Progress in magnetostrictive sonar transducers

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Abstract

Continuous interest from the French Navy (DRET and CERDSM) has permitted significant improvements to magnetostrictive transducers in order to produce low-frequency high-power sonar sources. These improvements can be appreciated by looking at three transducers. An attempt at the design of a third version of the Quadripode Tonpilz transducer led to a new Tonpilz transducer called the Tripode. Its aim is to reach at least 3 kW of acoustic power. It benefits from magnetic circuit design results and from the giant dynamic strain capability of Terfenol-D (Peak-to-Peak strain higher than 2400ppm). A 300Hz 3kW double-ended vibrator was designed as a low-cost reliable source for low frequency. A recent study of Flextensional transducers using giant strains has also shown the possibility to reach very high-power (higher than 100kW) around 300Hz. This paper presents these new transducers.

Introduction

Rare earth-iron magnetostrictive alloys discovered by A.E.Clark [1] feature 'giant' strains [2] when excited by a magnetic field. Among these materials, Terbium Dysprosium Iron alloy, often called Terfenol-D, is the most attractive material because of its high magnetostrain level (typically 1600 ppm). Sonar designers started using this material in the late seventies for low-frequency high-power sonar transducers [3]. French Navy research on this subject started in 1985, with the design of the Quadripode, a Tonpilz type transducer based on 4 Terfenol-D rods. The first version of this transducer built in 1986 had a 1,0kW acoustic power [4]. A second version tested in 1989 had an improved acoustic power, 1,6 kW [5,6] due to the use of Grain-Oriented Terfenol-D.

The discovery of more specific properties of Terfenol-D for dynamic use has increased considerably the interest for magnetostrictive transducers. Under a dynamic state, especially at resonance, the Terfenol-D strain is not limited by the static maximum magnetostrain [6]. For example with appropriate bias and prestress conditions, a dynamic peak-to-peak strain of 2440 ppm for Terfenol-D in an in-air transducer was measured 17]. In the same manner, strains of 3000 ppm were reached. These giant dynamic strains lead obviously to rather large displacements which are of primary importance in building high-power low-frequency transducers. The second interesting property is the very high magnetic limit of the material 16,8l. It permits reaching high dynamic strain not only in a non-loaded transducer but also in very highly loaded transducers. Thanks to both these properties, magnetostrictive transducers are theoretically much more powerful than piezoelectric transducers. These results have led to two areas of research.

The first area is related to the drivers. In order to apply this exciting 'giant' strain to sonar transducers, it is necessary to solve the problem of applying the high magnetic bias to Terfenol-D. The chosen method to deal with this problem consists at building and testing three drivers, the difference of which concerns their magnetic bias system [9,10]. The first driver is biased using a coil. The second one uses permanent magnets in a parallel configuration. The third one is biased using a series configuration. Their aspect ratios as well as their properties are different. These drivers can now be used as components for the electromechanical energy conversion in any transducer.

The second area is related to low-frequency transducers. Three different transducers are studied. A new Tonpilz-type called the TRIPODE was built which integrats the experience developed from the QUADRIPODE and the drivers as well as the giant dynamic strain property. A second transducer, a double-ended vibrator called the JANUS 300 was designed under specifications of the French Navy to provide a low-cost, low-frequency source as a possible competitor to the piezoelectric class IV Flextensional. A third transducer, a class IV Flextensional type has been studied in comparison with an equivalent piezoelectric transducer to evaluate the potential of magnetostrictive Flextensional transducers.

The aim of this paper is to present these three new transducers and to discuss their advantages and disadvantages compared to piezoelectric or former magnetostrictive transducers.

Tonpilz Transducers

A preliminary study was performed by Cedrat on the QUADRIPODE II transducer in order to see if the giant dynamic strains could be applied to this transducer. The expected advantage should be an increase in its acoustic power. The QUADRIPODE is a Tonpilz transducer based on 4 Terfenol-D rods of 100mm in length and 18mm in diameter. In this transducer, the level of peak-to-peak strain at resonance reached about 1950 ppm leading to an acoustic power of 1.6kW (Table 1). As the power of a transducer is proportional to the square of the strain in the active material, the use of a 3000ppm strain in the Terfenol-D should lead to a 3.8 kW acoustic power. In principle, such increase of strain could be obtained simply by using a higher prestress and excitation level [7]. In practice several technological problems have to be solved. A higher prestress implies modifying the prestress bolt. A higher excitation implies changing the magnetic circuits (because of larger fluxes), the coils and the cooling device (because of higher dissipated power). Moreover, the use of a higher prestress implies also using a higher magnetic bias [8] in order to keep a low Youngs modulus and a good coupling coefficient. So the bias magnetic circuit and the bias coil must also be changed. Finally considering all the changes to be done, it was decided to design a new transducer that could be compared to the Quadripode.

This new transducer (figure 1), designed by Eramer and Cedrat for CERDSM, is called the TRIPODE because it is based on 3 Terfenol-D rods. This choice has been made for obvious mechanical reasons and because the concept of an open magnetic circuit has been proven valid in recent studies of drivers [9,10]. On that point and with the objective of high power, the design is different from a former 3-rod US transducer [3]. Since it has been decided to re-employ material already used in the driver study (cylindrical rods of 100mm in length and 20mm in diameter), the total volume of Terfenol-D is 8% smaller than that of the Quadripode. However, in spite of this reduction of active material volume, the stiffness of the transducer remains nearly the same because the diameter of the prestress rod was increased. Its headmass is the same as that of Quadripode. It is made of aluminium and its diameter is 287 mm. Its tailmass is also nearly the same than that of the Quadripode. So both tranducers have the same in-water resonant frequency, around 1200 Hz. Also the acoustic load of the transducers is the same. Under these conditions any increase of acoustic power between the Tripode and the Quadripode can be attributed to an improvement in Terfenol-D strain level.

The transducer was designed to gather all the conditions required to get giant dynamic strains. The objective is to double the acoustic power to between 3 and 4 kW (table 1), in spite of a smaller amount of Terfenol-D. This leads to a source level around 209dB (ref. 1µPa @1m) (figure 2). The new transducer benefits also from coil improvements which permits a reduction of the electric reactive power. The excitation coils are different from the bias coils. Work on the magnetic circuits, coils and mechanicals permit a loss reduction, leading to an improved efficiency. The hydrostatic compensation is realized by a bladder inside the transducer and permits reaching at least 50m. An auxilary high depth gas compension device could be added to go down 300 meters deep. Work on the cooling device and the hydrostatic compensation led to a reduction in volume by a factor of 2.5. Thus, the transducer total length is only 310mm and its diameter is 300mm. These performances lead to a high figure of merit FMV. This figure is defined by the ratio of acoustic power to frequency, the mechanical Q and the transducer volume. It is equivalent to an energy density. Typical values for a piezoelectric Tonpilz are around 2 J/m3, 10 times lower than for the Tripode [6]. Today tests are not finished but preliminary experimental results tend to confirm the predicted performances of table 1. One can be rather confident in such predicted performances thanks to powerful modeling tools, experience with the Quadripode and the use of giant strains. Note however that with some slightly different assumptions on Terfenol-D properties, some performances are changed such as the over-voltage factor which could be better and the efficiency which could be lower. Conversely the maximum acoustic power does not change. The preliminary conclusion is that the use of giant dynamic strains is technologically ~~im~~possible and this permits the design of a powerful transducer with a compact size.

Double-Ended Vibrators

Cedrat Recherche was consulted by CERDSM to design a magnetostrictive transducer with the following specifications: A 300Hz resonant frequency, a mechanical quality factor lower than 5, a source level higher than or equal to 206 dB, no directivity, a maximum depth equal to 300m. These specifications are close to the features of a 320Hz piezoelectric Class IV Flextensional (Table 1) built by Eramer. Thus a comparison between magnetostrictive and piezolectric transducers may be made.

As a possible solution to these specifications, a free-flooded magnetostrictive double-ended vibrator called JANUS 300 (Figure 3) was proposed. It is based on only one driver, the active element being one Terfenol-D rod of 300mm in length and 38mm in diameter. The prestress is developed by means of 3 steel rods in parallel with the driver. The head-masses are made of aluminium and are 540 mm in diameter. Their thickness was reduced as much as possible to minimize the weight, but trying to avoid flexure. To find a good compromise, computations with the ATILA code [11] have been made (Figure 4). This finite element code is able to deal with magnetostrictive transducers in water and is now equiped with the PREATI interactive parametrized preprocessor [12] which permits perfoming fast optimization. The final weight of one head-mass is 25 kg.

Two versions of the transducer were studied. The first one uses a driver biased by a coil which is separate from the excitation coils. The second one uses a driver biased by permanent magnets in a parallel configuration (PM version). This type of driver had already been built. The test provide interesting results, such as a very good effective coupling coefficient, explained by the fact that the magnets are outside [9, 10]. Its potential disadvantage is a rather large diameter, but it is not a problem in the present case because of the large diameter of the head-masses. The features of the PM version are given in table 1. These performances have been calculated assuming a hard baffle condition (Figure 5). In practice, the inside of the transducer is filled by a PVC foam, the whole being free-flooded, which permits achieving the desired maximum depth. So, as these acoustic conditions are a bit different from that used in modelling, some performances will probably be slightly altered. Due to its mechanical Q, the transducer is stress-limited. The high acoustic power is obtained thanks to the use of giant dynamic strains in Terfenol-D. The good effective coupling coefficient and the low over-voltage coefficient are due to the driver type and to an optimized excitation coil. The calculated figure of merit is a bit better than that of the reference piezoelectric Flextensional because of a more compact size and a higher power, but with more realistic baffle conditions, it should be more or less the same. The performances of the coil bias version are close to that of table 1. Its figure of merit reaches 33 J/m3 because it is a bit shorter. The advantage of the Janus 300 is its simplicity, compared with a piezoelectric Flextensional. In principle it should be more reliable than the Flextensional, whose shell is subjected to fatigue. At last, in spite of the high price of Terfenol-D, the Janus is cheaper than the piezoelectric Flextensional because it uses one tenth the active material and its other parts are easy to build and to assemble. The required electronic power input is also cheaper due to a lower voltage requirement.

Flextensional Transducers

A long term study, realised by ISEN, Eramer and Cedrat for DRET/SDR G24, intended to evaluate the performance of magnetostrictive Flextensional transducers compared to a piezoelectric Flextensional of the same size, the same resonant frequency and the same mechanical Q [13].

The reference transducer choosen is the 320 Hz piezoelectric Class IV Flextensional. This choice is interesting because this transducer is field limited and the strain of the PZT stack is only 160 ppm (320 ppm peak-to-peak) giving a small acoustic power relative to the large amount of PZT material. An increase of acoustic power using magnetostrictive drivers instead of PZT drivers is expected for the following reasons. The first one is the high strain capability of Terfenol-D even against high load. Due to the stiffness of the shell it appears that for the first time the magnetostrictive rods are field limited. As no trials has been done on Terfenol-D at resonance under field limit, one has to be careful. In theory a 1950 ppm peak-to peak strain could be reached. In practice a conservative 1600 ppm appears more reasonable because it corresponds to the static magnetostrain. As it is 5 times more than the strain of PZT in Flextensional, the gain in power should be equal to 25. The second reason to expect an increase in power is due to the low Youngs modulus (25 to 30 GPa) which is about one half than that of PZT. First of all one should note that if the shell is not changed, the compliance of the Terfenol-D drivers must be equal to that of the PZT drivers to keep the same resonant frequency. So the section of Terfenol-D must be twice that of PZT to keep both the same compliance and the same driver length. The result is an increase of acoustic power by a factor two. This supposes, however that it is possible to solve a space problem: In addition to the active material, coils and possibly magnets are required. Considering these design parameters, a magnetostrictive version of the 320 Hz Flextensional could be 50 times more powerful.

Following these considerations, a magnetostrictive version has been designed. The most suitable driver is the type biased by permanent magnets in a series configuration [9,10]. It is the most compact radially and presents the highest energy density. To maximize the amount of Terfenol-D, the shape of the shell has been slightly changed, while keeping the same volume, resonant frequency and mechanical Q. The performance of the transducer computed with the conservative assumption of 1600 ppm strain is given on table 1. A tremendous power improvement is predicted proving that there is a real potential in magnetostrictive Flextensional that it is worthy of further studies. Note however that this theoretical analysis does not deal with several technological problems. A lot of heat due to losses has to be dissipated. The shell is subjected to 5 times more stress. To avoid cavitation, a very high depth is required, which implies a depth compensation system that is not easily compatible with the Flextensional structure. A future effort should be to take into account all these factors while still taking advantage of the full potential of Terfenol-D.

Conclusion

The study of different types of magnetostrictive transducers has shown the potential of the giant dynamic strain capability of Terfenol-D for high acoustic power. In any case, magnetostrictive transducers are better than piezoelectric transducers. The Tripode is a very compact 3kW 1.1kHz transducer. The Janus 300 is a reliable and low cost 300 Hz source compared with the unique piezoelectric solution at this frequency, the Class IV Flextensional. The very high theoretical power of the 320Hz magnetostrictive Flextensional transducer shows that the Flextensional structure is particularly well suited to Terfenol-D but complementary work must be accomplished before such a transducer may be built.

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Name of the transducer		Quadripode	Tripode	Flext. 320	Janus 300	Mag. Flext.
Type of transducer		Tonpilz 4 drivers Coil Bias	Tonpilz 3 drivers Coil Bias	Flextensional Class IV	Free Flooded Double end. P.M. Bias	Flextensional Class IV P.M. Bias
Type of active material		Terfenol-D	Terfenol-D	PZT	Terfenol-D	Terfenol-D
Transducer volume	(dm^3)	51	22	144	125	144
Active material volume	(dm^3)	0.102	0.094	4.5	0.34	8.2
Resonant frequency	(Hz)	1150	1200	320	305	320
Mechanical Q		2.5	6	5	4.3	5
Over voltage factor		2	0.7	2.5	0.4	1.1
Coupling coefficient	(%)	50	50	28	60	30
AC-efficiency	(%)	25	45	85	52	61
Directivity	(dB)	2	2	0	0	0
DC power (Bias)	(kW)	2.0	2.3	0	0	0
Excitation voltage	(V$_{rms}$)	1000	540	2000	550	3300
Active electric power	(kW)	7.2	8.5	4.0	8.4	326
Reactive electric power	(kVA)	15	6.4	10.0	1.0	587
Total efficiency	(%)	17	36	85	52	46
Acoustic power	(kW)	1.6	3.8	3.4	4.4	151
Source level	(dB)	205	209	206	208	223
Figure of Merit	(J/m^3)	10	24	15	27	655
Status		Built, tested	Built, test in progress	Built, tested	Ready to be built	In study

Table 1 - Comparison of different low-frequency high-power transducers (according to the status, values are experimental or predicted data)

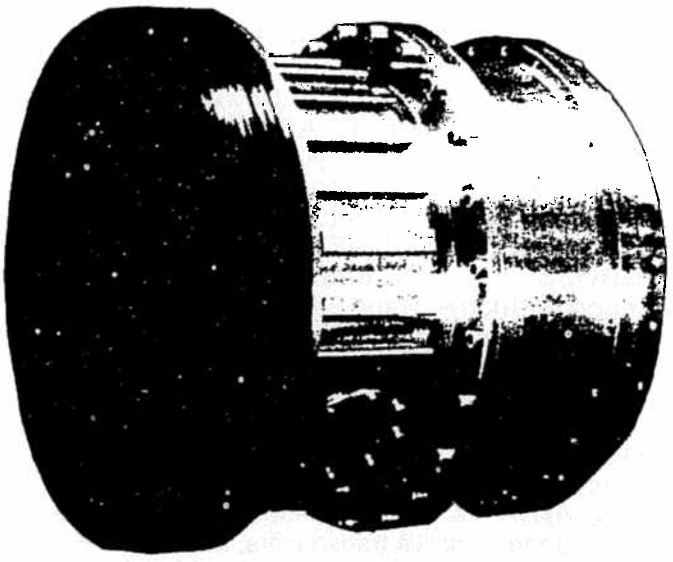


Fig.1 : View of the Tripode

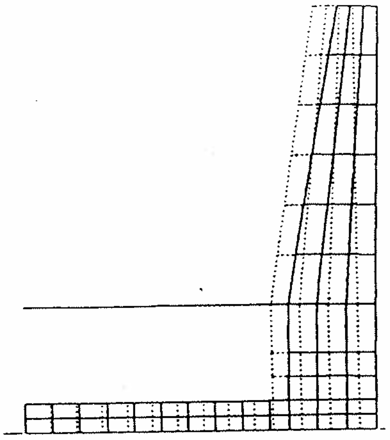


Fig. 4 : Displacement field of the Janus
(ATILA computation at resonance)

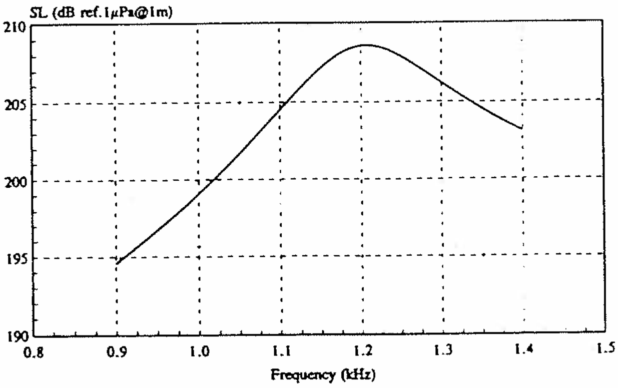


Fig.2 : Tripode Source Level

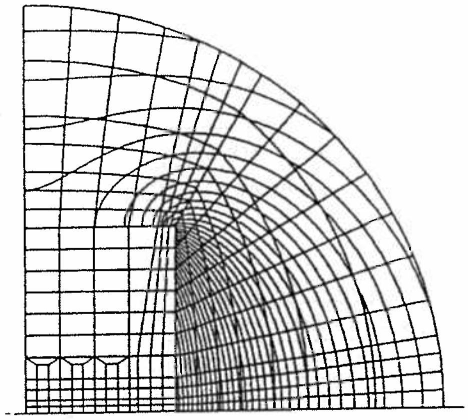
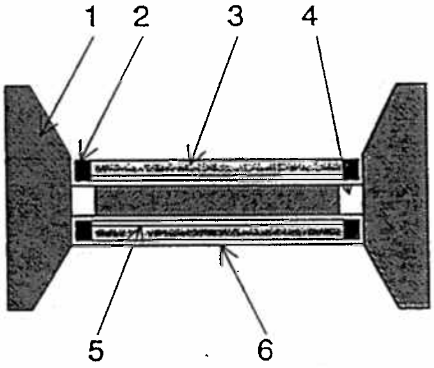


Fig. 5 : In-water pressure generated by the Janus
(ATILA computation at resonance)



1 : Head Mass
2 : Magnetic ring
3 : Bias coil
4 : Magnetic ring
5 : Excitation Coil
6 : Prestress rods (3)

Fig.3 : Scheme of Janus 300 (bias coil version)

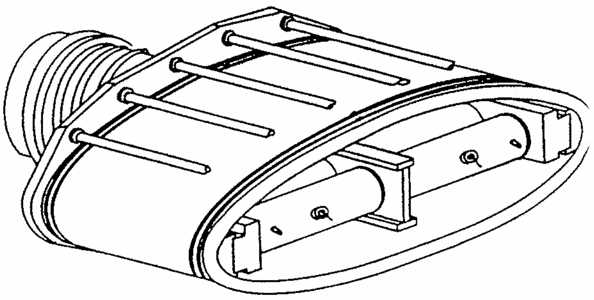


Fig.6 : View of a Magnetostrictive Flextensional