ICA 2013 Montreal
Montreal, Canada
2 - 7 June 2013

Physical Acoustics
Session 3pPAa: Borehole Acoustics Logging for Hydrocarbon Reservoir Characterization II

3pPAa3. Research on a kind of low-frequency broadband cross-dipole projector
Dai Yuyu*, Xiuming Wang, Peng-Lai Xin and Hong-Bin He

*Corresponding author's address: Chinese Academy of Sciences, Institute of Acoustics, No. 21, Bei-Si-huan-Xi Road, Beijing, 100190, Beijing, China, daiyuyu001@126.com

The finite element method (FEM) is used to simulate a low-frequency broadband cross-dipole projector based on trilaminar bender bar in this paper. In the simulation model, four long trilaminar bender bars and four short trilaminar bender bars are attached on a fixing skeleton to form two square arrays, and every array excite two different response frequencies. The four response frequencies distribute at the range from 400Hz to 5kHz to reach broadband exciting. Finally, a prototype is fabricated and calibrated in an anechoic tank. Though comparison, it is shown that the test results meet the simulation very well.

Published by the Acoustical Society of America through the American Institute of Physics
Introduction

Monopole and multipole sonic sources can excite different kinds of mode waves in borehole. By using the time delay and amplitude attenuation of these mode waves when they propagate along the wall of borehole, it is able to evaluate the characteristics of the formation. This is the basic principle of sonic logging. Now the sonic logging is becoming one of the most popular geological exploration technologies, especially in petroleum exploration industry.

The method of sonic logging is first proposed about half a century ago. The first sonic logging instrument only installs a monopole source and is just able to test the compressional wave of the formation. With the development of borehole propagation theory, today the newest instruments have contained not only monopole sonic source but also dipole and quadrupole sources and are capable of exciting the compressional wave, shear wave, stoneley wave and pseudo-rayleigh wave. The plentiful operational modes supplied abundant information of the formation, which is very useful in well logging interpretation.

Array transmitting and receiving are considered as the most typical characteristics of modern sonic logging instruments. There are a series of sources, such as monopole, dipole and multipole, in the instruments to form transmitting arrays. Meanwhile, the hydrophones are equally divided into several groups to form receiving arrays. The transmitting and receiving transducers form the most important parts of sonic logging instruments. Among all of them, the dipole transducer, which is also called dipole projector, is no doubt the most difficult design part, as it not only need to transmit efficient at a low frequency but also keep the lobes of the dipole directivity consistent. Hence the focus in the paper is mainly on the dipole transducer, which is used to transmit the dipole wave.

According to the acoustic propagation theory, dipole source can excite a flexural wave in the borehole, and a cut-off frequency would exist when the flexural wave propagate in the borehole formation. When the flexural wave frequency tends to cut-off frequency, the velocity of the flexural wave tends to the velocity of shear wave. This characteristic can be used to test the shear wave of the formation, especially the soft formation.

When flexural wave transmit in an inhomogeneity formation, the wave would be divided into two parts: the fast flexural wave and the slow flexural wave. The inhomogeneity could be identified by testing the directions of the fast and slow flexural waves. Many aspects could result in the inhomogeneity, such as formation anisotropy, stress concentration, crack development and each aspect has different influence to the flexural wave. So it can also be used to judge the particular incentives.

As the key component of the array sonic logging instrument, even many famous petroleum service companies around the world invest huge efforts in the research of the low frequency cross-dipole projector. Up to now, there are two mainstream design methods: the first method is based on the coil-moving structure that the typical representative is SLB and the second method is based on the trilaminar bender bar structure that Baker Hughes and Halliburton are the typical representatives. Both of the methods have their advantages and disadvantages. For the coil-moving structure, there are the advantages of low operational frequency, ultra-wide bandwidth and excellent consistency of dipole directivity. However, some disadvantages exist unneglectablye yet. Firstly, the response sensitivity is not high enough. Secondly, the sound centrals of the X-axis and the Y-axis are not at the same point, which would result in increasing the numbers of the receiving arrays to achieve the same effect that the sound centrals coincide with each other. Compared with the coil-moving structure, the response sensitivity of the trilaminar bender bar structure is higher and the sound centrals of the two axes are at the same point. However, the bandwidth of the structure is very narrow, and the consistency of the
dipole directivity is some kind of difficult to control because of needing to match the two trilaminar bender bars on the same axis.

In this paper, we will adopt the trilaminar bender bar structure to design a low frequency broadband cross-dipole projector. Fig. 1 is the schematic diagram of the projector, including a fixing skeleton and two kinds of different length trilaminar bender bars. Both of the two kinds of bars have four pieces, and the same length four bars are fastened on the skeleton to form two square arrays. The two arrays superimpose along the Z axis, and weird in electrical parallel. The opposite bars should vibrate homodromously to realize the dipole excitation. Both the long and the short trilaminar bender bars have two useful resonance frequencies at the range of operational frequency. In designing, by making good use of the characteristic vibration of the two kinds of bender bars, transducer can realize good excitation performance in the whole operational frequency, reaching the target of wide bandwidth excitation.

FIGURE 1. The schematic diagram of the projector

The finite element method (FEM) is adopted to simulate the transducer, mainly focusing on the analysis of the modes of vibration and input electrical admittance in air and in water. A prototype is fabricated and tested, and then the test results are compared with simulation. It is shown that both of them match very well, and the simulation could be used to guide the design and optimization of this kind of transducer.

Simulation and Analysis

To better realize the working style of the transducer, finite element method (FEM) is used to simulate the vibration characteristic of the transducer in this paper\(^1\). FEM is a useful approach in transducer design, as it is capable of analyzing the dynamic performance of a structure quantitatively, finding the potential problems during the process of design, thereby, condensing the design cycle and economizing the cost of design.

Before analyzing, a physical model of the transducer should be abstracted based on the fixing and working ways. According to the working ways of the transducer in the instrument, the boundary condition will be set as follows: two ends of the fixing skeleton are supported by two rubber blocks in the instrument, hence, the ends can be seemed as a free boundary condition; every trilaminar bender bars are screwed on the fixing skeleton by fastening bolts, so the two ends could be thought as weld boundary condition. As there are some symmetries about the structure as well as the exciting approach, the analysis model only need to built 1/2, which is very useful in saving computing time.

In the section, the discussions will take into in air and in water two categories according to the working condition of the transducer.

1 In air

Because the acoustic impedance of air is quite small and the effect on the structure is very weak,
the influences of air need not take into consideration when analyze the vibration of the transducer structure in air. The FEM model is shown in Fig.2. The red color is fixing skeleton, the violet color is inert substrate, the blue color is doping modification PZT-4 piezoelectric ceramics.

1.1 The input electrical admittance in air

The input electrical admittance, which is defined as the ratio of input current to voltage is used to reflect the vibration characteristic of measured transducer. Ridges will exist on the curve of the input electrical conductance at resonance frequencies, which stand for the electrical power could be transformed to mechanical power more efficient at these frequencies. Fig.3 is the diagram of transducer input electrical admittance in air. The simulation results show that there are four obvious resonance peaks at the frequency range of 500Hz~7kHz.

1.2 Modal Analysis

In order to conform which parts generate these resonance peaks, the Modal Analysis is adopted in this section. The Modal Analysis can get every possible modes of vibration of a given structure, nevertheless, which one could be excited is based on the load. According to the admittance curves in Fig.3, the vibration shapes are extracted at the resonance frequencies, listed as the Fig.4.
According to the vibration shapes, the first and the third resonance peaks of the transducer correspond to the first and the third order of flexural modes of vibration of the long trilaminar bender bars respectively, and the second and the fourth resonance peaks correspond to the first and the third order of flexural modes of vibration of the short trilaminar bender bars.

2 In water

The transducer used in the borehole need to overcome the super-high hydrostatic pressure, so a pressure-balance design is adopts to improve the performance of withstanding hydrostatic pressure at this design. According to the design, the transducer inserts a fluororubber encapsulation, filled with silicon oil to balance the hydrostatic pressure. However the characteristic impedance of silicon oil is about 1MRayl, the influence of the oil to the structure is not able to neglect anymore. Furthermore, the transducer should be hung in infinite waters or anechoic tank to calibrate the directivity and transmitting sensitivity, so, in the process of FEM simulation, the problem of transducer working in water became a fluid-solid coupling problem and the influence should be taken into consideration. Fig.5 is the FEM simulation model in water. With the boundary is defined as fully absorption boundary, the hemispherical volume is built as infinite waters or anechoic tank.
2.1 Input electric admittance

When a vibration excites to sound field, reacting force from the field would back force on the source, which is commonly described as radiation impedance. The radiation impedance is a complex number, the real part called radiation resistance and the imaginary part named radiation reactance. The radiation impedance is thought as an electronic element connecting to the equivalent circuit, used to analyze the dynamic characteristic, in series. As the radiation impedance existed, the input electric admittance would decrease in a certain degree. Meanwhile, the radiation reactance is thought as adding an additional mass on the vibration structure, which would decrease the resonance frequencies.

The simulation result is shown in Fig.6. Compared with the Fig.3, both the resonance frequencies and input electrical admittance are decreased, which are consistent with the former conclusion. A further comparison shown that all the resonance frequencies exist spurious modes except the first order of mode of vibration. The primary reason is that the flexural bender bars can also be though as drivers when they are working. They will force the bars of the fixing skeleton vibration at the flexural modes.

3.1 The comparison of input electric admittance in air

Firstly, we will compare the simulation results with the prototype test results in air. The Fig.7 is the input electric admittance of the prototype and the simulation in air.
FIGURE 7.  the input electrical admittance comparison between test and simulation (in air)

The table.1 is used to compare the quantitative results between prototype test and simulation. The first row of the table stands for the number of resonance frequencies. The second row is the comparison items, including frequency and conductance. ‘S’ in the second sub row of the second row stands for the simulation result, and ‘T’ means the prototype test result. The third row stands for the simulation error.

TABLE 1. The comparison between test and simulation (in air)

<table>
<thead>
<tr>
<th>Mode</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F /Hz</td>
<td>G /μS</td>
<td>F /kHz</td>
<td>G /mS</td>
</tr>
<tr>
<td>S</td>
<td>T</td>
<td>S</td>
<td>T</td>
<td>S</td>
</tr>
<tr>
<td>54</td>
<td>56</td>
<td>14</td>
<td>5</td>
<td>1.1</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>3</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Error %</td>
<td>2%</td>
<td>61%</td>
<td>2.6%</td>
<td>6.7%</td>
</tr>
</tbody>
</table>

According to table.1, the frequencies of each resonance peaks meet very well, however, the electrical conductance of some resonance peaks don’t meet well enough, such as the first and the forth order of modes. There are several reasons: Firstly, as a composite material, it is difficult to keep the piezoelectric matrix of all used ceramics consistent; Secondly, the physical model is not able to reflect the truly working condition perfectly; Thirdly, in the process of fabricating, there are also some errors, etc.

2.2 The comparison of input electrical admittance in water

In water, as the mutual interaction between transducer and sound field, the electrical admittance change greatly. Fig.8 is the comparison diagram of the prototype and simulation. By comparison, the resonance frequencies meet each other well enough, but the electrical admittances meet not well enough. The reasons are probably that the elasticity matrix of the doping modification PZT-4 ceramic changed little but the piezoelectric matrix change a lot in contrast with the reference[2]. The elasticity matrix changes little because most part of the materials is still the basic PZT-4. But the piezoelectric matrix changes a lot because the piezoelectric property has to change a lot to meet the need of high temperature working, which is a basic concept in materials science[3]. So we will analyze the frequency characteristic in this section mainly.
Table 2 is the quantitative results of the transducer in water. Similar as the table 1, the first row of the table stands for the number of resonance frequencies. The second row is the frequency comparison. ‘S’ in the second sub row of the second row stands for the simulation result, and ‘T’ means the prototype test result. The third row stands for the simulation error. It is easily find that the simulation meet the test results very well.

**Conclusions**

Both the simulation and prototype test results indicate that the design low frequency broadband cross-dipole transducer exist several resonance frequencies at the operational range of 400Hz~5kHz. When it is working in the vicinity of resonance frequencies, the transducer is capable of radiating sound efficiently. Meanwhile, there are several spurious resonances at the range of operational frequency too. They are generated by the flexural vibration of the bender of the fixing skeleton. These peaks, motivated by dipole loading, can also used to broaden transducer’s bandwidth, however, the performance of dipole vibration is based on the perfect installation, if not, the symmetry would be broken and not be able to excite with dipole pattern any more. This is the worst situation in dipole transducer design. Hence in the process of this kind of transducer design the spurious resonances should be avoided. The comparison in the third part of the paper shows that the FEM is a useful tools to simulate the solid-fluid coupling problem, widely using in the designing and optimizing transducer.

**Acknowledgements**

Test results of the prototype are provided by my colleagues Dr. Cong, jiansheng and Dr. Wei, qian. I will express my great thanks to all of them.

**References**

2. WANG Rong-jin, “the handbook of underwater acoustic materials, Chap. 10, pp. 144–145.