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Complex dynamics in non-Newtonian fluid-structure interaction

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Abstract. This paper presents the results of an extensive experimental campaign focused on the analysis of the dynamic interactions between an elastic structure and a non-Newtonian fluid. The structure is a circular cylindrical shell clamped in one end to a shaking table and in the other end to a heavy rigid disk. The shell has been investigated both in presence and absence of fluid. The fluid is a mixture of water and corn starch flour, commonly called Oobleck. The experiments were carried out at low and high vibrating energy, in order to clarify the influence of the fluid in different conditions: changing of modal properties, onset of complex dynamics when the fluid-solid transitions take place in the fluid.

Introduction

Fluid structure interaction (FSI) phenomena are of interest for several engineering fields as well as in medical science, and, of course in bioengineering or biomechanics. One can find countless examples of FSI problems in engineering, e.g. flutter of airplane wings, galloping in powerlines and bridge cables, supersonic panel flutter, pipes flutter, fully or partially filled tanks, heat exchangers. In the field of Medical Sciences an important example is the human aorta, where the fluid is highly viscous and non-Newtonian and the artery wall is hyper-elastic, this is a combination of exceptionally difficult problems.

At the end of the previous century (1983) Babcock [1] published an interesting review paper, where he counted, at that time, about 50,000 papers published on the topic of shell stability; he pointed out the attention on open topics such as post-buckling and imperfection sensitivity; dynamic buckling; plastic buckling; experiments. Further reviews, see Ref.[2-4], confirmed the need of further research on the dynamics and stability of shells, which is a topic not well understood.

In the sixties and seventies a series of studies regarding dynamic shells instabilities were published. Further studies addressing the parametric excitation of thin circular cylindrical shells, using the Donnell's shallow shell theory, can be found in Refs. [5-9]. More recent studies on dynamic instabilities of cylindrical shells considered more refined theories such as the Sanders-Koiter theory [13-18] validated from lab experiments; in such series of studies it was clarified the role of axial loads generated by inertial effects on the onset of chaotic vibrations, very high amplitudes of vibration with associated extreme noise production.

In order to have a comprehensive description of fluid structure interaction phenomena, models and applications, the reader is suggested to read the monumental work of Paidoussis [19], [20]; in such treatises the main fluid-interaction models are described as well as methods of analysis. Another interesting paper to be mentioned is a review published in 2003 by Amabili and Païdoussis [21], where more than 300 papers on the topic of nonlinear vibrations of shells with or without FSI were listed; among the deep and interesting comments on the literature the authors pointed out the attention on two aspects, we report their full sentences: "only 23 of the more than 350 papers discussed in the present review give experimental data on large-amplitude vibrations of complete shells", "most of the papers reviewed are dedicated to various theoretical aspects of the problem, with very few experimental results, although more experimental data are available for supersonic flutter of shells".

In the following, the bibliographic analysis is focused on FSI papers strictly related to the present study; it is worthwhile to stress that almost all studies deal with inviscid or Newtonian fluids.

In the 1967 Chu & Kana [22] published a paper focused on nonlinear vibrations of partially filled tanks; the nonlinearity was attributed to free surface waves. In the 1979 Ramachandran [23] analyzed large amplitude nonlinear vibrations of circular cylindrical shells in contact with a dense fluid, no free surface was present. The study was theoretical using the Donnell's shell theory and the potential theory for the inviscid incompressible fluid.

Using a semi analytical model based on the Donnell shallow shell theory for the structure and the potential flow theory for the inviscid and incompressible fluid, Amabili et al. [24]-[29] published a series of papers where the effect of a quiescent or flowing heavy fluid was investigated. Further investigations focused on the interactions of circular shells with supersonic flows, compressible, annular and unbounded flows can be found in Refs. [30]-[34]; in such series of studies the presence of compressive forces was accounted for as well.

In 2012 Girchenko et al studied numerically the interaction of a nonlinear viscous fluid, having a pseudoplastic nature, with a helical shell. They combined two commercial software FlowVision (finite volumes) and Simulia ABAQUS (finite elements). They showed the differences between Newtonian and Non-Newtonian flows in terms of stresses caused on the helical structure. Another study regarding FSI and non-Newtonian fluid was focused on arterial bypass [36], the effects of wall elasticity and non Newtonian rheology were investigated numerically through the commercial software ANSYS.

An experimental study on the rheology and processing of solvent-free core shell "polymer opals", see Ref. [37], analyzed an elastic shell grafted to hard colloidal polymer core particles in order to study the optical properties under deformation.

In 2019 Wu et al. [38] presented a numerical study on interaction between elastic multilayered spheres and a non-Newtonian fluid. They analyzed gold nanospheres immersed in water and calculated theoretically the natural frequencies and the quality factors.

The bibliographic analysis clearly shows that, even though a huge number of publications can be found about FSI problems, and many papers are available about non-Newtonian fluids, the interactions between vibrating structures and non-Newtonian fluids appear to be an almost unexplored field.

Experimental setup and Specimen definition

The studied structure is a polyethylene terephthalate (PET) shell, vertically placed, wedged in an aluminum base rigidly connected to the shaker at the bottom, and constrained at the top by a C-40 steel disc, which is called top mass.

The internal face of the shell was fixed to the external face of both the top mass and the basement by means of an instant cyano-acrylic glue. In addition, the lower end of the shell was secured to the basement via an aluminum ring, lying on the basement and tightened to it with screws. This ring was inserted to guarantee the interlocking constraint. The realized setup leads to a lower end of the shell solidary oscillating with the shaker, since the basement is anchored to the shaker horizontal plate with screws, whilst the top mass induces a rigid body motion at the upper end of the shell, preventing this end from moving freely.

The material of the shell was chosen to be PET, since, as a polymer, it can reach high oscillation amplitudes without addressing plastic deformation phenomena [16]. The shell is a center-holed cylinder characterized by a length (L = 135 mm) greater than the diameter (D = 80 mm).

The steel disc acting as a top mass is highly compact to avoid not wanted side effects, such as the spectral proximity of two vibration modes, especially the one to be excited (axial-symmetrical) and the tilt modes.

The tests were performed using a Dongling ES-340 shaker; a dynamic characterization of the shaker was realized in order to study the coupling with the shell.

The accelerometer on the shaker plate was dedicated to the measurement of the excitation produced by the shaker on the system basement-shell-top mass. Three accelerometers were placed on the top face of the top-mass, close to its circular edge and angularly spaced by 120°. Each sensor was positioned with the X-axis tangent to the circular edge and the Z-axis perpendicular to the top mass face and pointing upward (opposite to the shell). The goal of these three sensors is to measure the acceleration of the disc in the Z-direction, i.e., the axial (along L) oscillation of the shell, since under non-linearity conditions this acceleration/oscillation is not directly linked to the shaker excitation which is measured via the accelerometer on the shaker plate. However, the realized setup also allows to detect possible rotations of the structure around axes lying on a plane perpendicular to L and passing through either the structure mass center (tilt modes) or the basement fixing (beam modes). The detection of these modes is performed by correlating the signal acquired in the three directions by the three accelerometers.

The vibrometer and the telemeter are used for the study of the shell radial modes, namely possible vibrations of the shell along the radial direction (planes perpendicular to the shell length). As shown in Figure 3, the laser ray of both sensors focuses on points at half-length of the shell. Specifically, in order to obtain a proper refracted signal by the shell, needed for the vibrometer and telemeter measurements, a refractive sticker and a black mark were applied on the shell in the points where the rays imping the shell, respectively. The angle between the vibrometer and the telemeter was chosen to be 57°, because this value allows to avoid a redundancy in the measurements of the drift velocity (vibrometer) and the displacement (telemeter) of the shell wall in the radial direction for a wide range of possible radial modes which can be excited in the non-linear dynamic regime.

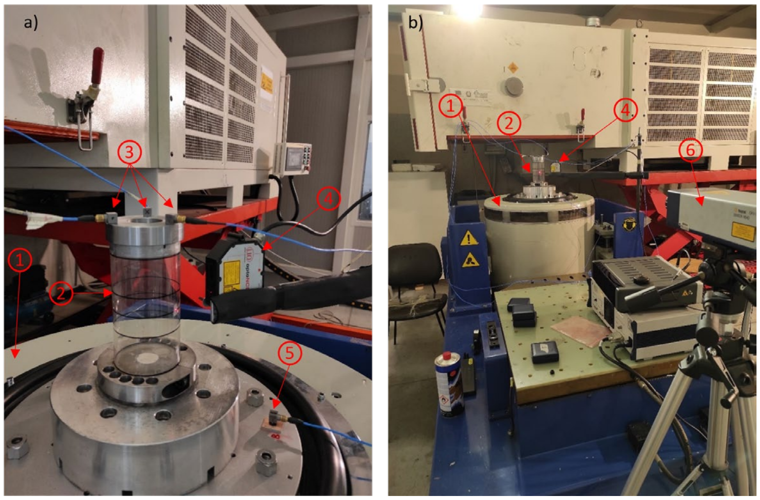

Figure 3 – a) Setup: (1) shaker, (2) shell, (3) measurement accelerometers, (4) telemeter and (5) control accelerometer on the shaker plate. b) Overall experimental setup.

Nonlinear dynamic scenario

Experiments are now carried out considering an empty and a fluid filled shell. The shell is now excited from the base, the excitation signal provided to the amplifier is harmonic with different amplitudes (0.01-0.08V) and frequencies (150-310Hz for the empty shell and 150-270Hz for the fluid filled shell).

Figure 4 shows a bifurcation diagram obtained from Poincaré sections obtained by using a single signal (lateral displacement). The dynamic scenario is extremely rich, we observed different sub-harmonic responses: ½, 1/3, ¼, 1/8 as well as quasiperiodic and chaotic dynamics in a very wide frequency range. For the sake of brevity bifurcation diagrams obtained by the other signals (accelerometers, Laser Doppler) and by changing the excitation levels are not reported for the sake of brevity.

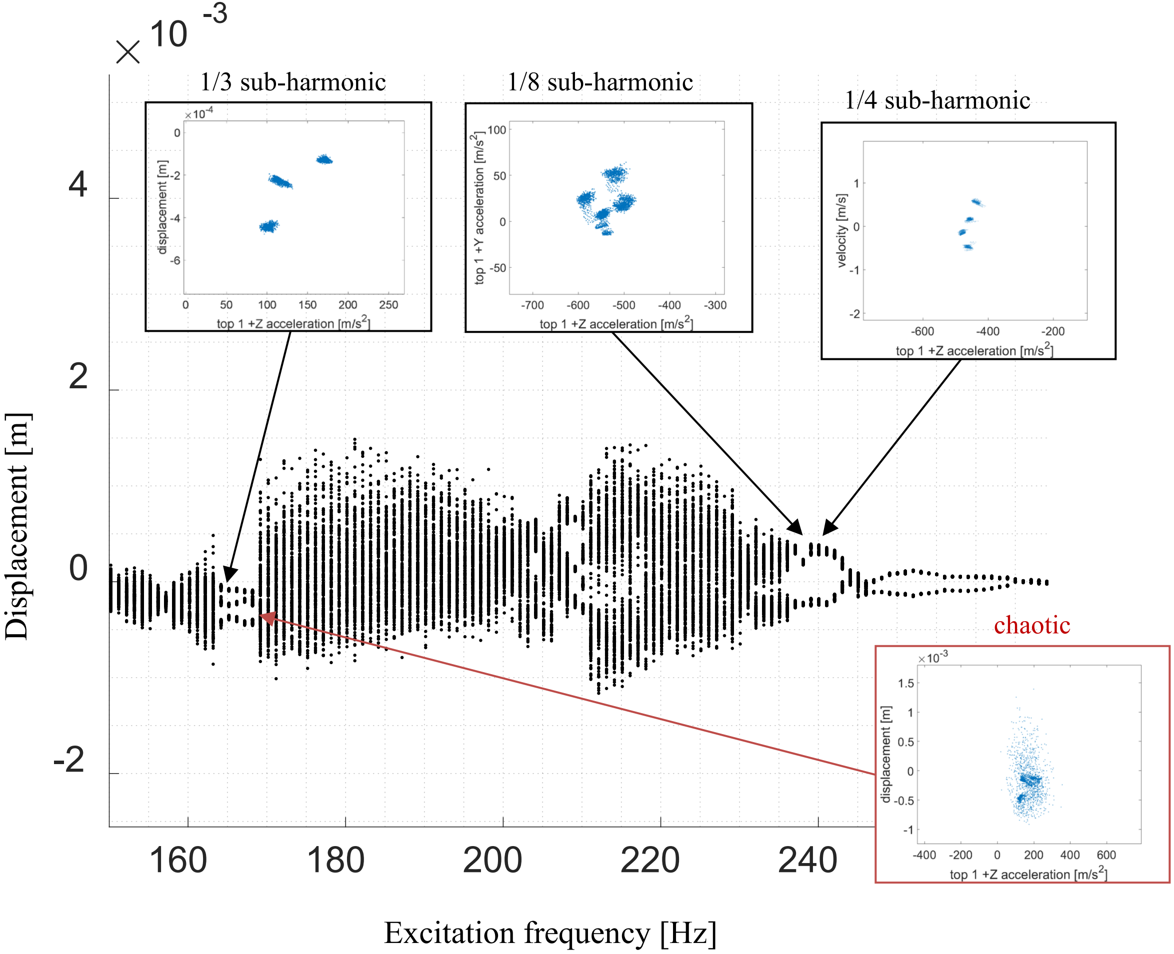

Figure 4: Bifurcation diagram of Poincaré maps: excitation level 0.06V, downward frequency sweep.

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