Measuring mud properties with a tuning-forks device

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The use of tuning forks for measuring and estimating mud properties appears as a very promising alternative to other available technologies. However, the physical principles governing their operation remain to be fully documented. In this work we present a theory that explains the response of an externally forced tuning fork when vibrating inside fluid mud.

Introduction

Following PIANC (2014) the nautical bottom is defined as 'the level where physical characteristics of the bottom reach a critical limit beyond which contact with the ship's keel causes either damage or unacceptable effects on controllability and manoeuvrability'. If the bed is composed of cohesive sediments the transition from water to a consistent bed is progressive and diffuse, making the above definition ambiguous. This progressive change, from water to sediment, complicates the interpretation of sonar returns, as the acoustic return depends on both the sound frequency and the density gradient. It is therefore necessary to use intrusive techniques, which allow for direct contact of the measuring device with the mud, in order to determine its properties (density, shear strength, yield strength, viscosity). The RheoTune developed by Stema Survey Services, the Netherlands (Stema, 2013) is based on the tuning-fork technology. The authors have used the RheoTune during nautical bottom surveys in the Rio de la Plata and Amazon River.

Theory

The tuning fork tine oscillation is forced with an adjustable frequency by a piezoelectric element placed on its base, while the tine motion/deformation is measured by another piezoelectric element. The instrument forcing frequency ω is adjusted in order to produce a given phase shift between the forcing and the tine displacement.

Generalizing the results of Allwright (2002), the tine motion can be represented as a forced oscillator moving with a frequency ω

$$F = -M_0\omega^2 x - \rho V_0\omega^2 x + B_0 i\omega x + (1-\alpha)(i\omega)^{3/2}\sqrt{\mu\rho}A_0 x + K_0 x + \alpha A_0 k x \,. \tag{1}$$

Here F is the amplitude of the external forcing $F\exp(i\omega t)$; x is the complex amplitude of the sensed displacement $x\exp(i\omega t)$, with i the complex unit and t the time; M_0, V_0, B_0, K_0 and A_0 are the mass, volume, damping, elasticity, and surface area of the tuning-fork; ρ, μ, and k represent the density, viscosity, and elasticity of the mud; α is a parameter that may take any value between 0 and 1, and represents the type of response of the mud. If $\alpha=0$ the mud is behaving as a viscous fluid, if $\alpha=1$ the mud is behaving as an elastic material, while values of α between 0 and 1 represent that a part of the mud ($1-\alpha$) that has a viscous behavior and the rest (α) that has an elastic behavior.

It is possible to adjust the frequency of the external forcing to a value ω_B such that the forcing is $3/4\pi$ ahead of the tine displacement, in other words, in phase with the mud viscous damping. This gives equations for the frequency ω_B and modulus $A_B=|x/F|$ of the displacement.

$$\omega_B = \frac{B_0 + \sqrt{B_0^2 + 4(M_0+\rho V_0)(K_0+\alpha k A_0)}}{2(M_0+\rho V_0)}, \quad A_B = \left[\sqrt{2}B_0\omega_B + (1-\alpha)\omega_B^{3/2}\sqrt{\mu\rho}A_0\right]^{-1}. \tag{2}$$

Note that ω_B depends on the elastic response of the mud ($\alpha k A_0$), and A_B depends on the mud viscosity, density, and elasticity both explicitly and implicitly through ω_B.

Results

The values of ω_B and A_B recorded as the tuning-fork moves inside a uniform mud with a particular density, viscosity and elasticity, but under different strains states (represented by different values of α), may be used to calibrate the tuning-fork response (Fig. 1). The field recorded pairs of ω_B and A_B values can be used to determine the mud density.

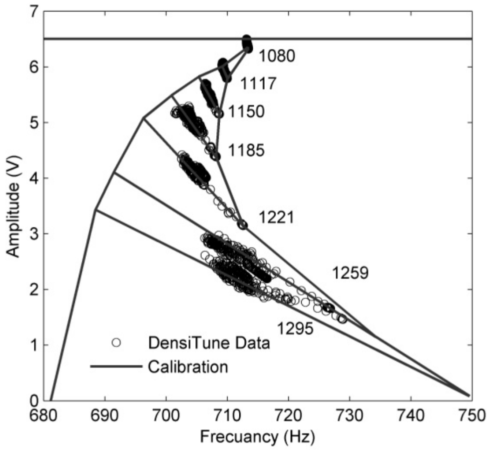

Fig. 1. RheoTune calibration diagram, numbers refer to densities in kg/m^3.

Discussion

Equation (2) for A_B shows that it is possible to detect the location of the nautical bottom from the tuning-fork raw amplitude readings as it would be strongly reduced when the instrument penetrates into the bed, and the density and viscosity rapidly increase. In the above result a viscoelastic response of the mud has been assumed which certainly is an oversimplification. It is also clear that the mud properties measured by the tuning-fork correspond to the mud directly surrounding the tine. Mud is actually a two phase material (or three if gas is present), since the tine vibration frequency is on the order of 1 kHz, the effect of the water compressibility and permeability may affect the tuning-fork response as the water can flow in the pores inside fine sediment matrix.

Conclusions

The above results showed that the tuning-fork should be calibrated with local samples of the mud as little disturbed as possible, and if possible, dilution or drying of the samples used for calibration should be avoided. Additional theoretical developments, not included here, showed that it is possible to directly obtain an estimation of the mud viscosity from the tuning fork calibration procedure.

References

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