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Damage detection in elevated spherical containers partially filled with liquid

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ABSTRACT

Damage detection through changes in the dynamic properties has received considerable attention in recent years. However, approaches in structures supporting tanks partially filled with liquid are scarce in the technical literature.

In this paper, a numerical–experimental study of damage detection in coupled fluid–structure elevated spherical tank systems is presented. The main objective is to investigate the feasibility to detect structural damage in the support structure by monitoring changes in natural frequencies. The major difficulty arises due to the changes in natural frequencies when the liquid level varies. Thus, in order to gain insight into the dynamical behaviour of the spherical containers and distinguish between the frequency shift caused by container filling conditions or by structural damage, experimental free vibration tests with small vibration amplitudes on a scaled spherical tank model are performed. The dependency of the identified frequencies on the structural damage severity is studied assuming three increasing levels of damage in the support structure. The results indicate that it is possible to detect structural damage, with acceptable confidence, up to liquid filling level of 30%. Moreover, only the "associated structural frequency" reflects the structural damage with a perceptible drop. Next, a numerical model of a real spherical container that takes into account the coupling between fluid and structure is presented to demonstrate the usefulness and validity of the results.

1. Introduction

Structural integrity and reliability are concerns for civil and industrial structures, especially for essential civil structures such as hospitals, emergency facilities, communication and operation centres, and critical components in petrochemical industries, refineries, and nuclear power plants. During its lifetime, the structural integrity condition of a component may be affected by natural degradation, aggressive environments and ambient factors (atmospheric corrosion, oxidation, erosion), and principally after exposure to exceptional events such as earthquakes. In these cases, structures might become damaged, and an early overall evaluation of their integrity is necessary in order to take pertinent and quick decisions to avoid failures or, eventually, collapse. From security and economic points of view, this initial diagnosis has significant consequences. For example, after an earthquake, it is important to determine the current serviceability of the affected structure to ensure safe operation in the present condition, and remaining service life; in the case of detecting small damage, the structure may be returned to an operational condition, so reducing the economic impact. These potential benefits, hence, justified the developing of methods for structural damage identification and led to the rapid growth of a research field known as structural health monitoring (SHM) [1].

According to the depth of diagnosis, the methods of damage identification may be classified into four levels [1].

- Level 1, Detection: Methods allow establishing if damage is present in the structure.
- Level 2, Location: Methods allow the location of the regions where damage occurred.
- Level 3, Quantification: Methods allow evaluating the intensity of damage.
- Level 4, Prediction: Methods allow predicting the remaining life of the structure.

Within level 1 of SHM, perhaps the most frequently used techniques, which have received considerable attention in recent literature, are global monitoring methods based on vibration measurements. The main advantage of global methods is that the measurement locations are not required to be close to damaged regions, (which, in general, are difficult to access), as required by local techniques. The basic idea springs from the notion that spectral properties, described in terms of the so-called modal parameters (frequencies, mode shapes, and modal damping), are functions of physical properties of the structure (mass, energy

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dissipation mechanisms, and stiffness). Thus, changes in the physical properties will cause changes in the modal properties.

Literature reviews of damage identification and SHM of structures based on changes in their measured spectral properties have been presented, for example, by Doebling et al. [2,3], Zou et al. [4], Sohn et al. [5], Salawu [6], Chang et al. [7], Chen et al. [8], Wang et al. [9], and Choubey et al. [10].

Bastidas-Arteaga et al. [11] developed a probabilistic lifetime prediction model for reinforced concrete (RC) structures under the coupled effect of corrosion and fatigue.

The techniques for structural damage identification are as diverse as the functions, type of construction, operating conditions, and materials in the different process equipment are. In this context, because there is no generalized method for predicting damage that covers all cases, only some review works with regard to structural integrity assessment are cited herein. Studies of typical research activities in the field of structural integrity of vessels and piping in Japan were collected by Yoshimura [12]. Bullough et al. [13] reviewed methods and applications of reliability analysis for structural integrity assessment of UK nuclear plants. Two papers by Dai [14,15] described a methodology for predicting the occurrence of failure events, damage, and remaining life of process equipment. Particularly in the oil and gas sector, the standard procedures for damage assessment of components such as vessels and piping are provided by API 579 [16], which are based on the ASME B31G [17] and the RSTRENG criteria [18] under the concept denoted as fitness for service (FFS). A comprehensive FFS guide extracted from API 579 was reported by Anderson and Osage [19]. Li et al. [20] described a structural integrity assessment procedure used in China for pressure vessels containing defects. Seshadri [21] proposed a procedure based on elastic analysis classified within level 2 (FFS) assessment provided by API 579, for thermal hot spot evaluation in cylindrical shells. Indermohan and Seshadri [22] extended the application of the assessment methodology proposed by Seshadri [21] and concluded that the remaining strength factor (RSF) is conservative and comparable with the RSF from inelastic finite element analysis (FEA) results. Ramkumar and Seshadri [23] studied a thicker cylindrical shell with both internal and external corrosion using similar model and yield criteria. The conclusions were similar in both studies [22,23]. Specifically in respect of the structural integrity of spherical vessels, one can mention the work of Sims et al. [24], who studied local round thin areas (RTAs) using FEA with elastic–perfectly plastic material and limiting the maximum strain to 2%. Tantichattanont et al. [25,26] proposed a level 2 (FFS) assessment scheme for spherical shells with hot spots and localized corrosion, respectively.

In most studies proposed in the technical literature, the main concern is the structural integrity evaluation of the vessel itself, while completely ignoring the support structure. Widespread research on the structural integrity of the support structure of spherical vessels has not been carried out by way of technical development or experimental investigation.

The present work demonstrates that it is possible to detect structural damage in the support structure of elevated spherical containers partially filled with liquid by a vibration-based method. The procedure consists of calculating the natural frequency shifts produced by an expected type of damage, normally localized on the bottom of the support columns. Typically, in the model, the damage is taken into account numerically by a local stiffness reduction. Then, to estimate the structural damage in the analyzed structure, the natural frequencies determined from the measured vibration response are compared with those frequencies predicted by the numerical model. Once the natural frequencies shifts are correlated with stiffness reduction, it is possible to define an integrity criterion to indicate specific actions on the damaged structure. The usefulness and validity of the results obtained by experimental free vibration tests on a scaled spherical tank model are demonstrated by a numerical model of a real spherical container that takes into account the fluid–structure interaction.

2. Free vibration tests of the experimental model

Considering that the analyzed structural typology presents difficulties in studying its dynamical behaviour due to the dependence of the resonant frequencies on both container filling (strong coupling between part of the liquid and structure) and possible damage on the support structure, vibration experimental tests for eight liquid levels, from empty to full container, were conducted on an undamaged model and a damaged model.

2.1. Undamaged model

The first step of the proposed methodology is to determine the natural frequencies at each liquid level in the undamaged structure (reference state).

The 1/75 scaled model consists of a plastic sphere with radius $R = 81.3$ mm, wall thickness $e = 3$ mm, and mass density $\rho_s = 980$ kg/m^3 (see Fig. 1a and b) . The sphere is supported by two legs clamped at the base with a length $L = 250$ mm, a rectangular cross-section of 3×35 mm^2, and the following material characteristics: Young's modulus $E = 2.35$ GPa, Poisson ratio $\nu = 0.3$, and mass density $\rho_l = 980$ kg/m^3. The liquid contained is water, with a density of 1000 kg/m^3 and bulk modulus of 2.25 GPa. The dimensions of the model are according to the available laboratory equipment (instrumentation, anchorage systems, etc.).

The structure is excited in two different ways: an impact on the base and an initial displacement on the equator of the sphere. For each liquid level, four time histories of the structural free response on the equator of sphere are measured, only in the horizontal direction, by means of a Piezotronics capacitive accelerometer (700 mV/g). As an example, Fig. 2a shows a measured acceleration time history sample obtained from experimental tests for 71% filling. A data acquisition Computerboards PCM-DAS16D/16 with 16-bit resolution is used to record the signals with a sampling rate $n = 500$ sps, and a total number of points $N = 10\,000$. The data are recorded and processed (low-pass filtered) by the HP VEE environment [27] and the Fourier spectrum of the signals is estimated using Welch's method [28]. A general view of the average natural frequencies measured in the range 1–5 Hz (peaks of spectrum) for each water level is shown in Fig. 2b. The dependence of the resonant frequencies on the container filling is shown in Fig. 3.

In the range 1–5 Hz, Figs. 3 and 2b provide valuable evidence of the influence of rising liquid level on the natural frequencies.

As displayed in Fig. 2b, for an empty container, the frequency identified is only at 4.815 Hz, corresponding to the fundamental mode shape. From a filling level of approximately 10% and up to approximately 70%, the dynamical behaviour is characterized by three resonant frequencies. However, up to liquid filling level of 20%, there is a major natural frequency (third frequency) that dominates the dynamical behaviour and it is mostly "*structural*"; that is, the liquid has little influence on the system vibration. The two lower frequencies become more important as the liquid level increases. At about 35% filling, these two first frequencies are more important than the third one. The intermediate frequency seems to correspond mainly to the sloshing liquid mass, because it becomes the most important at approximately 50% filling, when the free liquid surface has maximum area. As is expected, its amplitude is imperceptible in the Fourier spectrum for the empty and the full container. At relatively high water surface level (about 70% filling), the third frequency disappears. Finally, when the container is full,