a B&K linear transmitter and pulse transmitter with high level output power .

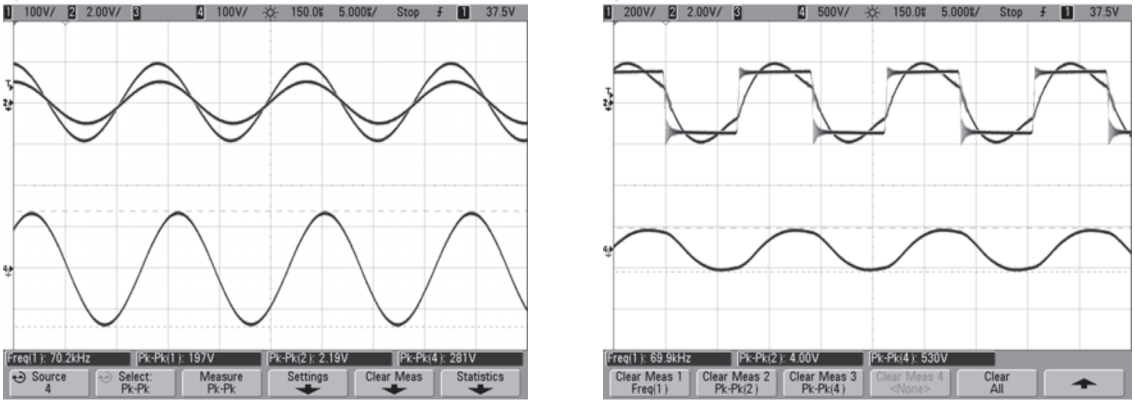
Active electrical power P_e was determined using amplitudes U_N and I_N of voltage and current at transmitter output. Both were recorded using a DSO oscilloscope. The powers were determined for ideal compensation of transducer susceptance only. For the linear transmitter the relation is as follows:

$$P_e = \frac{1}{2} U_N I_N .$$

In the case of a pulse transmitter which is the constant voltage source of a rectangular wave with amplitude U_N, and loaded by a loss resonant circuit, the output current has the shape of a sinusoid with amplitude I_N. With correct compensation the phases of both operations are the same and the power is active:

$$P_e = \frac{2}{\pi} U_N I_N \cong 0{,}64 U_N I_N .$$

Examples of transmitter output signals are presented in the upper part of the oscillograms in Fig.4. The lower part shows voltage on the transducer.



a) B&K linear amplifier,
U_N = 100V, I_N = 1,1A, P_e = 55W

b) pulse transmitter,
U_N = 150V, I_N = 2,0A, P_e = 192W

Fig.4. Examples f voltage and current at transmitter outputs which excite 16 element, series compensated module of DDS transducer for f_N = 70 kHz. The bottom part of the oscillograms shows recorded voltage on the transducer

Source level *SL* was measured in an free field pool using a B&K 8105 hydrophone. Because the measured value of *SL* was as a rule different from the expected value 205 dB re 1μPa at 1m, we determined the level of electrical power P_{e205} of the transmit pulse for source level 205 dB. To that end the following relationship was used:

$$10\log(P_{e205}/ P_e) = 205 - SL. \qquad (1.2)$$

The curves in Fig.4 correspond to source levels 202.3dB for the linear transmitter and 207.6dB for the pulse transmitter with corresponding powers P_{e205} at 102W and 110W.

The nominal available powers of group transmitters should be higher. This is because of the transition phase at the beginning of the transmit pulse and because a significant amount of reactive power must be delivered to the array in those parts of the working bandwidth where compensation is not perfect. It was assumed that nominal powers should be 250W for the 8 element module and 500W for the 16 element module.

3. FREQUENCY CHARACTERISTICS IN THE WORKING BANDWITH

While the envelope of a classic LFM signal is rectangular, the results of the measurements in Fig.3 show that the source level changes together with the frequency both for a single transducer section and for multi-element modules. The source level reduces further away from the centre of the working bandwidth to reach 6 dB for individual sections and 5 dB for 8 element modules and 4 dB for 16 element modules at the ends of the bandwidth (60 and 80 kHz).

The frequency characteristics in Fig.3 was measured for a constant amplitude of voltage signal exciting the transducer, i.e. when compensation is parallel. It is easier to arrange group transmitters for multi-element modules (high power modules) in pulse topology with compensation achieved using a series induction coil. The susceptance of the transducer module can be then completely compensated usually at one point of the working bandwidth only. Compensation will not be perfect, however, for the other frequencies. As a result, the transmitter will have to supply a significant amount of reactive power to the transducer. Active power will change as well, the result of changes of the conductance. Fig.5 shows the results of two-terminal network parameters for the 8 element modules.

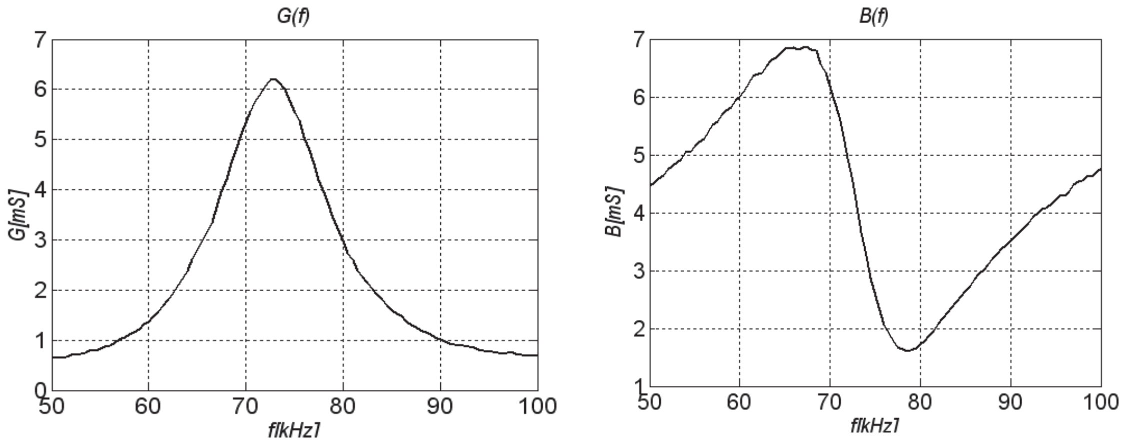


Fig.5. Conductance *G(f)* and susceptance *B(f)* for the 8 section transducer module

Where series compensation is used, the changes in transducer admittance in the frequency function change the transmitter voltage despite a constant voltage amplitude U_N at transmitter output. The frequency characteristics of the transmitting channel are going to change as a result. Fig.6 shows the results of measurements of the *SL(f)* relationship. Series compensation was selected for the centre of the working bandwidth (70 kHz).

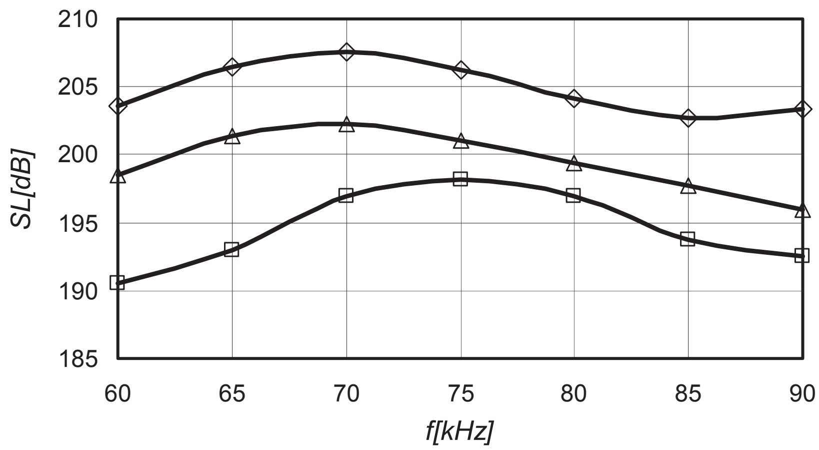


Fig.6. Source level *SL* in the frequency function for the 16 element transducer module for: a) the linear transmitter with U_N= 100V and parallel (squares) or series compensation (triangles) and b) pulse transmitter with U_N= 150V and series compensation (rhombuses)

Analysis of the charts in Fig.6 offers the following conclusions:

- The highest irregularity - about 8 dB - of source level *SL* in the working bandwidth (60÷80 kHz) occurs for a constant amplitude of voltage on the transducer, i.e. for parallel compensation.
- For series compensation selected for the centre of the working bandwidth, the irregularity of the transducer frequency characteristics falls down to 4 dB.
- For parallel compensation the irregularity of *SL* can be reduced to 5dB by shifting the working bandwidth from the range 60÷80 kHz to 65÷85 kHz.
- The DDS working bandwidth can be positively (in respect of reverberation) expanded by raising the upper frequency from 80 kHz to at least 90 kHz.

4. FREQUENCY CHARACTERISTICS FORMING

Frequency characteristics on the transmitting and receiving channel can be smoothened out in correlation processing by using the right replica of the transmitting signal. This can also be achieved through the system, for example by controlling transmitters with a signal whose amplitude depends on the frequency. The solution can be used in linear transmitters, i.e. with single element low power modules.

Group transmitters for large transmitting modules must be arranged in pulse topology and a series transducer compensation, which is the natural choice in this case. As already stated in the previous section the source level is affected by frequency changes of transducer and compensating coil immittances. It was observed that it had a positive effect on the transducer compensated in the middle of the working bandwidth.

A more in-depth analysis of the results of impedance measurements of the transducer showed that a different compensation would make more sense. If adequately selected, the inductance of the compensating coil leads to a total compensation at two points of the working bandwidth: at the lower and upper end. The results of the modelling are given in Fig.7.

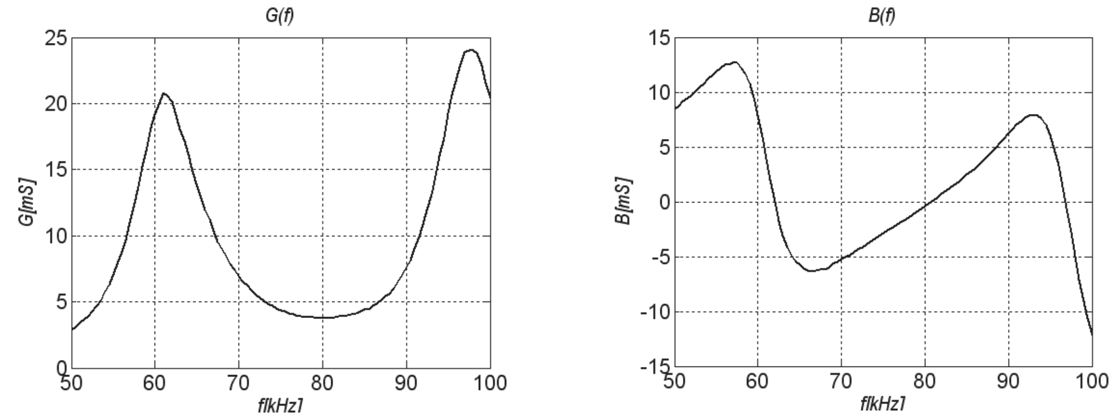
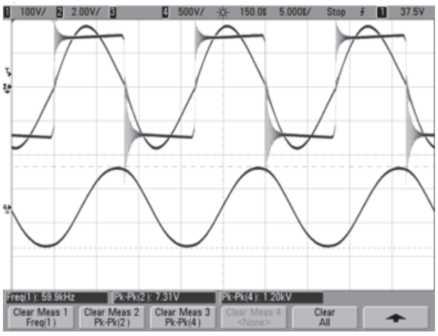
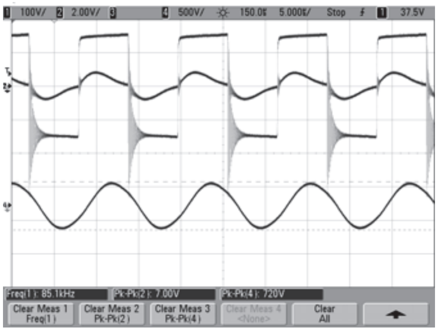


Fig.7. Conductance *G(f)* and susceptance *B(f)* of the transducer module, compensated at two points

The results at transmitter output for two point compensation are shown in the upper part of the oscillograms in Fig.8. The bottom part shows voltage U_P at the transducer with different amplitudes for both frequencies despite constant voltage at transmitter output.



a) f = 60 kHz, I_N = 3,6A, P_e = 345W, U_P = 1200V$_{PP}$, SL = 208dB



b) f = 85 kHz, I_N = 0,8A, P_e = 77W, U_P = 720V$_{PP}$, SL = 205dB

Fig.8. Voltage and current at pulse transmitter outputs with U_N=150V, exciting a 16 element transducer module with series compensation at two ends of the working bandwidth. The bottom part of the oscillograms shows transducer voltage

Fig.9 shows the frequency characteristics measured for transducer module with compensation as described above.

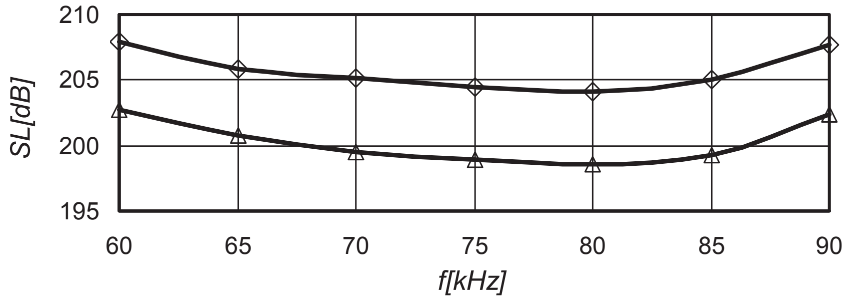


Fig.9. Source level *SL* in the frequency function for a 16 element transducer module and a two point series compensation. At the bottom (triangles) is the characteristics when the excitation is with a linear transmitter with $U_N = 100$V, at the top (rhombuses) for pulse transducer with $U_N = 150$V

The following are the observations based on Fig.9 charts:

- The frequency characteristics of source level *SL(f)* for the transducer in question can be shaped to some extent by changing the inductance of the series compensating coil.
- If adequately selected, compensation can not only stop a decrease in *SL* at the ends of the working bandwidth but can even make it rise. As a result, we can achieve the additional effect of a compensated irregularity of the analogous characteristics on the receiving side. This, however, cannot go on indefinitely because as *SL* increases at the ends of the bandwidth, transducer power and voltage increase (Fig.8a).

5. SUMMARY AND CONCLUSIONS

The paper presents a concept of DDS sounding pulse source with transducer elementary sections grouped on the transmitting side into modules comprising 8 or 16 elements. The basic advantage of this is a significant reduction in the number of group transmitters. The output power of these transmitters is estimated in section 2. It takes account of the required source level *SL*. The estimation was verified in an experiment using a hydrophone measurement. It was demonstrated that for the specific output powers group transmitters should be pulse transmitters and transducer compensation should be series compensation.

When multi-element modules are used it is no longer possible to control the transmitting characteristics of transducer elementary sections. This limitation, however, has no bearing on beam patterns. What the measurement results in section 2 show is that even in the case of non-identical elementary sections, both patterns have a shape and ripples similar to those when identical elements are used.

The use of group pulse transmitters in fact means that the frequency transmitting characteristics *SL(f)* can no longer be corrected the way it is done in the case of linear topology, i.e. by changing the excited signal. But when the sonar uses broadband LFM, the characteristics should be as regular as possible. As a result, the focus of the work was to examine the real frequency characteristics of the transmitting channel with a group pulse transmitter. It was equally important to ensure that corrections of the characteristics can be reasonably made, given the pulse topology used.

The results of transmitting frequency characteristics measurements are presented in section 3. Please note that the characteristics were defined for the entire transmitting channel which includes the group transmitter (voltage source with amplitude $U_N(f) = \text{const}$) and its load (multi-element transducer module together with a parallel or series compensating coil). The measurements were taken at 60÷90 kHz which is 10 kHz above the upper end of the sonar working bandwidth.

For the transducer in question the relationship between the irregularity of characteristics and type of compensation was examined. It was demonstrated that the highest irregularity (8dB) of source level *SL* in the working bandwidth occurs when the transducer voltage amplitude is constant, i.e. when compensation is parallel. For series compensation selected for the centre of the working bandwidth the irregularity goes down to 4dB.

By analysing the results we can see that the DDS working bandwidth can be positively (due to reverberation) expanded by increasing the upper frequency from 80 kHz at least to 90 kHz.

Section 4 showed that by selecting elements for series compensation of the transducer, we can not only significantly improve the regularity of frequency characteristics but also increase *SL* at the ends of the working bandwidth. As a result, we can simultaneously compensate the irregularity of the analogous characteristics on the receiving channel. It should be stressed, however, that this involves some costs. Despite $U_N(f)$ = const, the frequency changes of transducer and compensating coil immittances increase significantly the transmitter output electrical power at the ends of the working bandwidth. Hence, a compromise is needed, a combination of the circuit and correlation processing solutions.

ACKNOWLEDGMENT

This work is financed by fund dedicated for research and development Project No R 00 000 11/3 realized during 2007-2010 years.

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