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Using Data Sonification to Enhance Building Structures CAI

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INTRODUCTION

Although sound is now extensively used to enrich multimedia applications in the form of simple audio signals, earcons, musical passages and speech, it has unfortunately been under-utilized as a means of data representation. Sound, having many characteristics which enable it to convey multi-dimensional information, provides a broad channel for dynamically presenting data in a learning environment. This paper looks into how teaching concepts of building structures to students of architecture and engineering through computers and multimedia can be enhanced by enlisting the use of appropriate sound parameters. Sound is useful in presenting redundant or supplementary information such as in portraying building structural response to static and dynamic external loading. This process of audiolization, which refers to the use of sounds to present data, can alleviate much of the cognitive load that usually burdens visual displays and has been used to some degree of success in various studies on scientific representation. Where appropriate, audiolization can be synchronized to more established visualization processes to provide more effective multi-modal multimedia systems for the study of building structures.

For professionals in the field of structural engineering, the use of computers for building structural analysis and design has always been effective and virtually indispensable. Robust computer software are usually tailored for them to serve as tools for rigorous cycles of structure assessment and refinement. However, the needs of students of building structures are very different. In order for students to gain a better appreciation for the bottom line end results of structural analysis, it would be beneficial for them to first "experience" structural behaviour. The multi-modal multimedia system of this project is primarily geared to be a learning tool providing students with a setting for real-time progressive exploration rather than just a method for structural assessment of buildings. For instance, observing the various factors influencing the time-varying progressive response of a building structure to continuously incremented loads or dynamic excitation provides significant insight which is just as valuable as the final assessment of its structural adequacy. Observing the temporal progress of structural performance can be achieved through a highly interactive multi-modal & multimedia system that not only allows observation but also extensive control of the various parameters of structural action.

Structural behaviour involves time-varying multivariate data. Static and dynamic external loading, mass, material, configuration, different components and modes of stress, deformation and vibration all influence and/or characterize structural response. Creating an environment where students have immediate control over these various parameters while observing structure response in real-time requires that compact, sufficiently reduced computations be made and that multi-dimensional information be conveyed simultaneously. The use of both the visual and auditory channels in the interface makes it possible to convey a greater bandwidth of information than would be possible through a single sensory modality.

1.0 STRUCTURAL BEHAVIOUR THROUGH ACTIVE MULTIMEDIA

To portray the states or conditions of a building structure as a function of several user-controllable factors through time, sufficiently quick and reduced computations need to be embedded thereby requiring that the multimedia documents be active. Unlike animation or video which are basically sequences of fixed states, these active multimedia documents need to respond tightly to users actions. Each state of a building structure requires some form of recomputation, it being a function of numerous parameters to be placed at the control and direction of the user. Without the computations, the alternative of developing and relying on a database containing all conceivable permutations of state would, for even the simplest structure, be extremely enormous and inflexible.

In such a highly interactive and tightly user-controlled interface, granularity, or the size of the most basic component which constitutes the information conveyed, becomes a key issue. It would be ideal if all the relevant parameters defining the state of a building structure are continuously variable throughout their ranges. This is however difficult to implement at the interface and may be unnecessary or even undesirable in some instances. As this project involves learning modules, the perception of resolution and absolute value of the various parameters involved are less crucial than the perception of their relationships and progression. The extent of granularity is therefore governed mostly by issues of audio-visual perception and the resolution permitted by the media devices.

2.0 STRUCTURAL DATA SONIFICATION AND VISUALIZATION : MIX AND SYNCHRONIZATION

The visual interface has long been an important tool for conveying structure geometry and response. Graphical visualization tools for structure deformations as well as internal force and stress distributions have been utilized extensively and are extremely useful in evaluating the overall adequacy and efficiency of structures. However, the enormous amount of information available in the visual mode although rich, can result in a saturated screen display and cognitive overload. This is particularly apparent when one is observing the temporal progression of various stress/strain components of a structures response. “Experiencing” structural behaviour becomes difficult as understanding is only achieved after "compartmentalizing" the structure in terms of space and time for analysis and subsequent correlation and synthesis. This may be acceptable when dealing with largely independent data, but most aspects of structural behaviour are significantly coupled and intertwined and better presented simultaneously in order to develop a better understanding of their relationships.

The role that audiolization can play in providing additional and redundant information to the visual interface is significant. The combined use of sight and sound when utilized concurrently and in resonance when observing simulated structural behaviour makes it possible to digest large amounts and various patterns of "fleeting" information. This is particularly so when dealing with temporal variations and spatial distributions of stress, deformation and vibration. Sounds, where appropriate and advantageous, can replace some of the traditional visual representations thereby decongesting the graphical interface and more efficiently manage the massive influx of information.

One crucial issue relating to the combined and synchronized graphics-sound interface is the apportioning of conveyed information between the visual and sonic bands. In other words determining which information is to be conveyed visually and which is better presented through sound. In concocting this mixture, careful consideration is given to the nature and characteristics of each sensory modality as well as the appropriateness of representation, in an effort to achieve an effective concerted presentation of information. The visual display is capable of not only conveying spatially defined data but also complex information. Auditory displays on the other hand are ideal for imparting short, simple time-varying data. As described earlier, the multimedia system in this project deals with very finely discretized events which present multi-dimensional information progressively through time. The fine granularity and temporal nature of the imparted data makes the use of sound display essential to the overall presentation of information.

A structure's deformation, vibration modes, and buckling or failure mode are most naturally shown via the visual interface. These are after all the visible aspects of the structures response. The non-visible aspects of structural behaviour such as the different stress components and damping can and have normally also been represented in graphical form. However, representation of these non-visible characteristics and behaviour can just as naturally be undertaken by the audio interface. The joint visual-audio interface becomes most effective when time-dependent behaviour is observed in real-time. In such cases streams of information have to be processed by the user instantly in order to gain a cohesive understanding of what is happening. It is not possible in many cases to overload a single sensory modality without fragmenting it into 'snapshots' of information for subsequent review and analysis later on.

One method of implementing audiolization is to establish a means of mapping the various structural data to different sound parameters that are to represent them. The ability of a sonic parameter to characterize particular structural data is a useful basis for assignment of representation. Furthermore, the ranges and limits of each sonic parameter have to be compatible with that of the structural data it represents. The granularity of the sonic parameters must be sufficient to allow the user to effectively discern changes or progression.

Sound parameters selected for use in the project include pitch, tempo, duration, attack and decay, vibrato, timbre, dynamics and spatialized audio. Pitch typically refers to our perception of sound of a fundamental frequency and timbre. Tempo refers to the relative speed of the beats of a musical passage. Duration is the relative length of time of a discrete sound. Attack is the rate at which a sound grows to maximum loudness while decay is the rate at which a sound dies away. Vibrato results from a slow flutter in amplitude of a sound. Timbre commonly refers to the musical complexity or richness of a sound. Dynamics is the relative loudness or softness of sound. Spatialized audio refers to the location of sound or the direction of its movement.

In addition to the continuous or regular representational sound, short audio signals superimposed but clearly distinct are useful for emphasizing discontinuities or important occurrences in structural behaviour such as the onset or termination of certain structural phenomena.

3.0 GENERAL STRUCTURAL DATA SONIFICATION

Descriptions of specific computer-assisted-instruction modules enhanced with structural data sonification is described in the latter part of this paper. The structural parameters used are common among these modules and as a result the models for auditory data representation as applied to all of them is consistent. This consistency is essential to establish conventions to some extent. Adherence to these conventions is important to eliminate the need for users to accustom themselves to the various sound parameter representations each time they move on to another module or application. The different structural parameters that are characterized by sound include stress density, local stress components, stiffness, mass, damping and natural frequency.

3.1 Stiffness, natural frequency and damping of a structure

The stiffness of a structure (or its subsystem or elements) may be represented through tempo. The rate at which steady pulses of sound are emitted can give an indication of its relative stiffness. As loadings are gradually incremented, one after another, critical portions of the structure reach their elastic limit and behave plastically, each resulting in formation of plastic zones in frames or the initiation and growth of yield lines in plates. This results in subsequent reduction in the stiffness of the structure. This process is portrayed by a proportionate decrease in tempo or the slowing down of sound pulses. This may be thought of as a healthy heartbeat that slows down as the structures resistance decreases. In the case of plate structures the reduction in stiffness (represented by the slowing down of tempo) after initiation of first yield line is continuous over time whereas frame structures could follow a piece-wise linear reduction in stiffness with points of discontinuity at each formation of a plastic hinge or zone. When loads are large enough to form a collapse mechanism in the structure, the overall stiffness of the structure is nil. The sound changes from pulsating to a single continuous sound with no basis for tempo.

A structures natural frequency has a strong and direct relationship to its stiffness. It is therefore useful to map values of tempo (which represents stiffness) such that it is scaled to the natural frequency of the structure (substructure or element). This becomes particularly useful when dynamic response behaviour is being observed. The user can ingest the sonic rhythm of the structures natural frequency while visually observing its' actual vibration (at perhaps another frequency resulting from external dynamic load excitation). Their juxtaposition together other aspects of structural response presents relevant insights to structural behaviour.

Damping is vital to controlling vibration in structures. It can dissipate much of the energy imposed by dynamic loads and results from hysteresis, viscosity, friction and yielding, energy transfer to ground, support action and air resistance. As damping is basically energy dissipation it is appropriate to represent it in sound with decay. The sound pulses which indicate the structures' stiffness would also exhibit some degree of decay portraying the degree of damping in the structure.

3.2 Stress density and local stress components

The density of stress throughout the structure and/or local stress components are represented by pitch and volume. Increasing stress density is characterized by rising pitch and volume. Furthermore, the resolution of the hierarchy of a structure into system, subsystem, component or point can be distinguished through the use of various timbres as well as distinct registral ranges. The higher up the hierarchy of the structure (towards the whole structure) the richer the timbre of sound is used. Furthermore, the use of two registers clearly distinct from each other helps the user to further discern position in the structure hierarchy. The sound range portraying the stress density of whole structural systems or subsystems occupy a low register while that of components or points are assigned a higher registral range.

Both temporal changes as well as spatial distributions of stress can be monitored. In the case of vibrating structures which undergo fluctuating stress reversals the sound associated with the stress can be made to monitor just the peak amplitude of the stress or represent it more faithfully by means of vibrato. The sound would flutter within the range of the stress reversal and at the same frequency.

3.3 Signaling attention to structural phenomena

Messages in the form of earcons are superimposed at certain instances to provide signals of relevant events in the process of structural behaviour such as at the formation of each plastic zone, initiation/end of yield lines, occurrence of buckling, locking in of vortex shedding, etc. Visual cues acting along with the earcons provide locational, directional and numerical information.

4.0 PERCEPTION OF SOUND REPRESENTED DATA

The sounds produced for the data representation described above will consist of simultaneous auditory streams. The perception and cognition of these streams is relevant to the effectiveness of the human-computer interface. All the sound parameters which are used for representation as described above are actually grouped into 2 continuous auditory streams. The first stream comprises of auditory signals which characterize stiffness, natural frequency and damping. As earlier described, it consists of sound pulses occupying a low register with each pulse having some degree of decay. The second stream contains the auditory signals which represent either the stress density or local stress component. This is a continuous sound staying within the range of a higher register. Its fundamental frequency goes through smooth transitions but can have some degree of vibrato in cases where fluctuating stress reversals need to be characterized as described earlier. Earcons which are used to signal attention to special structural phenomena actually comprise a third sound. These are however discrete sound objects occasionally superimposed and are not continuous auditory streams.

It is important that the two auditory streams be easily segregated by the user. Bregman [viii] points out that experiments suggest segregation is more effective when two streams are sent to different ears, if they are separated by at least an octave, and if they have difference in timbre. Improvement in segregation was less affected by differences in attack, decay, and rhythm. Segregation seems best when the differences between streams of most sound parameters was maximized.

In order to ensure segregation is obtained between the two main auditory streams in this project care was taken to provide sufficient parameter distinction. A sizable separation between the ranges of the fundamental frequencies of each stream was made such that the first stream is at a register 2 octaves lower than the other. Timbre is also differentiated in that the first stream is a simple clear sound synthesized from sine waves whereas the second stream is defined by a range of much richer, complex sound. The first stream is emitted in pulses somewhat like the percussion section of a band while the second stream is basically continuous with possible vibrato in some instances. To further improve segregation, techniques for the spatial manipulation of sounds are attempted such that the two streams are perceived to be emanating from clearly different sources.

5.0 APPLICATIONS TO SPECIFIC MODES OF STRUCTURAL BEHAVIOUR

The project has focused on 3 specific multimedia structural behaviour instruction modules for enhancement by sonification. The first module studies the plastic-zone behaviour of steel frames. The second module portrays wind-excited vibration of structures while the third module looks into free-form shell structure optimization.

5.1 Plastic zone behaviour of steel frames

This learning module portrays second-order inelastic behaviour of steel frames on the basis of plastic zone theory which is recognized to be most analytically accurate. Current limit-state specifications require an understanding of the various stages of structural performance up to its serviceability limit or until failure under severe conditions (ultimate limit state). The joint visual and audio interface can explicitly trace the progress of various factors defining the structural state of a steel frame as plastic zones are initiated and gradually spread in the sections and along members. The visual channel of the interface shows loads as they are gradually incremented and also the progressive frame deformation (in real-time and in response to user-controlled adjustments of various structural parameters) which is vital to understanding second-order effects. It also shows location of plastic zones as they develop. Synchronous with the visual channel the audio channels impart, through various sound parameters, other structural data such as stiffness reduction at various stages of plastic zone formation, overall stress density, and/or local stress components, and other relevant information in the manner explained previously. In addition, earcons signal the onset of plastic zones, the serviceability limit and the ultimate limit state.

5.2 Wind-excited vibration of structures

This instruction module focuses on two causes of wind-excited vibration of structures, namely, vortex shedding and gust buffeting.

Vortex shedding is a phenomenon that occurs at sufficiently high wind speeds causing relatively slender members to vibrate in the direction of and transverse to the wind flow. The forces produced by vortex shedding have constant static components and superimposed alternating dynamic components. The amplitude and frequency of these pulsating forces depend on wind velocity, member dimensions, wind density and Strouhal number for the section. The Strouhal number for all practical purposes may be taken to be a function of section shape and orientation. The visual channel in this module portrays the pulsating wind forces, the structures modes of vibration and other effects such as ovalling as the structure responds to the dynamic forces resulting from vortex shedding. Synchronously, the different sound parameters provide indications of the relative stiffness, natural frequency, damping, overall stress density, and/or local stress components. The user will be able to detect important relationships among the different structural parameters such as that of damping, mode of viration and natural frequency. Superimposed earcons signal the locking in of vortex shedding, the onset of significant resonance effects and the formation of any plastic zone.

The other part of this module presents the effects of gust buffeting or strong alongwind pulses. The visual interface shows the coupled 3-dimensional vibration (alongwind, crosswind and torsional) of the structure. The audio channel imparts information on other structural parameters in the same manner as described above for vortex shedding.

5.3 Free-form shell structure optimization

This module portrays shell structure stability and behaviour as well as shell shape optimization. The visual channel presents progressive deformation and modes of buckling. As in the steel frame module, the joint visual and audio interface can explicitly trace the progress of various factors defining the structural state of a shell structure as yield lines are initiated and gradually spread. The visual channel of the interface shows loads as they are gradually incremented and the progressive shell deformation in real-time and in response to user-controlled adjustments of various structural parameters. It also shows location of developing yield lines and eventual modes of buckling. Synchronous with the visual channel the audio channels impart, through various sound parameters, other structural data such as stiffness reduction at various stages of yield line formation, overall stress density, and/or local stress components, and other relevant information in the manner explained previously. In addition, earcons signal the onset of yield lines and buckling.

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