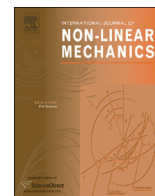




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Complex dynamics of circular cylindrical shells

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ABSTRACT

Complex dynamics of circular cylindrical shells subjected to inertial axial loads are investigated. The shell is vertically mounted on a shaker, i.e. its base is clamped to the shaker fixture, which induces a vertical motion along the shell axis. On the top of the shell a rigid disk is mounted, the vertical motion induced by the shaker induces huge inertial forces due to the rigid body motion. A complicating effect is due to the base actuator, which is an electro-dynamic shaking table; the interaction between the shell and shaker dynamics changes dramatically the system behaviour. The non-linear Sanders–Koiter theory is considered for the structural dynamics; the resulting set of non-linear partial differential equations is coupled with the linear ordinary differential equations that govern the shaker dynamics. A deep analysis of the non-stationary response of the shell is carried out in order to clarify the transition from stationary to non-stationary response. The model is validated by means of experimental results.

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1. Introduction

In the second part of the previous century Bondarenko and Galaka [1] published an interesting work regarding a dynamic phenomenon of violent vibration, defined as a “bang”, arising when a circular cylindrical composite shell is excited from the base motion. They interpreted such experimental results as parametric instability and identified instability regions of several modes.

Shells were deeply analysed in the past and a huge scientific production can be found in the literature, generally it is focused on linear vibrations and static stability, see e.g. Refs. [2–11] for a deep analysis of the literature.

The main reason of such huge production is certainly the big practical interest in shell-like structures due to their large use in several Engineering fields such as Aerospace, Nuclear, Civil, Automotive, Mechanics, and Energy. Several examples of applications can be given: building vaults, heat exchangers, aircraft fuselages, missile and space vehicle structures, structural and non-structural car elements, tanks, pipelines. It is to note that shells theories are also applied to create effective models of nanotube dynamics, as counterpart of computationally expensive Molecular Dynamics models.

The improvement of structural performances in terms of strength to weight ratio is of primary importance for industries; for example, in Aerospace and Automotive the goal is the reduction of fuel consumption. In other applications, for example heat

exchangers, the reduction of thickness is needed for improving the thermal behaviour. On the other hand the reduction of mass gives rise to a magnification of vibration and stability problems or the combination of them.

The availability of commercial software, having enormous capabilities in analysing structural problems, induces designers to consider needless the development of new models. On the other hand, thin walled structures under dynamic excitation can experience complicated types of responses such as non-linear vibrations, combined resonances, parametric instabilities; in such cases the performances of commercial software are not sufficient both in terms of computational efficiency and accuracy. In addition, when the structural element is connected with other mechanical or electro-mechanical devices, the need of developing specialized models is often mandatory.

The early studies on the behaviour of shell structures date back to the begin of previous century [12]: at the time it was not yet clear the post-critical behaviour of shells and in particular the discrepancies between models and experiments were not understood. The reason of such discrepancies should appear clear nowadays, i.e. many important phenomena appearing in shell stability and dynamics can be studied by means of non-linear theories only. Unfortunately, most of the designers are not aware about this issue and have quite little practice in non-linear dynamics; in addition, commercial structural software packages do not yet have specific tools for analysing non-linear responses.

The general problem, strictly related to the present work, regards parametric excitations of thin walled structures. On this topic the literature mainly displays theoretical studies only; few experimental studies can be found and theoretical/experimental papers are infrequent. Interesting works can be found in

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Refs. [8,13–25]; most of them are based on the Donnell shallow shell theory, others consider linear modelling for thin or thick shells. Almost all these studies consider shells excited by axial forces, without interactions with other systems.

Low dimensional models are presented in Refs. [26,27] to study the non-linear response of shells under the action of periodic axial loads; similarly to other studies, interactions between excitation source and the shell were not accounted for.

Complexity in the response of shells under periodic axial loads was investigated in Ref. [28] using a low order model based on the Donnell Shallow shell theory, and in Ref. [29] by means of the refined Sanders–Koiter model. The effect of combination of pre-compression and periodic axial loads was investigated, showing that chaotic dynamics are possible, and evaluating the dimensionality of chaotic attractors as well as the basins of attraction. The effect of a contained fluid was investigated in Refs. [24,29–32].

The role of geometric imperfections in the onset of parametric instabilities, was deeply investigated in Refs. [24,25,29,33] for empty and fluid filled isotropic shells, and in Ref. [27] for isotropic and anisotropic shells.

The effect of pre-stress and elastic foundations on free non-linear vibrations of shells was investigated in Ref. [34].

In Ref. [35], non-linear Donnell's shallow shell equations were used to analyse shells excited by parametric dynamical loads, using a multi-degree-of-freedom dynamical system without dissipation, the system was analysed by means of the Harmonic Balance Method.

Most of previously cited works were concerned with “force” excitations, i.e. external loads having a specific time law. On the other hand, a certain interest should be addressed to inertial forces generated by base motion. One of the first studies on this topic can be found in Ref. [1], where experimental results were reported together with a simplified analytical analysis developed for interpreting and explaining the parametric instabilities found experimentally; the shell was in a clamped-free configuration. In Ref. [36] instability regions and the character of non-linearity was investigated both experimentally and analytically.

Even though the clamped free configuration of a circular cylindrical shell subjected to a base motion is of a certain practical importance (e.g. tanks with open top), many important practical examples imply the connection of the circular shell with other structures or with solid bodies. For such reason, at the beginning of this century a series of papers were published on this topic. Initially, linear models were developed [37], spending big intellectual energies in managing analytically the complex boundary conditions arising from the connection of a rigid body with one end of a circular cylindrical shell. To such purpose, the use of mixed expansions of the displacement fields was necessary: it included the combined use of harmonic and polynomial functions (Legendre polynomials). In Ref. [38] the analysis was extended and reformulated in order to prove both the capability of dealing with complex boundary conditions and non-linearities, in such work a combination of Chebyshev polynomials and harmonic functions was used for expanding the displacement fields in linear modelling, with a successive re-expansion in terms of approximate eigenfunctions for the non-linear modelling; experiments in linear field completed the analysis. The performance of this kind of approach for non-linear analysis was investigated in Refs. [39] and [40].

On the view of the pioneering studies of [1], recently new experiments are presented in Ref. [41]; a circular cylindrical shell having a vertical axis and carrying a rigid disk on the top was excited from the base. It was found that, when the first axisymmetric mode is in resonance conditions, the top mass undergoes to large amplitude of vibrations and a huge out of plane shell vibration was detected (more than 2000 g), with a relatively low base excitation (about 10 g); no subharmonic response was detected. In this study, the presence of a payload on the top of

the shell made the system significantly different with respect to Refs. [1] and [36], both in terms of boundary conditions and inertial excitation.

In Refs. [42,43] a first theory was developed in order to create a model for the dynamic behaviour of the system analysed in Ref. [41]. More recently, [44–46], experiments were carried out to study the problem of the seismically excited shell carrying a top mass, in such series of works the coupling between the excited system and the shaker, that provides the base excitation, was modelled; results were quite promising, but the match between theory and experiments was not yet satisfactory. It is to point out that, one of the first studies regarding the general topic of shaker–structure interaction date back to the seventies [47].

Other experimental results are published in Ref. [48], it describes an experimental work focused on shells made of composite materials; they pointed out the inadequateness of the linear viscous damping models. A clamped free shell was considered; the principal parametric instability was analysed. It was found that experimental dynamic instability regions were wider than predictions of theoretical models; the conjecture made by the scientists was that the disagreement was due to the shell geometric imperfections. Such paper summarizes some of the experimental results published on a previous book [49] (see e.g. page 123, Fig. 2.23 gives an interpretation of the enlargement of instability boundaries).

In Ref. [50] a new model was developed in order to reproduce and explain experiments of Ref. [41]; the model combined the theory developed in Refs. [38] and [46] for which concerns the non-linear shell and the shaker interaction modelling respectively. A good matching between theory and experiments was found; moreover, the model gave some information regarding the cause of the violent phenomenon. On the other hand, some mismatches were still present: the theoretical model did not give non-stationary responses observed during the experimentation; the width of theoretical instability regions was significantly smaller than experiments.

The aim of the present paper is to improve the accuracy of the model developed in Ref. [50] and furnish a deep dynamic analysis of the phenomenon observed experimentally. Therefore, the present theoretical model is based on the approach proposed in Ref. [50], that is briefly summarized in the following sections. Q2

The non-linear Sanders Koiter shell theory is considered and the electromechanical shaker is modelled. The shell displacement fields are expanded using a mixed series (harmonic functions and orthogonal polynomials); geometric boundary conditions are respected exactly. The analysis is carried out in three steps: (i) linear analysis of the shell-disk model, which gives the eigenfunctions of the system; (ii) suitably selected eigenfunctions are used for a re-expansion of the displacement fields using the full non-linear version of the Sanders–Koiter theory; and (iii) the interaction with the shaker is considered by additional electro-mechanical equations.

The novelty of the present work with respect to the original paper [50] consists in (i) the displacement field expansion is much richer and includes the presence of conjugate (double) modes; (ii) geometric imperfections are considered; (iii) the analysis of the dynamical system is much more detailed as it includes bifurcation analysis and the use of continuation techniques for following stable and unstable periodic orbits.

A clear explanation regarding the onset of the instability observed in Refs. [41] and [50] is given.

2. The model

The aim of the model is to explain and reproduce with good accuracy the complicated phenomena found in Ref. [41] and

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