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Statistical characterisation and modelling of random geometric imperfections in cylindrical shells

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ABSTRACT

Thin cylindrical shells are the most prevalent and important structural component of vessels across the process industries. Such structures are prone to accidental buckling due to inadvertently induced vacuum. Minor deviations in the nominal geometry of the shell can affect the apparent initial buckling load. One common deviation is that the radius of the vessel is not constant but rather varies randomly with location on the shell. This paper presents extensive experimental data permitting a full statistical characterisation of defects of this nature. The data was obtained from detailed measurements of 39 replicate test vessels at the laboratory scale. Both amplitude and frequency content of this type of imperfection is quantified. Furthermore a methodology whereby the variation in radius is characterised as a two dimensional random field is outlined. An algorithm to generate realisations of this field is developed and the output is shown to be consistent with the measured results.

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1. Introduction

Thin cylindrical shells are very efficient structures and have a wide range of uses. They are especially prevalent in the process industries forming the major component of storage and reactor vessels. Conventional mechanical design that is based on limiting the maximum membrane stress in the vessel, leads to the adoption of thin-walled vessels. Thin-walled, large diameter vessels are prone to buckling, either local or global, due to compressive loading in the axial or radial direction or both. This mode of failure, if it occurs, tends to be catastrophic resulting in complete destruction of the vessel. Resistance to buckling of these vessels is sensitive to magnitude of minor deviations in geometry from the ideal shape. These geometric imperfections can comprise any geometrical feature of the shell which alters it from a perfect cylinder. These can include out-of roundness, ovality [1], wall thickness variation [2], welded seams [3] or other random geometric imperfections such as dents [4]. Fundamentally there is the premise that the pattern of imperfections in the shell is as a result of the interaction between the material of construction and the manufacturing process that is adopted.

It is now accepted that the existence of these initial geometric imperfections can help explain the discrepancy between theoretically predicted critical buckling loads and those measured experimentally [5]. Furthermore because of the intrinsic random and unpredictable nature of these imperfections, varying from vessel to vessel, there will be scatter or dispersion in the structural response of nominally identical vessels. Hence characterisation of these imperfections performed on a statistical basis could then inform reliability-based structural design of these vessels, [6]. This should prove superior to conventional deterministic design with its reliance on conservative factors of safety to ensure reliability of the whole population.

This paper will report on work that was carried out to measure the geometric imperfections in laboratory scale steel cans (having a nominal 5 l capacity) that are representative of industrial-sized vessels in the food, pharmaceutical and biotechnology sectors. Section 2 develops the theoretical basis for the statistical characterisation of the measured imperfections. In Section 3 the measurement rig is described and the measurement procedures are outlined. Section 4 presents the analysed experimental data, the characterisation of the imperfections and the residual random imperfection data obtained by the removal of any systematic trends. The two-dimensional random field representation of the data is then developed and an algorithm is generated that enables numerical realisations of the field. Section 6 concludes the paper.

2. Theory

2.1. Random field description

The primary imperfection in the shells under study was found to be the departure of vessel radius from the nominal cylinder

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Nomenclatures

A_n	Fourier cosine coefficient for circumferential auto-correlation waveform,
a_n	Fourier cosine coefficient for circumferential radius waveform, m
a_x	Radial deviation realisation (axial direction) coefficient
a_θ	Radial deviation realisation (circumferential direction) coefficient
B_n	Fourier sine coefficient for circumferential auto-correlation waveform
b_n	Fourier coefficient for circumferential radius waveform, m
b_x	Radial deviation realisation (axial direction) coefficient
b_θ	Radial deviation realisation (circumferential direction) coefficient
L	Vessel length, m
n	Number of full circumferential waves (Fourier frequency harmonic number)
R_r	Two dimensional field auto-correlation function
Rr_X	Axial auto-correlation function
Rr_Θ	Circumferential auto-correlation function
$S_r(\omega_x)$	Normalised mean square spectral density of radius in the axial direction, m
r	Vessel radius, m
x	Axial position (coordinate), m
x_L	Auto-correlation lag distance, m
β	Axial auto-correlation parameter, m^{-1}
η_x	Axial de-correlation length, m
η_θ	Circumferential de-correlation angle, rad
θ	Circumferential position (coordinate), rad
θ_L	Auto-correlation circumferential lag angle, rad
σ_r	Standard deviation in radius, m
σ_{rx}	Standard deviation in radius in the axial direction, m
$\sigma_{r\theta}$	Standard deviation in radius in the circumferential direction, m
ω_x	Circular frequency in Fourier domain (axial direction), rad/m

radius. The theory of Gaussian random fields may be applied to capture the spatial variability in radius both within any given vessel and between vessels, [7]. Specifically, the vessel radius, r is treated as a two dimensional random field. This means that the radius at any location depends on the axial coordinate, x, and the circumferential coordinate, θ, as determined by some random function, f.

$$r(x,\theta)=f(x,\theta) \tag{1}$$

A number of simplifying assumptions are employed to determine the nature of the random function of Eq. (1). It is assumed that the variation of the imperfection in the axial and circumferential directions are independent, [8]. This implies that the total random deviation in the magnitude of the radius at any point is the sum of the random deviations associated with the axial and circumferential directions, respectively.

$$r(x,\theta)=r_x(x)+r_\theta(\theta) \quad 0<x<L \quad 0<\theta<2\pi \tag{2}$$

An important distinction between random deviations in radius in the axial and circumferential directions is that for the latter, the following constraint must be satisfied:

$$r_\theta(0)=r_\theta(2\pi) \tag{3}$$

No such condition acts in the axial direction between $x(0)$ and $x(L)$. Another consequence of independence is that a fully separated correlation structure may be defined for the field auto-correlation function R_r. Furthermore, the random field is taken to be homogeneous in that the probabilistic dependence between radii measured at any two points on the surface only depends on the relative distance (also known as separation or lag distance) between these locations, (x_L and θ_L) and not on absolute position on the vessel surface, (x and θ) [9]. Taking a zero mean datum, the random field can be defined by two independent one-dimensional correlation functions:

$$R_r(x_L,\theta_L)=R_{rX}(x_L)\bullet R_{r\Theta}(\theta_L) \tag{4}$$

The key task is to identify the nature of the correlation functions R_{rX} and $R_{r\Theta}$, respectively and to obtain their parameters that will define the correlation distances in each direction. Correlation function identification must primarily come from analysis of the measured data informed by physical reasoning. A study of the literature reveals that correlation functions that have been employed to model imperfections in structures include harmonic, exponential [10], exponential-cosine, exponential-linear and delta functions (white noise) [9,11].

2.1.1. *Correlation structure in the axial direction*

Fig. 1 illustrates the experimentally measured correlogram (the correlation coefficient versus the lag distance) for a typical vessel in the axial direction. The structure of the data is very similar to that reported by Schenk & Schueller [8]. One potential correlation function, employed in the literature, and that agrees with the correlogram is the product of an exponential and linear term [12]:

$$R_{rX}(x_L)=e^{-\beta x_L}(1+\beta x_L) \tag{5}$$

where x_L is the axial separation or lag distance and β is the axial auto-correlation parameter. Eq. (5) describes the variation in the auto-correlation function (normalised auto-covariance function) in the axial direction. It implies the level of correlation between radii falls monotonically with increasing lag distance in the axial direction moving from one end of the vessel to the other. There is a point of inflexion in the function which means the rate at which the degree of correlation falls off has a maximum value. (Note that if Eq. (5) consisted of a single exponential term without the

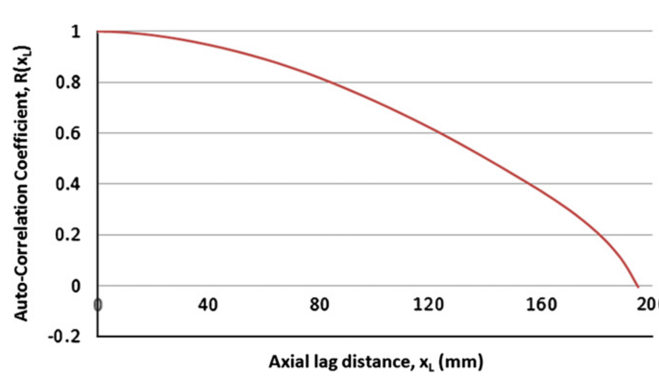

Fig. 1. Auto-correlation for radial deviation in the axial direction for a typical cylinder.

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