FM-6 | 347

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ANALYSIS OF FLUID SLOSHING IN TANKS FOR VIBRATION CONTROL

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ABSTRACT

The present paper reports the results obtained from an experimental investigation carried out to study the dynamic responses of partially filled fluid tanks exhibiting a sloshing motion. A simple test rig has been developed to simulate such a phenomenon using a horizontal harmonic excitation system. Both cylindrical and spherical tank shapes have been considered. Mechanical Impedance Data were acquired for the different system and operational parameters. These include the fluid mass, tank size, excitation frequency and force level. An equivalent linear viscoelastic model (modified Maxwell's model) has been adopted to represent the dynamic behavior of such systems. In addition, an imperical formula describing the fundamental frequency of the sloshing liquid in terms of the tank diameter and liquid height has been presented. High damping characteristics were observed for the tested system which make it suitable for vibration attenuation.

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INTRODUCTION

The design of large liquid containers and storage units subjected to exciting environment such as missile and space-flight vehicle liquid-fuel propulsion systems involves consideration of diverse dynamic problems. These are created due to the slosh action of the excited fluid mass and the associated forces and moments which act on both tank walls and supporting structures. In addition, if the fluid is allowed to oscillate undamped, the stability and integrity of the system can be greatly affected, [1].

Guthrie [2] and Rayleigh [3] reported theoretical and related experimental values for the fluid natural frequencies when partially filled cylindrical tanks are exposed to exciting harmonic forces. They represented the system by a simple pendulum and a spring-bob model to provide simulation of the stiffness and inertia terms. Housner, [4] derived an expression for the natural frequency of vibrating water tanks in the following form

$$f = .305\sqrt{\frac{g}{D}\,[\mathrm{Tanh}\,(3.68\,\bar{H})]} \qquad \mathrm{Hz} \tag{1}$$

He reported that only the dimensional aspects of the system such as tank diameter and fluid level affect the dynamic behavior of the sloshing unit. In his expression the effect of the fluid bulk volume and motion are shown to have dominant effects rather than the internal shear forces between fluid layers.

Due to the theoretical analysis complexity involved with the sloshing phenomenon in spherical tanks, little is found about it in the literatures, [5]. Abramson [6] reported several important features of sloshing in spherical tanks. His experimental results showed that the force response is quite dependent on the magnitude of the excitation amplitude. In addition he showed that large amplitude liquid free surface motions are excited more easily and show to be more important in modifying the total force response in spherical tanks than in cylindrical tanks.

In this study a search for an equivalent lumped parameter linear viscoelastic model which fully describes the dynamic behavior of fluid sloshing in spherical and cylindrical tanks has been carried out. Driving point impedance values were measured over a frequency range between 1 up to 100 Hz. These actual measured values provided useful response plots for the different system and operational parameters. Their patterns were used to select a suitable equivalent model.

A simple analytical exponential formula is deduced from the experimental results to evaluate the fundamental frequency of spherical partially filled sloshing tanks. Glycerine was used for the reported tests.

TEST RIG

Referring to Fig. 1, the developed actual testing system consists of a rigid liquid tank (spherical or cylinderical) which is mounted on an aluminum circular base plate (ϕ 300 mm) and guided by four fixation steel angles. Four vertical stainless steel leaf springs of thickness 1 mm supports the base. To affect the vibrating system mass, additive weights may be attached to the base plate.

The horizontal base excitation is induced by a general purpose head electro-magnetic shaker of rating 445 Newton. An impedance head (force and accelera-tion teransducer) with 370 PC/N sensitivity records the input force and velocity signal levels. As shown in Fig. 1, the instrumentation system consists of two subsystems. The first generates and controls the driving signals, the second records the measured parameters through a set of conditioning amplifiers and electronic (voltage-vibration) meter. These instrumentation for the test rig were used to measure the fundamental frequencies and the driving point impedance at a specific frequency range of interest. The height of the liquid in the tank has been changed to provide different sloshing masses.

RESULTS AND DISCUSSION

A set of seven impedance data plots have been obtained from testing the previously described unit for each tank shape. These plots are shown in Fig. 2 through 7. The runs cover selected values of tank size (ϕ), liquid mass (m) and exciting force level (F). The shown frequency response plots reveal identical patterns. The modified Maxwell's model shown in Fig. 8 was found to possess a similar function shape and which is described by the following expression:

$$Z = [\,(1/C)^2 + [[(1/\Omega m_1) - (\Omega/K)]/[\frac{m_1 + m_2}{m_1} - \frac{\Omega^2 m_2}{k}]]^2]^{-1/2} \tag{2}$$

In the above expression specific values of the apparent masses (m_1 and m_2), the dynamic stiffness (K) and the equivalent damping coefficient can be estimated for each specific running condition using the skeleton technique described in references [7], [8]. Accurate values can be further evaluated through an iterative procedure which starts with the roughly estimated values. This work is confined to the system modelling using response curve patterns. The different actual plots reported herein reveal wide band shapes which indicate that the sloshing tanks possess high damping characteristics.

Referring to Figs. 2 to 7, the reported driving point mechanical impedance plots show the effect of the supported partially filled tank with liquid mass (m_ℓ) and the additional masses (m_1, m_2). The increase in the peak impedance value associated with the increase in the peak frequency value are clearly shown for low masses.

An imperical exponential formula [9] has been deduced by the authors to fit the experimental fundamental frequencies for the partially filled spherical tanks. This relation includes the parameters of tank diameter (D) in mms and the fluid level ratio ($\bar{H}$ = H/D). From Fig. 9. One can see a reasonable agreement between the formulate expression and the experimental results. The formula can be written in the following form:

$$f = 12.786\ D^{-0.3246}\ (\bar{H})^{0.175} \quad \text{Hz} \tag{3}$$

For cylindrical tanks the experssion reported by Housner [eq. (1)] has been tested for Glycerine to justify its generality. The good agreement between the analytical expression and the experimental values as shown in Fig. 9 indicate the validity of such deduced formulae for fundamental frequency evaluation for different kind of fluids.

The maximum pessimistic error has been found for both cases to be 5.2%.

CONCLUSION

Experimental testings were carried out for cylindrical and spherical tank shapes of different sizes partially filled with Glycerine and the fundamental frequency and the driving point impedance were acquired using piezoelectric transducers integrated to a vibration measuring chain. New presented formula for fundamental frequency values has been verified by experimental observations. Partially filled tanks with sloshing fluids are proposed to control and attenuate vibrations if attached to oscillating structures since they possess high damping characteristics which have been observed in the work reported in this paper.

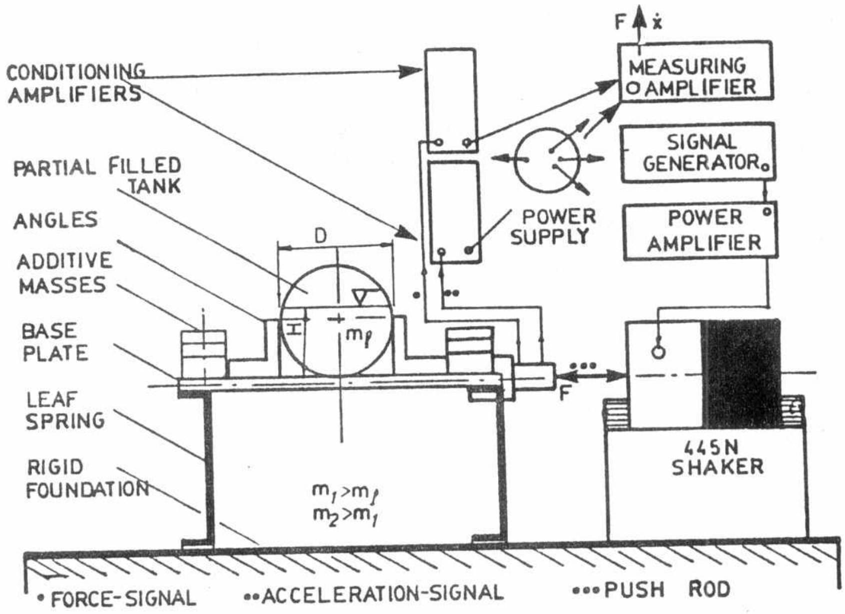


Fig. 1 Test rig.

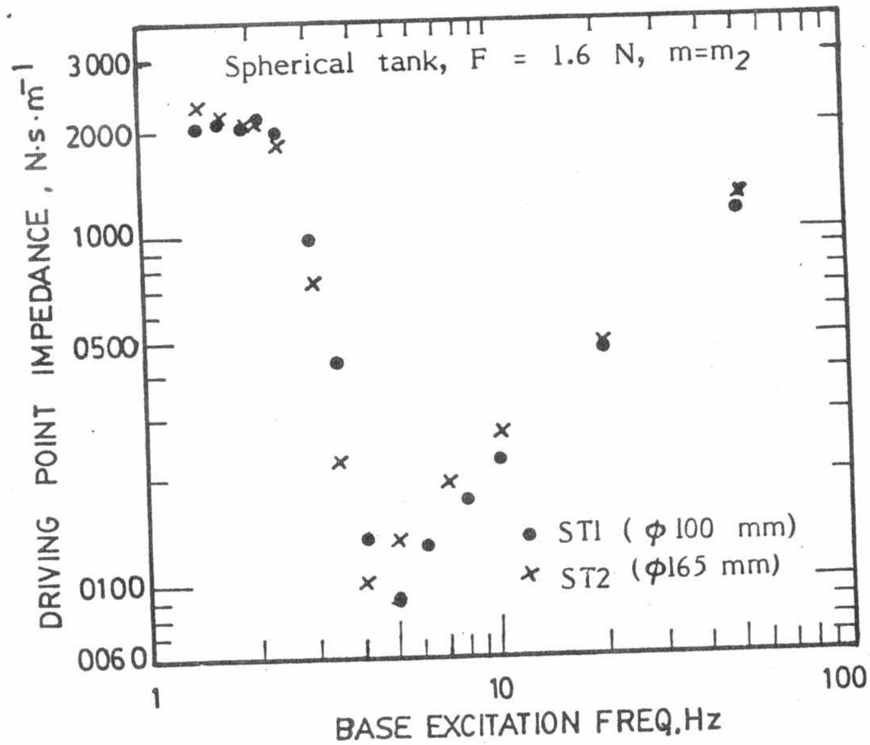


Fig. 2 Plots of driving point impedance

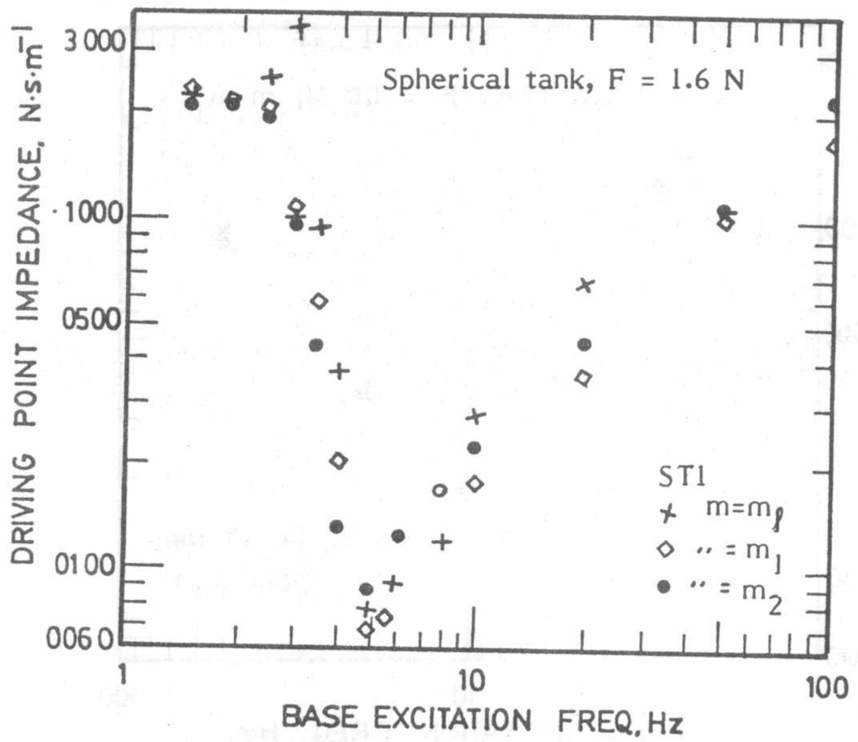


Fig. 3 Plots of driving point impedance

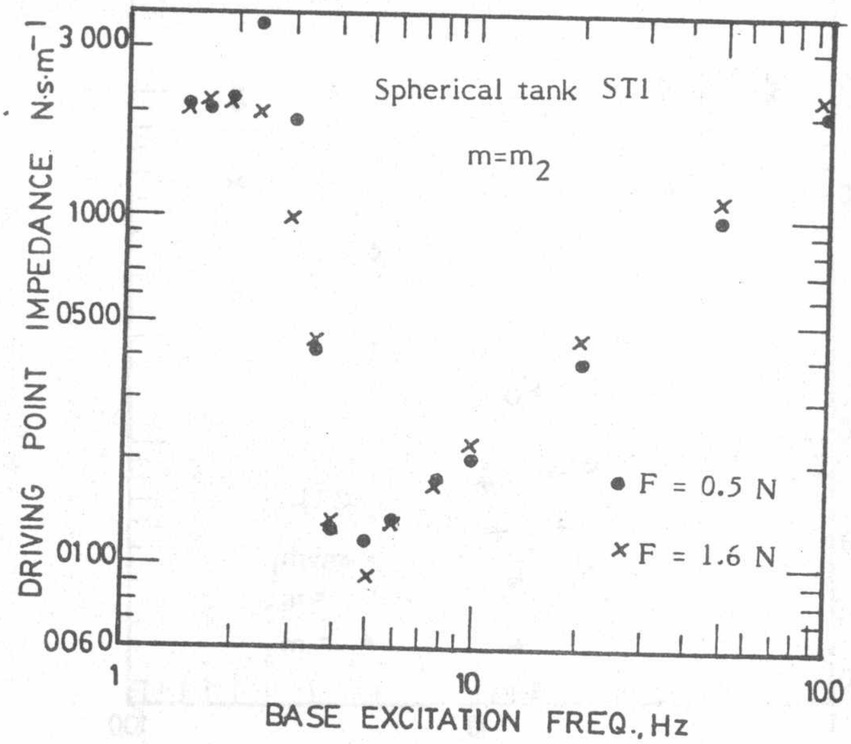


Fig. 4 Plots of driving point impedance

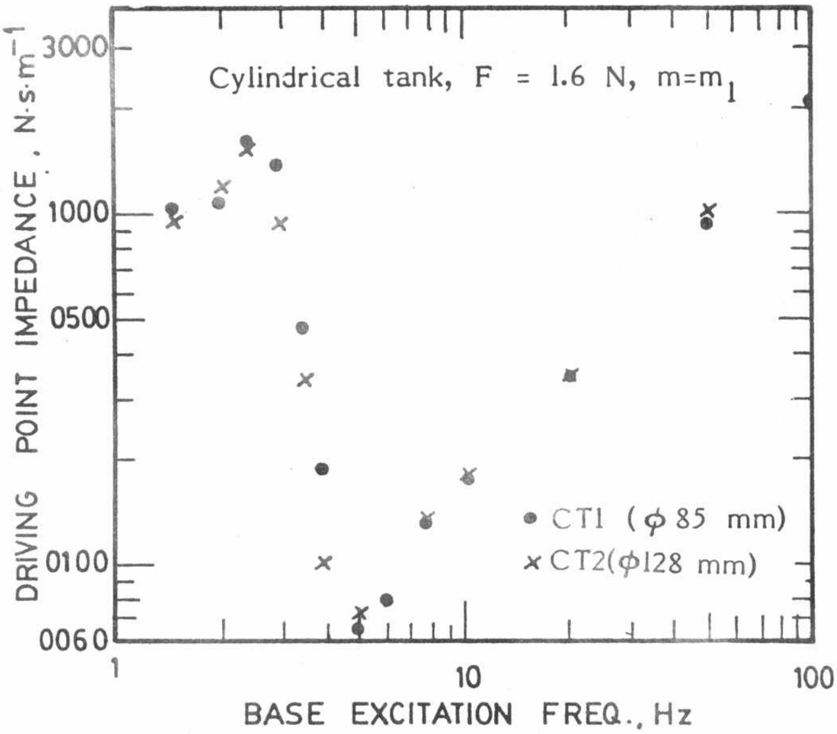


Fig. 5 Plots of driving point impedance

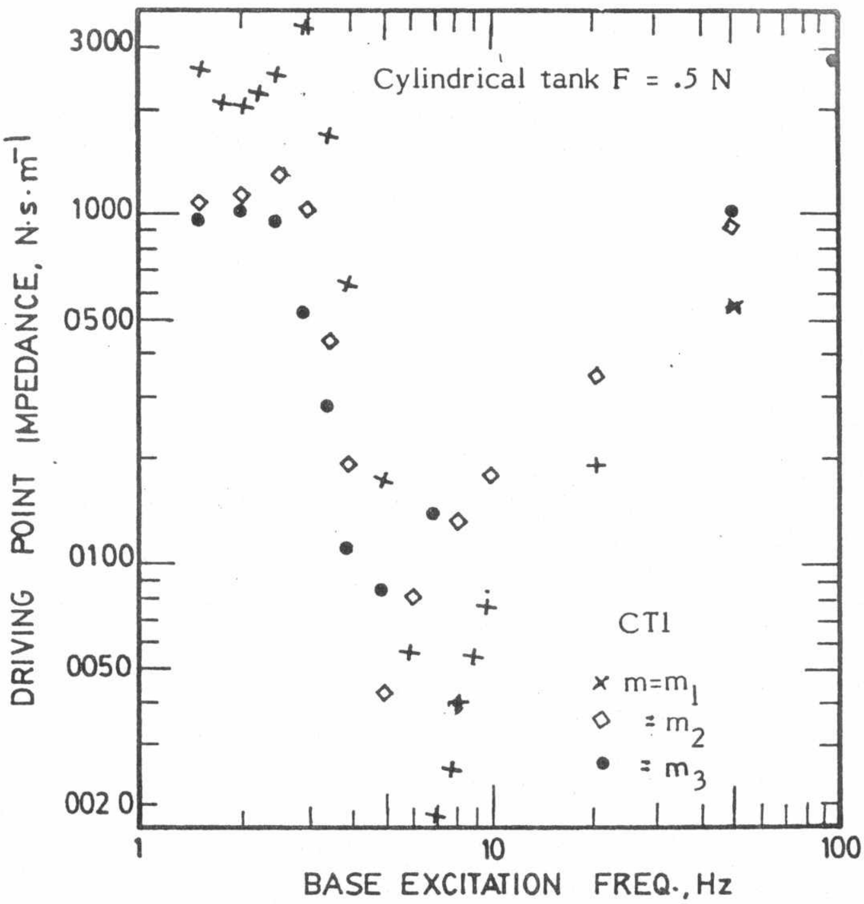


Fig. 6 Plots of driving point impedance

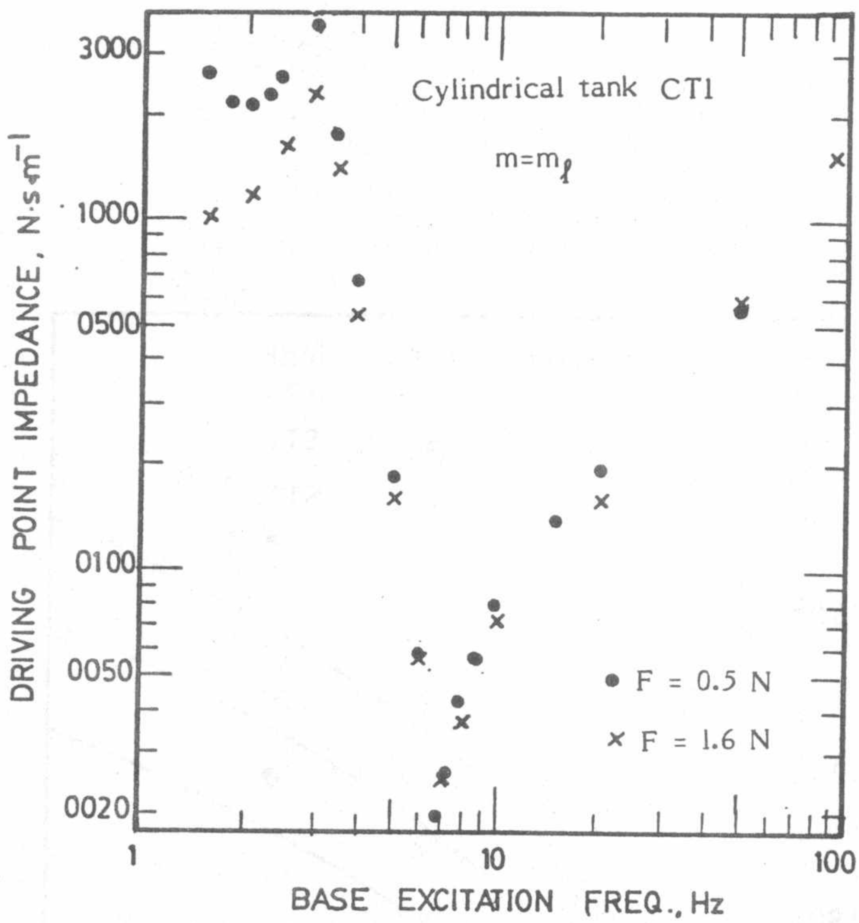
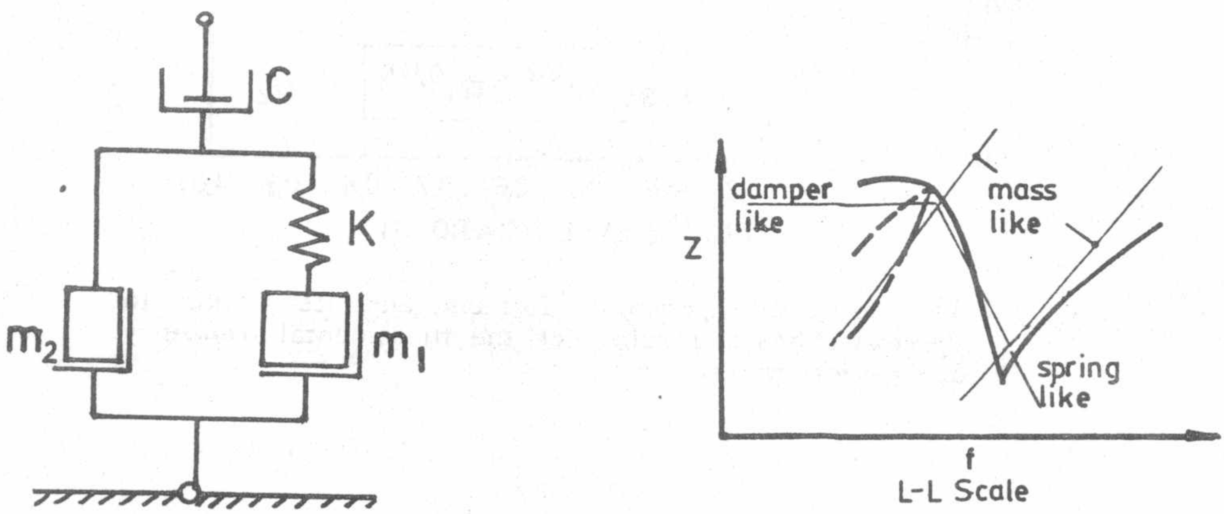


Fig. 7 Plots of driving point impedance



Typical modified Maxwell's model function

Fig. 8 Equivalent mathematical model.

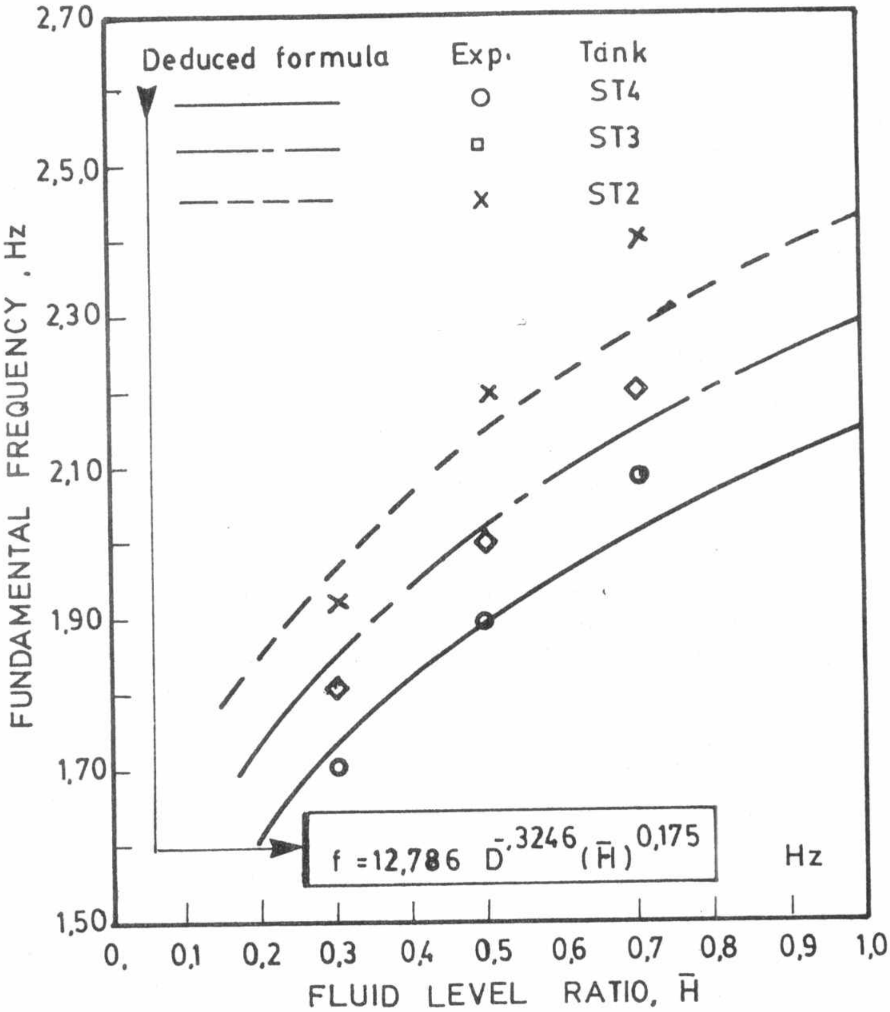


Fig. 9 The deduced exponential formula and its fitting to the experimental results, for the fundamental frequency of spherical tanks.

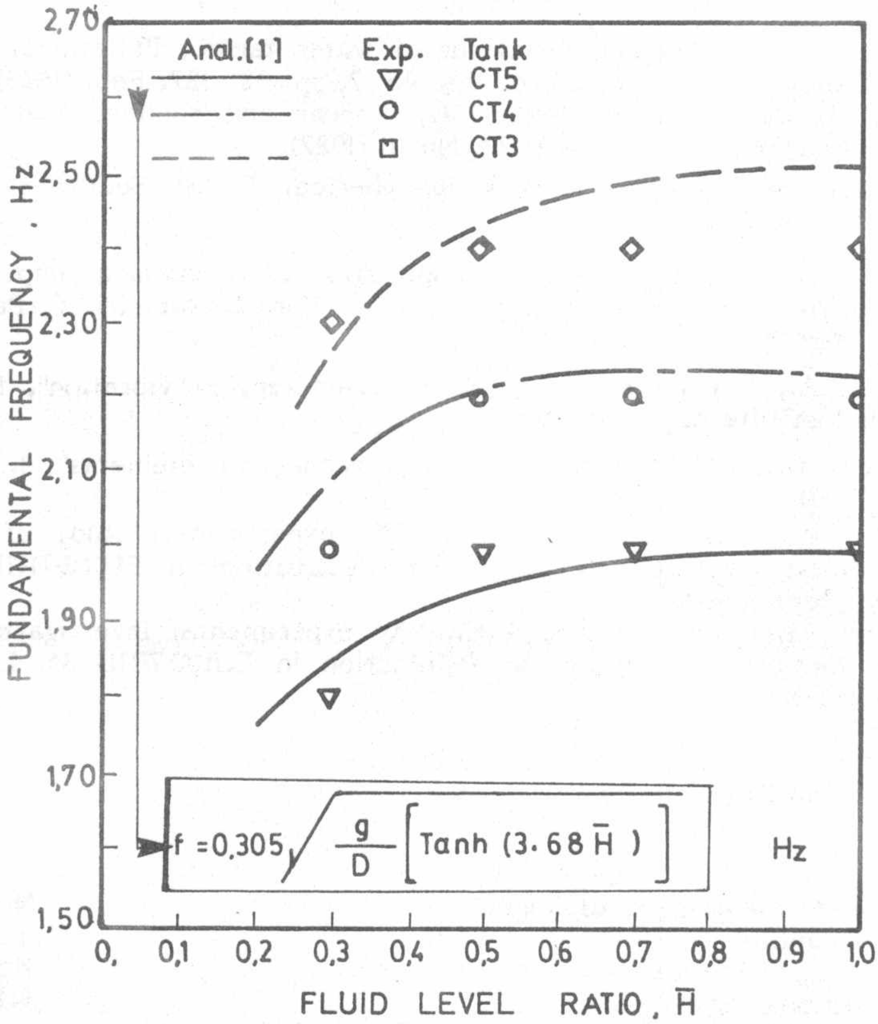


Fig. 10 Comparison between analytical [4] and experimental results for the fundamental frequency of cylindrical tanks.

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NOMENCLATURE

Lattin letters

C	Equivalent Damping Coefficient	$N. Sec. m^{-1}$
D	Tank Diameter	mm
f	Fundamental Frequency	Hz
g	Gravitational Acceleration	$9.81\ m.Sec^{-2}$
H	Height of Liquid	m
K	Equivalent Stiffness	$N.m^{-1}$
m	mass	Kg
Z	Driving Point Impedance	$N.Sec.m^{-1}$

Greek letters

Ω	Excitation Frequency	rad./sec.

Abbreviations

CT Cylindrical Tank
ST Spherical Tank