INCREASING DEPTH CAPABILITY OF « DIABOLO » FLEXTENSIONAL TRANSDUCER FOR ACTIVE LINEAR ARRAYS

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ABSTRACT

A slotted flextensional transducer called « Diabolo » was developed by TMS SAS initially for dipping sonar applications. This compact and light weight transducer (<1kg) has a fundamental resonance frequency close to 1.5kHz, and can deliver a source level greater than 191dB. Very attractive for linear arrays, the Diabolo technology is now used in active sonobuoys and is in development for active linear arrays. For this last application, the profile mission is more drastic. The limiting factor becomes the fatigue of the shell when submitted to both hydrostatic pressure and dynamic stresses. The paper details the fatigue analysis of the shell, based on static and dynamic FEM calculations. The design of a more robust one, and associated test results are also presented. The resulting transducer presents the same external dimensions, same performances, and provides an improved operational working depth.

INTRODUCTION

Barrel staves projectors are low frequency sources with unique properties of high power, reduced weight, and small size. The central frequency of the most extensively studied Barrel Staves [1-8] is in the range 800-2000Hz, with typical weight from 0.9 to 2kg, and length from 10cm to 20cm. Those devices are depth limited, often below 200m.

Recently, several projects in the world aimed at validating the concept of shallow water active linear arrays using Barrel stave technology. Using such devices, an active linear array may be integrated at the head of a standard towed array (Fig 1), preferably with the same diameter for handling facilities and flow noise concerns (typically 80 to 120mm). The handling is unchanged, but there is no more need of active towed body, dedicated reeling machine etc... With existing barrel stave technologies, the active system is limited to shallow water operations.

An active linear array using a TMS SAS transducer was selected for an Australian project LFAPS (Low Frequency Active Passive System). This transducer called Diabolo was initially studied for dipping sonar. Objective performances were the resonance frequency (1500 Hz), dimensions, array source level, and compatibility with actual dipping sonar reeling machine (diameter 400mm). The result of this study is a Barrel-Stave transducer called « DIABOLO » with regards to its resemblance to the well-known toy ([1] and fig 2).

Today, for Active Linear Towed Array application (ALTA), the mission profile is quite different than for dipping sonar and active sonobuoys. In dipping sonars, the array is immersed several minutes ten or twenty times a mission. In active sonobuoys, the lifetime is somewhere between several minutes and 4 hours. But, for active linear array integrated in towed arrays, the profile mission is much more

INCREASING DEPTH CAPABILITY OF « DIABOLO » FLEXTENSIONAL TRANSDUCER FOR ACTIVE LINEAR ARRAYS

drastic, especially the number of cycles. Table 1 presents comparison of typical mission profile of active sonobuoys, dipping sonars, and active linear towed arrays.

Parameter	Sonobuoy	Dipping sonar	ALTA
Cycles	2.10^6	10^8 - 10^9	> 10^{10}
Lifetime	< 4 h	3 years	> 3 years
Depths	2 distinct depths below 120m	between 10 and 300m	between 10 and 200m
Pulse duration	< 5s	< 10s	12s
Duty cycle	< 10%	< 10%	20%

Table 1: Comparison between typical mission profile of active sonobuoys, dipping sonars, and active linear towed arrays.

Due to the specific constraints of this new application for the Diabolo, a extended study was performed to assess the reliability of the technology in this configuration. The limiting factor was identified as the fatigue limit of the shell when both submitted to hydrostatic and dynamic stresses. This limit involves associated limits of the system especially in term of working depth (about 150m). Due to the high interest of the depth range between 150m and 200m for the LFAPS project, the design of a more robust shell providing similar performance with same overall dimensions was successfully carried out.

This paper describes the fatigue analysis of the initial Diabolo transducer (called Vo), the design of a more robust one, and associated test results.

DIABOLO TRANSDUCER: DESCRIPTION AND ANALYSIS

Barrel stave transducers are traditionally composed of a piezo-stack forced in an extension-compression vibration by an applied electric field, and a shell excited at its first flextensional mode. The shell can be concave or convex. The consequence of the concave curvature is an increase of the prestress with hydrostatic pressure while the convex curvature involves a decrease of the prestress. In both cases, the working depth of any un-compensated Barrel-Stave transducer is limited to less than 300m.

DIABOLO TECHNOLOGY: CONSTRUCTION

The Diabolo is composed of a piezo-active motor, two end caps, and a slotted shell.

The motor is composed of 16 axially polarised navy type III ceramics. Each ring is 4.8mm high and have an outside diameter of 28mm. Two end rings are machined with holes for dipping sonar, or are adjusted to use a glass bead for active linear towed arrays .

The end caps have three functions: allowing the transmission of the longitudinal vibration of the motor to the shell without bending, allowing the electrical connections, and applying a good prestress to the piezo-stack. The static prestress is applied by a torque when the end cap is screwed in the shell. The torque is calculated to apply a static stress superior to the dynamic one at the minimum depth. The

INCREASING DEPTH CAPABILITY OF « DIABOLO » FLEXTENSIONAL TRANSDUCER FOR ACTIVE LINEAR ARRAYS

value of this torque depends on the array configuration and on the type of emission (acoustic coupling and surrounding structure).

The titanium shell consists of a solid element where axial slots are machined to reduce the shell tangential stiffness. The shape of the slots was calculated to improve acoustic performances versus depth. Polyurethane is used to prevent the transducer from water ingress. The curvature of the concave shell is 200mm. External dimensions of the Diabolo are summarised in table 2.

Length	125mm
Outer Diameter	52mm
Mass	1kg
Density	3.5

Table 2: Geometrical characteristic of the DIABOLO

ACOUSTIC CHARACTERISTICS:

The acoustic performances of one Diabolo have already been presented [1]. Regarding the Diabolo adapted to active linear towed arrays, i.e. Diabolo Vo, central frequency at low depth is 1500Hz and the TVR is 127dB with a 3dB bandwidth of 200Hz. The resonance frequency shifts with the depth (+1.5Hz/m) while the TVR increases (130dB at 200m, Fig. 3).

WORKING OF THE DIABOLO

The working of the Diabolo can be represented by the equivalent circuit of figure 4. Co, ϕ, and c are obtained with ceramic characteristics and statistics onpiezo-stacks measurements. c1, c2, m1, Cf, and Zr are extracted from FEM calculations and measurements. R is estimated through in water measurements. The two first modes of the shell must be considered in the circuit. The flextensional coefficient Cf represents the average transformation of longitudinal motion to pulsating displacement of the shell. Both resonance frequency and TVR decrease with increasing Cf.

Component	Description	Unity
V	Driving voltage	V
I	Driving current	A
v	Average vibration speed of the radiating surface	m/s
fa	Acoustic force exerced on the fluid	N
Co	Blocked capacitance (constant strain)	F
ϕ	Electromechanical factor	N/V
c	Elasticity of the piezo-stack	m/N
c1, c2	Elasticity of modes 1 and 2 of the shell	m/N
m1	Dynamic mass of mode 1	kg
R	Losses in the transducer	kg/s (Ωm)
Cf	Flextensional coefficient	N/N
Zr	Auto-impedance of the transducer	Ωm

INCREASING DEPTH CAPABILITY OF « DIABOLO » FLEXTENSIONAL TRANSDUCER FOR ACTIVE LINEAR ARRAYS

EXPLANATION OF THE ACOUSTIC VARIATIONS WITH THE DEPTH:

In all Barrel-stave transducers of interest [2-8] an increase of resonance frequency with the depth is observed. This phenomena comes from a complex combination of three factors: geometric change of the shell curvature, effect of static stresses both in the ceramics and the shell, and compression of the moulding. The relative influence of each factor is extremely dependant on the device so that the following explanation is valid for the Diabolo but should be reconsidered for other Barrel-staves transducers. The effect of the third factor (moulding compression) is insignificant here. The hydrostatic pressure decreases the curvature radius of the shell which increases the resonance frequency and the sound level. The pressure is also creating static stresses in the device which were computed by FEM. The axial compression of the stack is about 0.25 MPa/m and its effect is to increase mainly the capacitance of the ceramics and the piezoelectric factor. Static stresses in the shell involve modifications of the two first resonance frequencies of interest for the shell. A simple physical analogy is the guitar string whose fundamental resonance frequency depends on its axial stress but the quantification of this effect remains analytically impossible for such a complex shape. Actually, both change of shell curvature and static stresses in the shell are experimentally merged by using a depth d dependant coefficient $\beta(d)$ on the two modal elasticity's (Fig. 5):

$$C_i = C_i/\beta^2(d)$$

The behaviour of the Diabolo is then well modelled by the equivalent circuit presented in figure 4.

LIMITING FACTOR OF DIABOLO Vo

In order to assess the reliability of the whole system, the limiting factors of each component, including the transducer, have to be identified. For an electro-mechanical design, manufacturing features, mechanical and electrical limits, and environmental conditions have to be considered in this phase. *In the Diabolo Vo, the limiting factor proved to be the fatigue of the shell when submitted to both static and dynamic stresses.*

Stresses in the transducer are due to the hydrostatic pressure, dynamic excitation, and initial pre-stress of the stack. The local resulting stresses in the shell are a combination of the three stresses which are studied separately. The following analysis focuses on two specific zones of the shell which are submitted to high static or/and dynamic axial stresses. Those two zones are called « middle » and « end » of the staves (Fig. 6). Critical zones correspond to extension. Only axial stresses are considered because they proved to be the main cause of crack propagation in this design.

The hydrostatic pressure creates a positive strain (extension) inside the middle and outside the end of the shell. The prestress, applied by screwing the end cap in the shell, has the opposite effect and reduces the effect of hydrostatic pressure. The dynamic stresses are obviously alternatively compressive and extensive so that only the worst case (extension) is considered. Table 3 summarises values of the three distinct axial stresses at the middle and end of the staves.

INCREASING DEPTH CAPABILITY OF « DIABOLO » FLEXTENSIONAL TRANSDUCER FOR ACTIVE LINEAR ARRAYS

	Axial static stress due to depth	Axial static stress due to pre-stress	Axial dynamic stress at resonance	Maximum Static	Maximum Dynamic
Middle of the staves	2.35 MPa/m	- 65 MPa	0.032 MPa/V	200m : 405 MPa 140m : 264 MPa	64 MPa
End of the staves	2.85MPa/m	- 80 MPa	0.012 MPa/V	200m : 490 MPa 140m : 319 MPa	24 MPa

Table 3 : Detail of static and dynamic stresses in the staves as a function of depth or driving voltage

Titanium is known to be an excellent material for the fatigue phenomena. At 200m and full power, stresses in the shell (cf. table 3) are approximately 470MPa with a corresponding Rratio of 0.75 (Rratio=$\sigma_{min}/\sigma_{max}$). Appropriate Wöhler curve (Fig. 7) shows that the total stress must remain below an asymptotic 400MPa to get a lifetime over 10^9 cycles. A predicted limit close to 10^6 cycles is then predicted in those conditions. On the other hand, the maximum depth providing a good security margin for full power is expected to be 140m. Two tests were performed at full power to validate this analysis: one at 200m, and one at 140m. Three broken staves in the middle for 10^6 cycles were effectively observed for the first test while nothing occurred during the second. The breakage was perpendicular to the symmetry axis.

The stress value at the end of the staves is higher than in the middle but no breakage occurred during test one. This is explained by the smoother shape and the higher local Rratio 0.9 (in this case the asymptotic value of the maximum stress decreases).

Even if the transducer in the array is obviously not excited 100% of time at resonance CW and maximum depth, 140m is considered as the maximum operational working depth of the Diabolo Vo *for ALTA application.*

DESIGN OF A MORE ROBUST SHELL

Due to the high interest of the depth range between 150m and 200m for the LFAPS project, the design of a more robust shell providing the same performance with same overall dimensions was decided. Main results, and definitive solution are presented hereafter.

The challenge for this new design is the preservation of electro-acoustic characteristics rather than the mechanical stress reduction. We worked on the design of a new shell more robust for static loads, and similar in dynamic. The main criteria for this design were as follow :

- Reduction of the static stresses in the middle of the stave.
- Same overall dimensions.
- No change in the stack
- Similar acoustic performances.

Effects of some parameters such as stave thickness, number of staves, curvature radius, on the performance exist for some specific Barrel-staves [2] but those curves should be re-calculated in our case because the constraints are restrictive (fixed dimensions and performance). Here, the influence of a parameter can depend on a specific design. The selected approach was different. After a preliminary

INCREASING DEPTH CAPABILITY OF « DIABOLO » FLEXTENSIONAL TRANSDUCER FOR ACTIVE LINEAR ARRAYS

analysis, the number of staves was increased to reduce the distance between the most stretched fiber and elastic neutral axis. Reduction of static stresses in the middle requires an increase of local thickness,.which also means an increase of the moment of inertia and the mass. It is then highlighted that the effect of the mass is more important than the moment of inertia due the dynamic mass enhancement. But the flextensional coefficient Cf is also to be considered because radiating impedance Zr seen by the ceramics is multiplied by Cf^2 which is good to lower frequencies but bad for the radiating power. Due to the overall dimension constraints, the stress reduction in the middle involves frequently an important increase at the end which can easily become the most critical zone. The optimisation of the transducer is then a complex compromise of several parameters: performances, stresses in the middle and at the end of the staves, coupling, performance, and variation with depth.

Several designs were calculated using FEM modal analysis and equivalent circuit of figure 4 because a complete FEM-BEM method would lead to too long calculation time. Three promising shells were machined and tested at sea between 20m and 200m. For each shell, thickness is increased both in the middle and at the end while internal and external curvature radius are different. Most interesting features are presented in table 4. The three shells show less variations with depth. Shell V12 gives interesting results but approximately 100Hz too high at 50m. This is partially compensated by the lower variation of Fr with depth (1.00 against 1.5 for Vo). The tendency is the same for V18 but with a higher Fr variation with depth. The V12L shell is clearly the best solution because of an equivalent resonance frequency at 50m, and lower variations with depth. The V12L shell was definitively selected to overtake the Diabolo Vo.

Parameter \ Shell	Vo	V12	V12L	V18
Fr at 50m (Hz)	1540	1640	1530	1670
TVR at 50m - dB ref µPa/V@1m	128.0	127.0	128.5	126.5
Variation of Fr with depth (Hz/m)	1.50	1.00	1.14	1.37
Variation of TVR_{max} with depth (10^{-3}dB/m)	19	30	22	28

Table 4: Main characteristics of the three promising shells V12, V12L, and V18

NEW DIABOLO V12L - PERFORMANCE AND LIMITS

The Diabolo V12L presents performance quite similar to Vo, sometimes more interesting (Fig. 8).

Parameter	Vo	V12L
Fr at 20m	1500	1500
Increase of Fr with depth	1.5Hz/m	1.1Hz/m
Sv min	127dB	127dB
Sv max	131dB	132dB
Bandwidth	200Hz	200Hz
Crush depth (*)	>300m	>350m
Masse	1kg	1kg

Table 5 : Comparison between performances of Diabolo Vo and V12L

INCREASING DEPTH CAPABILITY OF « DIABOLO » FLEXTENSIONAL TRANSDUCER FOR ACTIVE LINEAR ARRAYS

* The crush depth is defined as the maximum depth (transducer non working) for reversibility of the transducer performance

The equivalent circuit of the transducer was recalculated to predict both fatigue limit of the shell (see next paragraph) and performance of the complete array (on going paper). Comparison between equivalent circuit and measurements are in good agreement (Fig. 3).

ENDURANCE TESTS

Fatigue analysis of the V12L shell provides a maximum dynamic stress of the shell versus static stresses. The maximum dynamic stress corresponds to a specific displacement for mode one, obtained by FEM. Then, by using the equivalent circuit of Diabolo V12L, this maximum displacement is converted into maximum input power. This maximum power is valid for a transducer alone but must be reconsidered for a complete array. Theoretically it is then possible to extract a network of curves giving the maximum input power as a function of depth, frequency (and steering angle for a complete array). The selected solution to avoid such complex command laws was a maximum input power between 20 and 170m, and a significant decrease between 170m and 200m (Fig. 9). As the TVR is continuously increasing, the radiated energy remains quite unchanged.

Several endurance tests were performed to validate those limits with a sufficient number of cycles. Three V12L shells were successfully tested during more than 20 million of cycles at both 350W/17bars and 220W/20bars with the following conditions : CW at resonance, pulse duration 12s, duty cycle 25%. No problem was observed.

CONCLUSION

The limiting factor of the Diabolo Vo transducer was the fatigue of the shell when both submitted to static and dynamic stresses. The design of a more robust one allowed to push the depth limit from 150m to 200m, without any significant change neither in acoustic properties nor in transducer physical characteristics (weight and overall dimensions). A power limit is now defined for two depth ranges : 20-170m and 170-200m.This new transducer is currently being integrated in an active linear towed array. Now the complete emitting chain, including power amplifiers, transmission line, tuning inductances, transducers, and acoustic coupling, is to be modelled. Driving voltage laws may be extracted to provide a conservative threshold value below the power limit of the transducer for any case of depth and steering angle. Finally overall system performance may be assessed.

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INCREASING DEPTH CAPABILITY OF « DIABOLO » FLEXTENSIONAL TRANSDUCER FOR ACTIVE LINEAR ARRAYS

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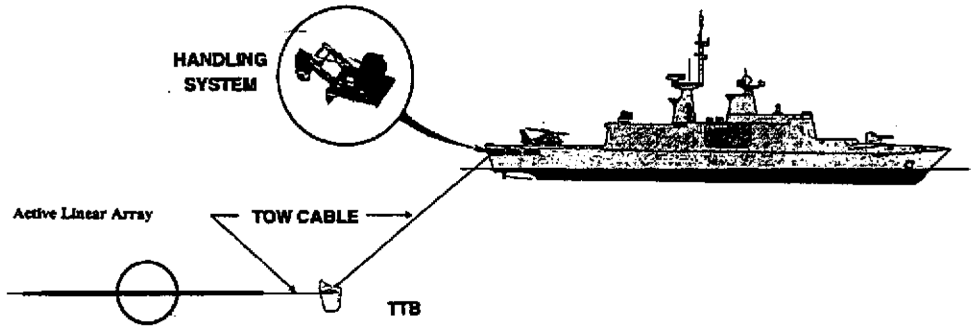

Fig. 1 : Concept of Active Linear Towed Array (ALTA)

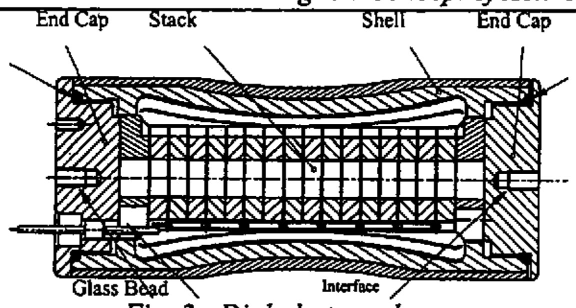

Fig. 2 : Diabolo transducer

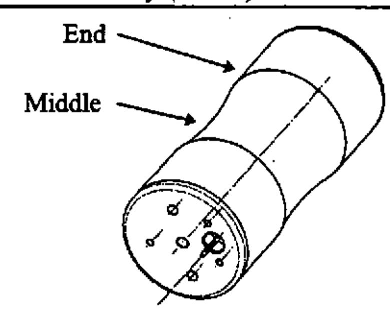

Fig. 6 : « Middle » and « End » of the staves

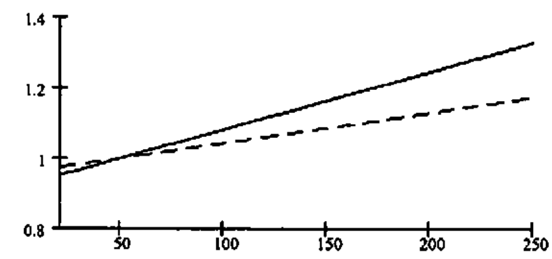

Fig. 5 : Comparison of elasticity coefficient β(d) for Diabolo V0 (solid line) and V12L (dashed line) versus depth (m)

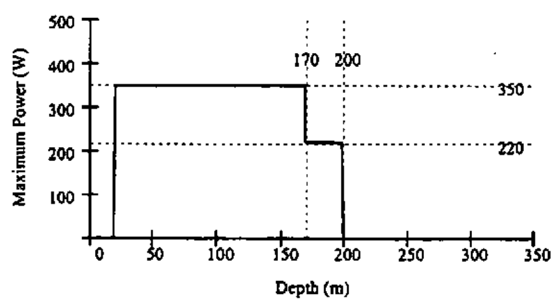

Fig. 9 : Maximum input power versus depth for Diabolo V12L alone

INCREASING DEPTH CAPABILITY OF « DIABOLO » FLEXTENSIONAL TRANSDUCER FOR ACTIVE LINEAR ARRAYS

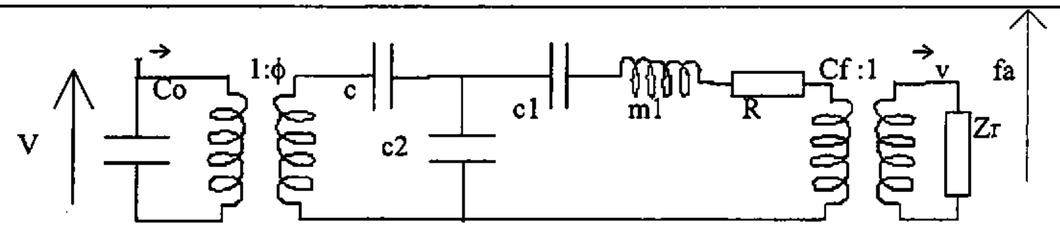

Fig. 4 : Equivalent circuit for the Diabolo

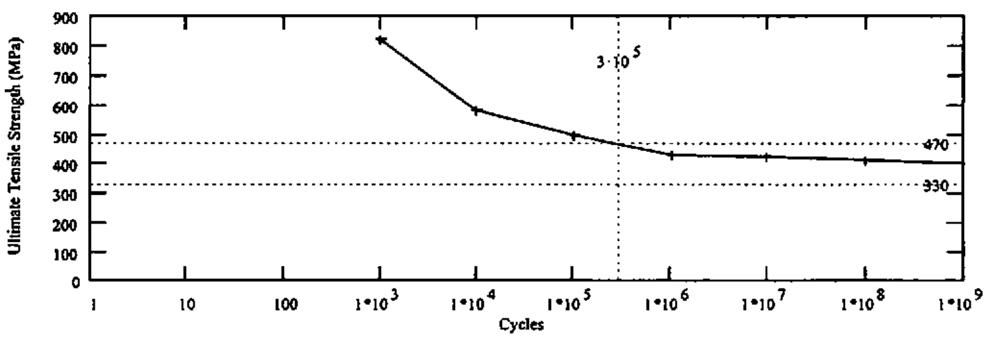

Fig. 7 : Ultimate tensile strength for Titanium - Maximum number of cycle for 200m (3.10^5) - Conservative value at 140m (330MPa)

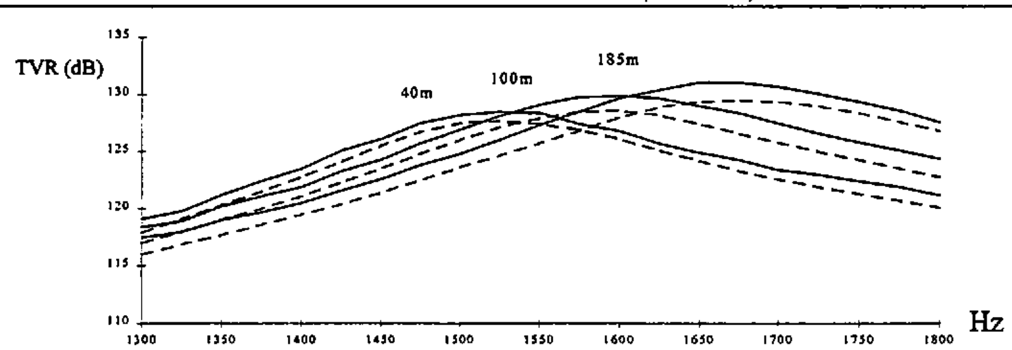

Fig. 3 : Comparison between equivalent circuit (dashed) and measurements (solid) for Diabolo V12L

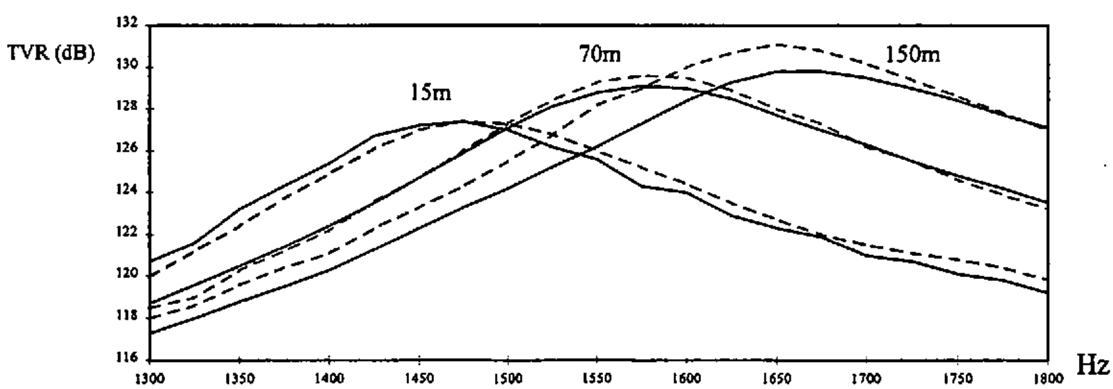

Fig. 8 : TVR comparison between Vo (solid line) and V12L (dashed line)