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Experiments on shells under base excitation

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ABSTRACT

The aim of the present paper is a deep experimental investigation of the nonlinear dynamics of circular cylindrical shells. The specific problem regards the response of circular cylindrical shells subjected to base excitation. The shells are mounted on a shaking table that furnishes a vertical vibration parallel to the cylinder axis; a heavy rigid disk is mounted on the top of the shells. The base vibration induces a rigid body motion, which mainly causes huge inertia forces exerted by the top disk to the shell. In-plane stresses due to the aforementioned inertias give rise to impressively large vibration on the shell. An extremely violent dynamic phenomenon suddenly appears as the excitation frequency varies up and down close to the linear resonant frequency of the first axisymmetric mode. The dynamics are deeply investigated by varying excitation level and frequency. Moreover, in order to generalise the investigation, two different geometries are analysed. The paper furnishes a complete dynamic scenario by means of: (i) amplitude frequency diagrams, (ii) bifurcation diagrams, (iii) time histories and spectra, (iv) phase portraits and Poincaré maps. It is to be stressed that all the results presented here are experimental.

1. Introduction

The complex dynamics of shells, under axial base excitation, is the object of the present work, which is part of a long research activity covering theoretical and experimental aspects of the shell behaviour. More specifically, here an intense campaign of experiments is presented in order to reveal the extreme complexity of simple structures such as circular cylindrical shells.

Predicting the mechanical properties of shells, panels and plates is one of the main concern of structural engineers; since shell elements present complicated stability behaviours, rich linear vibration spectra (high modal density), high sensitivity to perturbations and strong interactions with surrounding elements (fluid structure interactions, structure born sound).

Naïve operators are often convinced that any structural problem can be attacked using CAE technologies, for these people only the computational power appears as limitation. Nonetheless, experienced engineers are aware about the limits of traditional computational tools and more generally about limits of virtualization; lab testing appears almost mandatory when one is dealing with shell vibration, this is true *a fortiori* in the case of nonlinear vibration.

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Shell structures are likely to vibrate in resonance due to the high modal density, this can induce moderately large amplitude of vibration. Even though the amplitude is moderately high, shells can exhibit surprisingly strong nonlinear phenomena. This is well documented by a large scientific literature, mostly focused on modelling and much less on experimentation.

In Refs. [1–8] a comprehensive literature analysis of the western and eastern scientific production can be found, as well as details regarding theories and the most representative experimental findings.

Here a short description of the literature strictly related to the present paper is given. The literature review is subdivided into experimental and theoretical studies.

1.1. Experimental studies

In Ref. [9], 1977, one of the first experimental studies regarding shells subjected to base excitation was presented; an extremely violent dynamic instability, occurring when the vibration modes are parametrically excited in principal and secondary instability regions, was described. In Refs. [10,11] theoretical models were presented in order to give an initial explanation of several experimental results related to axially loaded shells; discrepancies between the theoretical forecasts and the experimental evidence were justified by imperfections (geometrical, material, loading) combined with the presence of conjugate modes that can split due to the perturbations. In Ref. [12] further experiments were presented about shells subjected to base motion (clamped free); both instability regions and nonlinear regimes were investigated; in particular, it was found a hardening behaviour for modes having two circumferential diameters ($n=2$) and softening type for $n>2$.

In Ref. [13] a new phenomenon of instability was discovered when a circular cylindrical shell connected with a rigid body on the top is excited by a base (axial) vibration. Again, a violent dynamic response was detected when the excitation frequency approaches the natural frequency of the first axisymmetric mode; out-of-plane (radial) huge vibration levels were measured, up to 2000 g (acceleration), with a moderately high base excitation (10 g). No subharmonic response was detected and a high frequency energy transfer was observed; conjectures about the possible excitation of high frequency shell-like modes ($n>1$) were made.

In Refs. [14,15,16] an intense theoretical and experimental activity regarding shells connected with rigid bodies under axial excitation was presented; the authors found interesting dynamic phenomena having chaotic character, beating phenomena as well as sensitivity to imperfections. They considered both isotropic and orthotropic models to simulate the experimental results. Moreover, they supposed that some of the complex dynamics found experimentally were due to the interaction between the vibrating structure and the excitation source; therefore, they developed an interactional theoretical model that considers both the shell and the shaker dynamics; by combining the structural and electro-dynamic equations they furnished an interpretation to their experimental results.

It is to be noted that, at our knowledge, the first publication regarding the modelling of shaker-structure interaction is due to Krasnopol'skaya [17], she was the first scientist who clarified the instability aspects due to such interaction.

In Refs. [18,19,20] the problem of shells connected with a top mass was analysed in detail both from a theoretical and experimental point of view. An accurate experimental modal analysis was used for setting up and validate a new semi-analytical modelling technique based on the Sanders–Koiter theory, capable of handling complex boundary conditions and nonlinear modelling; new experimental data were presented and compared with the new models, which allowed to clarify that the instability and the complexity of the response is due to a combination of effects: interaction between shaker and structure; parametric excitation; high modal density and presence of double modes.

1.2. Models

Regarding the theoretical and numerical studies, the scientific production is huge; for the sake of brevity and completeness, here a short list of papers strictly related to the present work is commented.

Since the second half of the last century several papers attacked the problem of shells under axial periodic loads. Initially the research was focused on linear modelling, see e.g. Refs. [21–25], the analysis of parametric stability was the first step for interpreting and explaining experiments. Such studies were extremely important as a starting point for further more sophisticated models; for example it was clarified that neglecting Poisson's effect in the axisymmetric bending vibration, i.e. considering only the membrane approach for in-plane stresses, can lead to highly inaccurate results, see also Refs. [26–33].

In Refs. [19,20] a theoretical model, based on the Sanders–Koiter nonlinear theory combined with the electro-dynamic shaker model, clarified that important non-stationary responses can be predicted if: (1) the energy source is not assumed as infinite (exciter modelling); (2) a nonlinear shell model is considered; (3) complex modal interactions are allowed, including conjugate modes activation.

Recent models correlated with the present work were published in the following papers: in Ref. [34] a theoretical approach based on Reissner–Naghdi's shell theory was presented and solved using a mixed series expansion similar to Refs. [18–20], this approach considers a modified variational principle, the work was limited to linear vibrations and no experiments were presented; in Ref. [35] a theoretical approach based on the Von Kármán nonlinear theory and the first-order shear deformation theory was presented, the study was limited to simply supported shells, no experimental results were presented; in Refs. [36] and [37] classical and higher-order shear deformation theories with von Kármán type nonlinearities were used for studying sandwich plates in large amplitude regime, Chebyshev polynomials were considered, a full experimental analysis was published.