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Finite Element Modelling of Steelpan Acoustics

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Abstract

In this paper the Finite Element Method is used to model acoustic vibrations of steelpan[1] shells. The steelpan surface is characterized as a three-dimensional compound shell, comprising notes (surfaces with reverse curvature) on a concave ellipsoidal surface attached to a cylindrical shell (the skirt). In this model note and inter-note surfaces are defined by geometric parameters which can be varied to define complex surface geometries. The geometric mesh model is used develop Tenor, Cello and Bass steelpans instruments and a 3D Finite Element shell vibration algorithm is used to demonstrate their vibration characteristics. Modes shapes and frequencies of the composite shell structures are computed for typical configurations of note and skirt geometry. The model demonstrates that there exist many composite natural modes of a playing surface involving the interaction between two or more notes. In addition, it is found that the frequency range of mode shapes associated primarily within skirt vibration overlaps with the musical range of the notes underscoring the potential for "skirt-note" coupling. The degree of frequency overlap was found to be largely dependent on skirt length and configuration.

1 Introduction

Since its discovery some 70 years ago in Trinidad and Tobago steelpan scientists and craftsmen have analyzed the acoustic behaviour of steelpans primarily through model prototypes; through making of the instruments themselves.

Analytical and/or numerical models have not been widely used in the study steelpans. The work of Dennis [1] is perhaps the first documented work on steelpan acoustics where analytical models of plate vibration were used to approximate measured mode shapes and frequencies of individual steelpan notes. It is the work of Achong however, that perhaps most embodies the use of mathematical modeling to study the acoustics of the steelpan. This work was presented through a series of papers from 1996 through 1998 [2-4]. The title of the series aptly describes his methodology, "*The Steelpan as a system of non-linear mode localized oscillators:*" In this work, the steelpan was modeled as a system of multiply connected non-linear springs using analytical expressions for their transient vibration behaviour and numerical techniques for the solution of the resulting equations. Vibratory modes of steelpan shells have also been studied by Rossing *et. al.* [5, 6] using electronic holographic techniques.

In this paper I shall report on the status of current research at the University of the West Indies (UWI) on the development of an integrated Finite Element (FEM) and mesh generation models, in the analysis of the acoustic vibratory modes of steelpan shells. At this stage of its development the numerical model is demonstrated in the analysis of the natural vibratory modes (eigen modes/frequencies) of two lower order (frequency) instruments of the steelpan family, the Tenor-Bass and Six Bass**.**

2 The Finite Element Model

2.1 Finite Element Modelling

The finite element technique involves the division of a domain into discrete parts (elements), where each can be uniquely described in terms of its material and geometric properties (mass density, elastic modulus, thickness, curvature, size etc.). The element in this case is a thin shell of variable 3D curvature defined only at its nodes as illustrated in Figure 1. Dynamic equilibrium equations of 3D continuum mechanics are then implemented over each element and the resulting equations are assembled to "reconstruct" the complete surface. Depending on the formulation, displacements, stresses, rotations, etc, can be obtained through the solution of the resulting set of algebraic equations. In the case of modal analyses, the frequencies (eigenvalues) and their corresponding displacement fields (eigenvectors) are used to construct the mode shapes of the vibrating surfaces.

The finite element implementation of the vibration analysis of thin shells follows the formulations of Bathe [7] and Lee [8]. Reissner-Mindlin assumptions are adopted for the shell elements where these are modeled using doubly curved three-dimensional linear elastic thin shells, as illustrated in Figure 1. 9 noded iso-parametric elements are implemented with six degrees of freedom per node, where, u_x, u_y, u_z, θ_x, θ_y, θ_z, are the displacements and rotations in the principal orthogonal directions.

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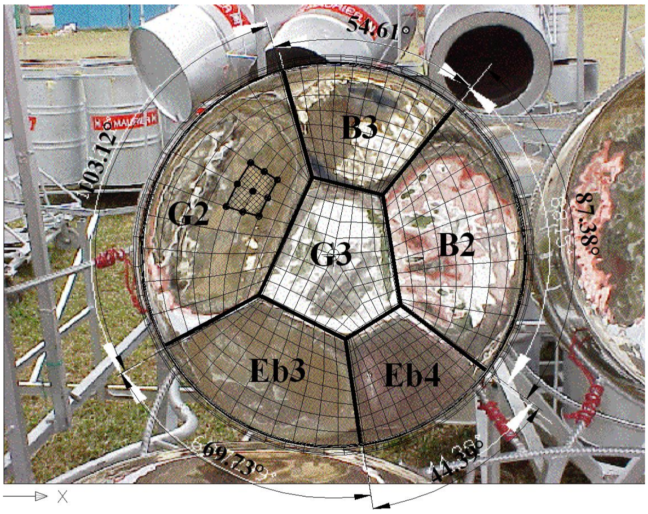
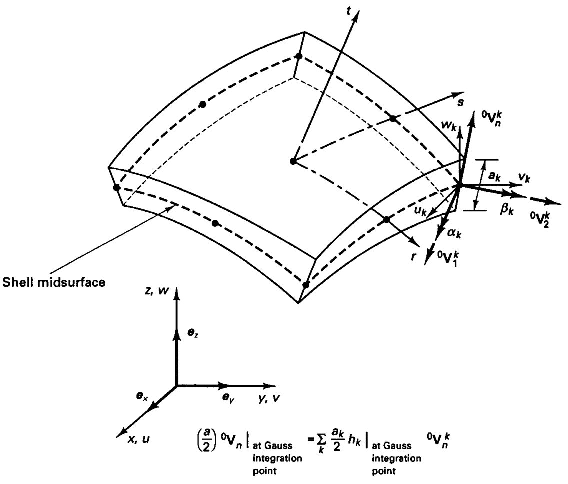
[1] Steelpan (also known as steeldrums or pans, and sometimes collectively with the musicians as a steelband) is a musical instrument and a form of music originating in Trinidad and Tobago. Steelpan musicians are called pannists.





Nine-node shell element; also, definition of orthogonal $\bar{r}$, $\bar{s}$, t axes for constitutive relations

Fig. 1 Finite Element idealization of a typical shell element.

2.2 The Steelpan Shell: the steel drum

The steelpan is derived from the steel drum by sinking its initially flat bottom surface into an approximately concave ellipsoidal surface. Note areas comprising surfaces of reverse curvature are then founded within this ellipsoid where their boundaries are generally marked by grooves (such grooves do not necessarily describe the principal musical note surface). The cylindrical surface of the drum is then cut to a desired length to form the skirt. In the case of bass instruments the full cylindrical form is left intact and in some cases the original top surface of the drum is cut to achieve an annular disc, as illustrated in Figure 1. Some tuners fashion this disc to invoke an acoustic resonator effect, whereas others just treat it as a bottom skirt "stiffener". The cylindrical surface (skirt) of tight head drums generally includes two rolling hoops whereas open head drums normally include three [9]. The American standards for steel drums [9] contain their geometric specifications for use as shipping containers. As indicated in a previous publication [10] the drum itself is in transition and configurations that are currently available that are not always included in the current ANSI standard. In this paper the dimensions and geometric configurations of the ANSI MH2 1997 standard shall be assumed.

2.3 Mesh Generation Modelling

In three-dimensional (3D) continuum finite element analysis of thin shells the domain is defined as a set of contiguous curved surfaces. These surfaces are defined only at discrete points (x, y, z in Cartesian coordinates) and constructed from analytical expressions of standard surfaces or interpolated from measured data. The process of constructing such model surfaces over a body (domain) is termed mesh generation. Although automatic mesh generators proliferate in finite element practice, few if any are appropriate to the requirements steelpan shells.

Mesh generation algorithms appropriate to steelpans can be considered as three dimensional numerical templates and likened to the note shape and drum-sinking templates traditionally used by steelpan tuners and makers [10, 11, 12]. These steelpan making templates typically define the two dimensional plan forms and sections of the foundation structure of the instrument, where the final note surface configuration is typically formed as part of the tuning process. The concept of a template and a mesh can also be appreciated from Figure 1, which illustrates a typical FEM mesh over a 6 note Tenor Bass by Bertie Marshall [10].

The foundation shapes used for the steelpan shell are simple two and three-dimensional forms that include cylinders, spheres, ellipsoids, paraboloids and sinusoids. For example; the sunk surface of a tenor steelpan approximates an ellipsoid defined by: $r^2/a^2 + z^2/b^2 = 1$, where, a = 315 mm, b = 385 mm and r = 288 mm (where a and b are the major and minor principal radii respectively of an ellipse in the r-z plane, and r is the radius of the drum in the x-y plane). In addition the rolling hoop on the steel drum can be modeled in section as a sine waveform of wavelength λ = 24 mm and amplitude A = 6 mm.

In the current implementation, note areas are modeled by reversing the sunk curved surface within the grooves and rim boundary, representing an un-tuned note surface. Expressing the surface in a fully parametric way enables models to be "built" rapidly and simply. This facilitates investigation of the effect of geometric configuration on the acoustic characteristics of the instrument (sensitivity analyses).

The approach to geometric modeling of the steelpan surface follows the following general methodology.

(1) Identify the foundation member surfaces that define the steelpan shell.
(2) Develop parametric equations that describe these basic forms and store them as objects (C^{++} type).
(3) Implement algebraic equation solvers appropriate to the solution of algebraic systems of equations derived from the intersection of these surfaces.
(4) Develop a sub-domain coordinate system and nomenclature for the definition of note shape and geometry. For example a pole is defined as the outward unit normal vector to the surface at its

point of maximum curvature, from which an entire note of any form can be constructed.

Compound surfaces formed in this way would typically possess sharp geometric discontinuities along intersections. The entire surface is then smoothed using Non Uniform Rational B-Splines (NURBS) to achieve the final smoothed surface. The algorithm is written in the C^{++} and in its current state this program can successfully develop Basses, Tenor basses (conventional and Marshall styles) and 4 Cellos. Typical configurations of these are illustrated in illustrations that follow.

3 Model Analyses and Results

3.1 Tenor Bass Shells

Steelpan shells of conventional tenor bass and six bass instruments are analyzed. The geometric configurations of the drum are consistent with the ANSI MH2 1997 [9] standards using an all 18 gauge drum. In each case the program is used to compute the first eight mode shapes and frequencies of an un-tuned shell with an assumed surface geometry as described previously.

The current study is directed toward investigating the following:

(1) The effect of skirt length on frequencies and mode shapes.
(2) The effect of rolling hoops on frequencies and mode shapes.
(3) The existence of complex modal shapes, which involve the interaction between the notes themselves and note-skirt coupling.

The Bertie Marshall Tenor Bass set comprises four steelpans of six notes each [10]. This set of instruments cover the range G_2 - D_4 (98 – 293.66 Hz).

3.2 Modal Analyses

In these analyses only the first (left hand side) instrument note template configuration is illustrated using five different configurations of steelpan shell (different skirt lengths). These analyses are as follows:

(i) The playing surface only, with a rigidly supported rim.

(ii) The playing surface with a 550 mm skirt cut above the first rolling hoop.

(iii) The playing surface with a 650 mm skirt cut immediately below the first rolling hoop.

(iv) The playing surface with a 760 mm skirt cut below the first rolling hoop, to the middle of the drum.

(v) The playing surface with a 879 mm skirt cut below the second rolling hoop.

The results of theses analyses are illustrated in Figures 2 through 6.

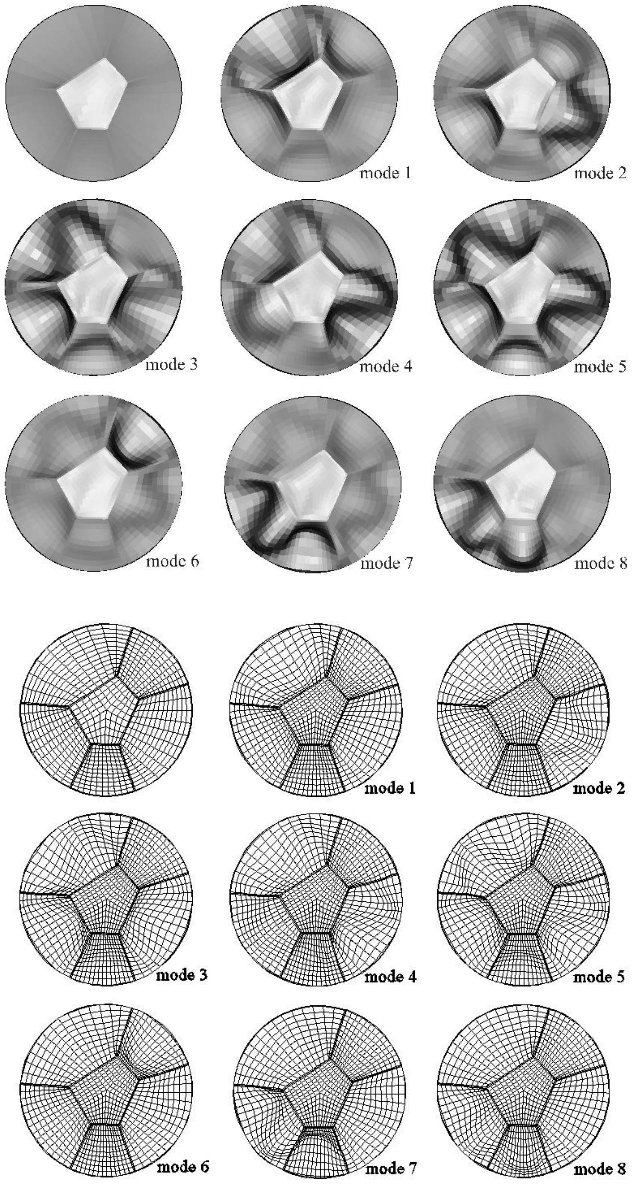


Fig.2 Mode shapes of the playing surface only, rigidly supported on edges. Interpretation of composite mode shapes (dominant) as follows:

Mode 1: G2 [0, 0]

Mode 2: B2 [0, 0]

Mode 3: G2 [1, 0], B2 [0, 0], Eb3 [0, 0]

Mode 4: G2 [1, 0], B2 [1, 0], Eb3 [0, 0]

Mode 5: G2 [2, 0], B2 [2, 0], Eb3 [0, 0], Eb4 [0, 0

Mode 6: G2 [2, 0], B3 [0, 0], B2 [1, 0]

Mode 7: Eb3 [1, 0], Eb4 [0, 0]

Mode 8: Eb3 [1, 0], Eb4 [0, 0]

3.3 Playing Surface + Skirt models

In the following figures the modes of the compound shell using varying skirt lengths are illustrated, skirt-surface interactions are noted.

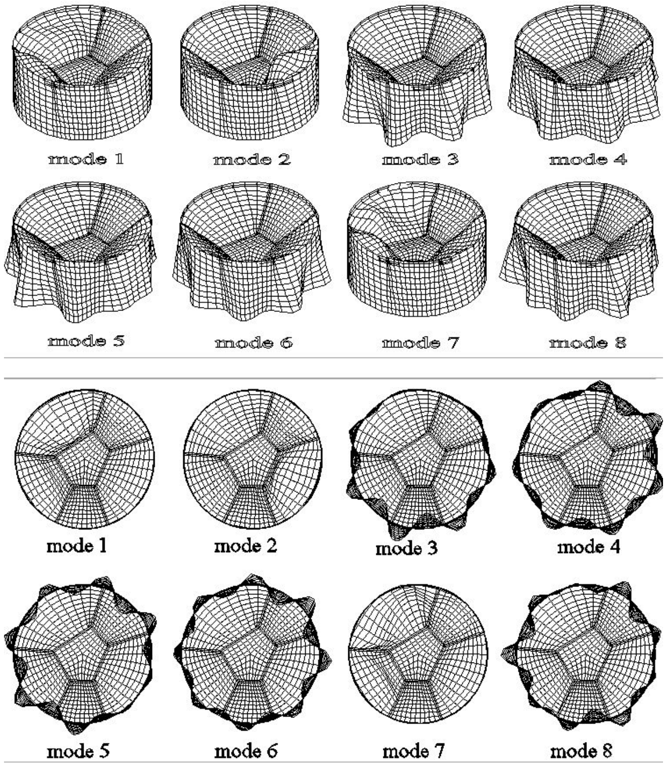


Fig. 3 In this model skirt length 550 mm, the 1st (G2 [0, 0]), 2nd B2 [0, 0]) and 7th (G2 [1, 0]) modes reside in the playing surface all other modes are within the skirt. The skirt modes are significant in that they are non-symmetrical and fall within the frequency range of the instrument notes.

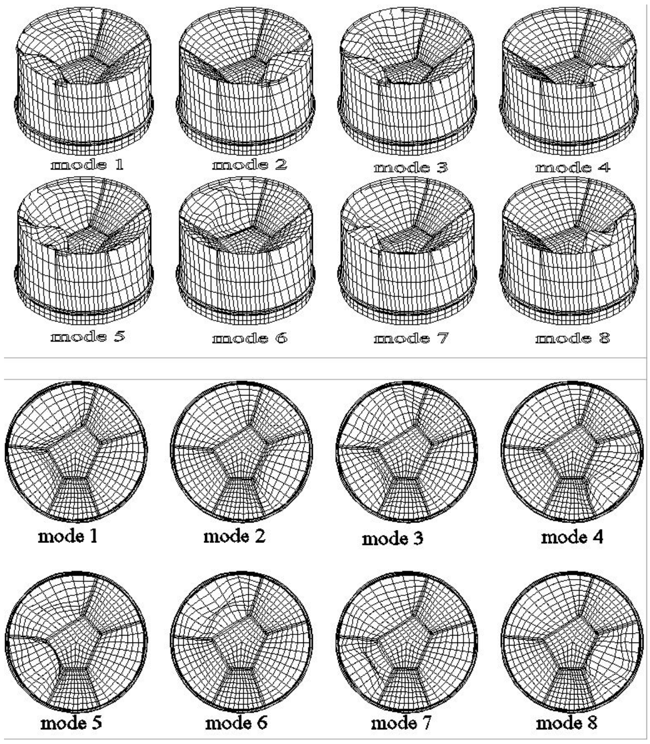


Fig. 4 In this model of skirt length 650 mm all modes reside in the playing surface. The rolling hoop appears to provide sufficient stiffness to the skirt to invoke its vibratory modal frequencies out of the range (higher) of the played surface notes.

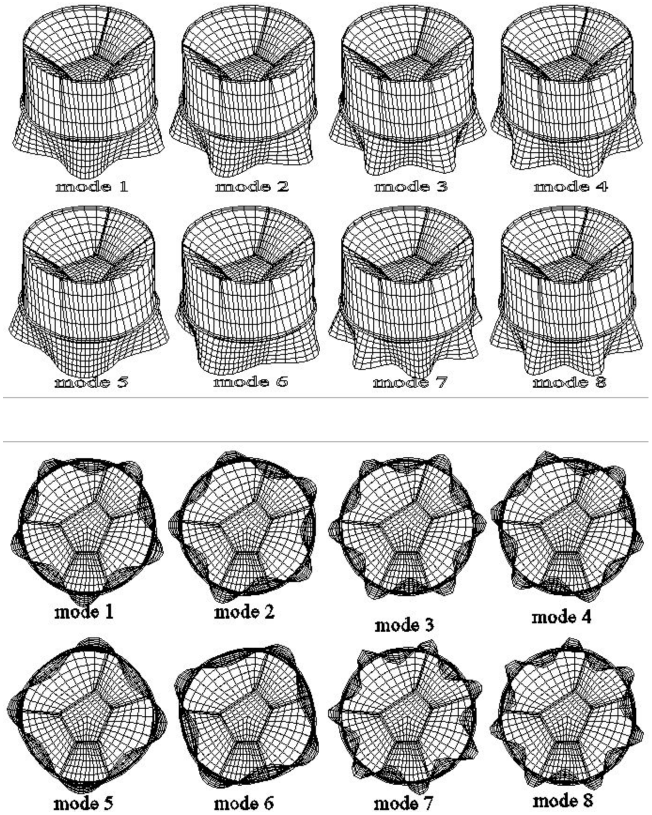


Fig. 5 In this model of skirt length 760 mm all modes reside within the skirt section below the rolling hoop. The rolling hoop appears to provide sufficient stiffness to the skirt to invoke its vibratory modal frequencies out of the range (higher) of the played surface notes.

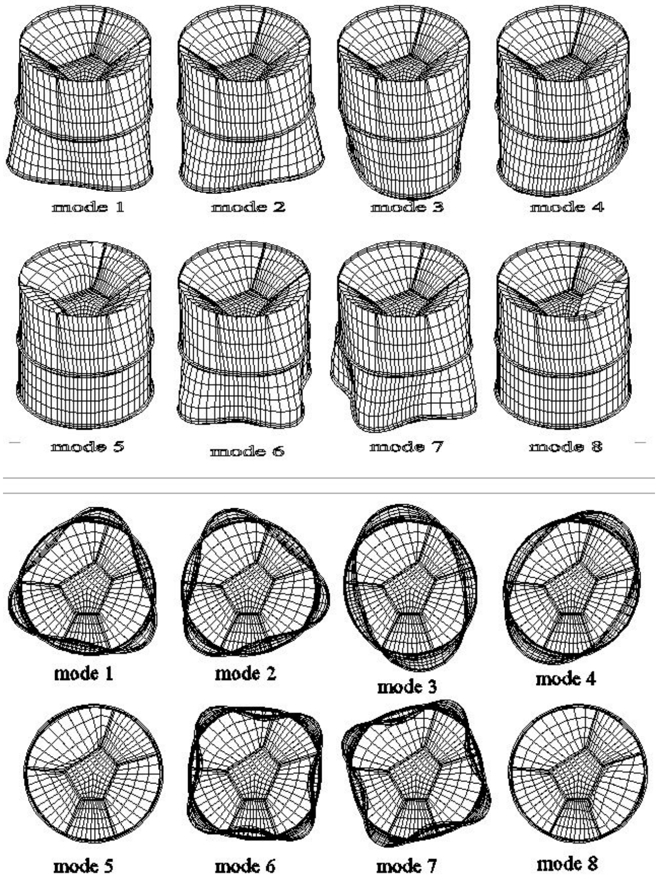


Fig. 5 In this model the skirt length 879 mm includes the two rolling hoops, although stiffer than model 2, most of the skirt modes appear to reside within vibratory modal frequencies of the surface notes

4 Future Research

This modeling effort is in its infancy and the results to date demonstrate the potential of the FEM to inquire into the complex world of steelpan acoustics. Future work in this field is required and shall include:

(i) Modification of the mesh generation algorithm to model the vibratory characteristics of "tuned" note surfaces.

(ii) Implementation of the nonlinear dynamical equations of continuum mechanics to adequately interpret nonlinear transient analysis, including impact analysis.

(iii) Implementation of structural/shape optimization techniques to facilitate the study and development of the "ideal" note shape in respect of the desired tonal structures of note. This is in essence an inverse problem similar to that investigated by Achong [3].

(iv) It is expected that algorithms demonstrated in the current paper would be used to investigate and calibrate the recently developed and patented ***G Pans*** in Trinidad and Tobago.

5 Conclusion

(a) The use of the FEM is demonstrated in the analysis of steelpan shells. Of particular interest is the ability of the method to model detailed characteristic geometric features of the drum, these include rolling hoops, rims, stiffening rings and changes in shell thickness. In addition, the spatial and non-uniform distribution of material properties can also be handled with equal facility.

(b) The modal analyses of the shells investigated demonstrate that many of the vibratory modes of the composite shell surface are associated with frequencies, which are typically "non-musical". However, in all cases these are sufficiently close to the musical note frequency to invoke the undesirable effects of coupling. This is more likely to occur where the modal frequencies of the shell overlap with those of the musical note range of the particular instrument.

(c) The effect of the rolling hoops on the vibration characteristic of all the three instrument types analyzed is clearly demonstrated. The results suggest that the hoop structure is sufficiently stiff to act as a point of relative fixity, from which skirt modal deformations are supported. The hoop configuration therefore can act as a decoupling device or filter of the skirt vibrations from the notes in the playing surface (underscoring their serendipitous role in the acoustics of the steelpan shell, nee the steel drum).

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