Tensorial Deformation Measures for Flexible Joints

Olivier A. Bauchau

Flexible joints, sometimes called bushing elements or force elements, are found in all multibody dynamics codes. In their simplest form, flexible joints simply consist of sets of three linear and three torsional springs placed between two nodes of a multibody system. For infinitesimal deformations, the selection of the lumped spring constants is an easy task, which can be based on a numerical simulation of the joint or on experimental measurements. If the joint undergoes finite deformations, identification of its stiffness characteristics is not so simple, specially is the joint is itself a complex system. When finite deformations occur, the definition of deformation measures becomes a critical issue. Indeed, for moderate deformation, the observed nonlinear behavior of materials is partly due to material characteristics, and partly due to kinematics. This talk focuses on the determination of proper finite deformation measures for an elastic body of finite dimension. In contrast, classical strain measures, such as the Green-Lagrange or Almansi strains, among many others, characterize finite deformations of infinitesimal elements of a body. It is argued that proper finite deformation measures must be of a tensorial nature, i.e., must present specific invariance characteristics. This requirement is satisfied if and only if deformation measures are parallel to the eigenvector of the motion tensor. It will be shown that these deformation measures accurately capture the kinematics of flexible joints for rather large motions. Implications to the mechanics of slender structures will be outlined.

Fourteen Years of Research into Momentum Exchange Tethers

By

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Space Tethers are long lines used to connect two massive objects in space with the purpose of exchanging momentum in some useful manner. They can be applied to orbit raising, lowering, maintenance, and also for interplanetary propulsion. There is a long history of highly innovative research in space tethers, and the early work on the related concept of the space elevator, or 'celestial tower' by Tsiolkovsky from 1895 is frequently cited as the beginning of this work. The first mission in which a tether was used as part of the programme was the Gemini 11 mission in 1966, and there have been several different test missions since then in which tethers of different types and lengths have been deployed. The success rate has not been particularly high to date, and this has mostly been due to minor practical problems with deployment. There is still a very strong international research activity in the dynamics and control of space tethers of all sorts, with electrodynamic tether development in the US progressing at a fast pace for satellite boost and de-boost.

This lecture will concentrate on work done within the Dynamics Groups at the Universities of Edinburgh and Glasgow since 1996, and in particular on the specialised design known as the Motorised Momentum Exchange Tether (MMET). This concept combines solar powered forced spin motion of a double-ended tether (to which two payloads are fitted) and orbital mechanics in such a way that a MMET can be used for significant boost of massive payloads from SEO through to the higher reaches of LEO and beyond, typically on lunar or Mars transfers. The presentation will highlight the evolution of this work and the contributions of the many people who have been involved with it over the last 14 years, and will set an agenda for our future research. The emphasis will be on the modelling work that has been done in this time. The second half of the presentation will be devoted to space webs, these being 2 dimensional offshoots of the momentum exchange tether which could be used as a basis for the construction of large flat or curved structures in space. Such structures could be used for space based solar power collectors, interferometers, telescopes, or even as specialised manufacturing sites in space on which crawler robots are deployed to exploit this large structure for different applications. A novel modelling strategy will be summarised and it will also be shown how a scale model has recently been designed and built for testing in space in 2012.

Mechanical Modelling of Lift Structures: the Influence of the Dynamic Behaviour of Slender Structural Components

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Abstract. The mechanical performance of a lift structure represents a complex task and forms an important step in the elevator system design procedure. In this approach first the mechanical characteristics of elevator components were identified experimentally. It was found that the response was highly influenced by the mechanical properties of the suspension means, guiding system and, surprisingly, by the mass and damping and stiffness characteristics of passengers. The stiffness and damping coefficients in the vertical direction based on a single degree of freedom model of the individual components were found to be suitable for mechanical characterization of the elevator system. The dynamic lift response is very sensitive to these coefficients. An experimental procedure, based on a two degrees of freedom model, is proposed to quantitatively determine the passenger's stiffness and damping coefficients exposing the human bodies to a very simple and fast vibration test. A six degree of freedom model of a lift system using the identified stiffness and damping characteristics of the components was developed. The model was implemented in the MSC Visual Nastran simulation environment and the response during a typical returned elevator trip was determined. The simulation results demonstrated the influence of various excitation inputs such as torque ripple and impact forces on ride quality of the elevator. Furthermore an efficient algorithm to simulate the transient response of the elevator was implemented in MATLAB. The proposed methodology and the results discussed in this paper will be used as benchmarks for further work to develop a software simulation tool for assessing the mechanical behaviour of elevator systems.

Advances in Understanding Stay Cable Vibration

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Cable-stayed bridges have frequently exhibited large-amplitude vibrations of the main stays, frequently associated with the simultaneous occurrence of wind and rain. These vibrations have been of concern because they potentially induce fatigue in the cables and cable anchorages. Early research on excitation mechanisms had generally been conducted using wind tunnels, and several distinct aerodynamic mechanisms were proposed. While considerable progress has been made in understanding and mitigating these vibrations, the state of the art has still not enabled the prediction of field behavior based on a set of supplied parameters, nor does a plausible, fully accepted model exist for the phenomenon.

This presentation will summarize recent research efforts that have attempted to advance the state of understanding of this complex fluid-structure interaction problem. Both early efforts and recent investigations – primarily based on the collection and interpretation of comprehensive full-scale data – will be considered. In presenting these perspectives, focus will be placed on the use of a combined approach comprising observation, full-scale and laboratory (wind tunnel) investigations, analysis, and computational tools to develop understanding of aspects of this phenomenon and its mitigation, with it often being necessary to question past assumptions or assertions on the part of researchers and designers. In both understanding of the basic phenomenon, as well as in understanding the performance of mitigation systems, it became evident that preconceived notions about performance and assumptions in some instances clouded rather than aided the advancement of understanding.

The overall goal of these efforts has been to better understand the mechanics of stay-cable vibration at a more fundamental level and enabling the recommendation of more effective and economical mitigation strategies.

The Space Elevator and Our Future

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The Space Elevator is a radical concept for accessing space. Indeed, the Space Elevator may be the ultimate slender structure. Its earliest beginnings date to the writings of Tsiolkovski. The first publication occurred in 1960 in the Soviet Union’s paper, Pravda. This presentation begins with the conceptual design which comprises a 100,000 km long carbon nanotube ribbon stretching from the surface of the earth out into space. Vehicles access space by ascending high on the ribbon and either dropping into orbit around Earth or being thrown beyond Earth orbit to other destinations in the solar system. The challenges of building the elevator are outlined and solutions for these problems are mentioned. The promise of the Space Elevator will be discussed in some detail as the elevator is expected to dramatically decrease the cost of accessing space. The primary challenge, the material and its properties required to build the Space Elevator, will be examined in some detail.

The dynamic stability of a moving oscillator on a long flexible structure

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In the mid-1980s, Denisov *et. al.* [1] and Bogacz *et. al.* [2] have shown that a linear oscillator that moves along an infinitely long, straight beam on a viscous-elastic foundation can be unstable. The instability implies that the initial transverse deflection of the moving oscillator grows in time until the contact between the oscillator and the beam is broken.

During the last two decades, a number of papers have been published [3-6], in which the instability of various moving objects on one-, two- and three-dimensional elastic structures has been considered. The interest in the subject is driven by the massive introduction of high-speed trains, whose stability at high-speeds greatly depends on dynamic interaction between the train wheels and the rails.

In the present work, the above-described instability phenomenon is first introduced by analyzing the natural frequencies of a two-mass oscillator that moves along a flexibly supported Euler-Bernoulli beam as shown in Figure 1(a).

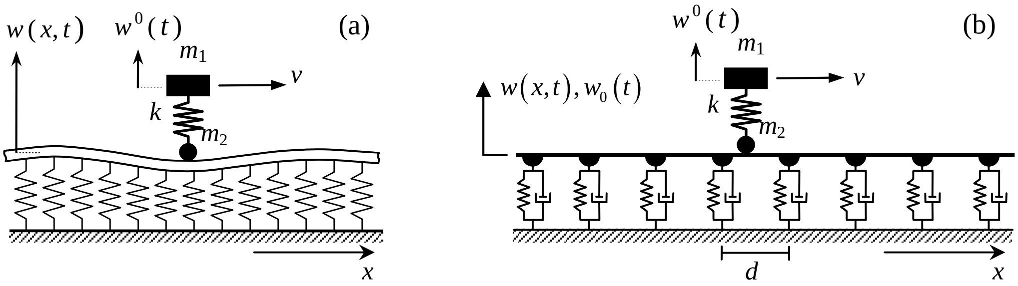

Figure 1. Moving oscillator on (a) continuously supported beam, (b) periodically supported string.

The natural frequencies of the oscillator can be real or complex, depending on the velocity of the oscillator and the system parameters. The imaginary part of the complex frequencies can be either negative or positive corresponding to decaying or growing (unstable) vibration, respectively. The complex natural frequencies occur because of the energy input by a force that maintains uniform motion of the oscillator along the beam and because of radiation damping associated with flexural waves that the vibrating oscillator generates in the beam.

To explain the different possible types of natural vibration of the oscillator, the energy and momentum variation in the system are studied on the basis of the following equations [7,8]:

$$\frac{dE^0}{dt}+\left(S-ve\right)\Big|_{x=vt-0}^{x=vt+0}=Rv, \qquad \frac{dP^0}{dt}+\left(F-vp\right)\Big|_{x=vt-0}^{x=vt+0}=R, \tag{1}$$

where E^0 and P^0 are the energy and the longitudinal component of the momentum of the oscillator, v is the oscillator's velocity, R is an external force that maintains the uniform motion of the oscillator along the beam, S and e are the energy flux through a cross-section of the beam and the linear energy density of the supported beam, and F and p are the flux and density of the wave momentum.

Using the energy and momentum variation laws given by Eq. (1), it is shown that the three regimes of natural vibration of the oscillator (harmonic, decaying and growing) are one-to-one related to the possible regimes of wave generation in the beam. Harmonic oscillations occur if the vibrating oscillator does not generate evanescent (not propagating) waves in the beam. Decaying and growing oscillations occur when the oscillator generates propagating waves in the beam. These waves can be either "normal Doppler waves" or "anomalous Doppler waves" according to the terminology introduced in [9]. Reaction of the former waves decreases the energy of the oscillator, whereas that of the latter increases it. It should be noted that the anomalous Doppler waves may be generated by the oscillator only if it moves at a velocity higher than the minimum phase speed of flexural waves in the beam. Therefore, the oscillator, when moving on a homogeneous system, may become unstable only if its velocity is high enough.

The above analysis of the energy variation of the oscillator shows that the energy increase in the unstable regime is due to the force that maintains the oscillator's motion along the beam. This force is essentially horizontal (directed along the beam), and, therefore, the work of this force may strongly depend on the description of longitudinal dynamics of the beam (friction in the contact, longitudinal vibrations, etc.). To check this, coupled transversal-longitudinal vibrations of the beam are considered, taking into account friction in the contact and longitudinal stiffness of the beam's elastic foundation. It is shown that due to the contact friction, a non-negligible axial compression and axial tension occur in front of and behind the oscillator, respectively (the compression and tension interchange their locations if a driving wheel of the train's locomotive is modeled by the oscillator). These axial forces strongly depend on the velocity of the oscillator. The higher the velocity of the oscillator and/or the higher the longitudinal stiffness of the beam's foundation, the stronger is the effect of friction in the contact on the stability of the oscillator.

If a beam on elastic foundation as shown in Figure 1(a) would be considered as a realistic model for the railway track, the instability of a train would be predicted to occur at train velocities higher than 2000 kilometers per hour, which is unreachable for high-speed trains (unless vacuum would be created in a tunnel in which the trains would run). However, the beam on elastic foundation is totally unacceptable as a model of railway tracks for high-speed trains. The main drawback of this model is that it does not account for dependence of the stiffness of the railway track's subsoil on the frequency and wavelength of vibration of the rails. To show the effect of this dependence, a three-dimensional model is considered of a railway track that consists of a beam on a viscous-elastic half-space. It is shown that the instability may occur as soon as the oscillator's (train's) velocity would exceed the Rayleigh wave velocity in the half-space. This velocity can be as low as 200 kilometers per hour if the railway track is built on soft subsoil, which is currently the case in some parts of Sweden, the Netherlands and China. Therefore, the instability phenomenon is of practical significance.

All models discussed above are homogeneous in the direction of motion of the oscillator. One may wonder whether a certain inhomogeneity of the model would influence the instability phenomenon. This question has a strong engineering background because nearly all railway tracks and overhead catenary lines for trains (the instability may occur also in the course of interaction of a current collector of a train with the overhead contact wire) are periodically inhomogeneous along their length. It can be anticipated that the periodical inhomogeneity can influence the instability phenomenon strongly because the anomalous Doppler waves can be generated in inhomogeneous systems at any speed of the oscillator [9]. Another, probably more “mechanical”, reason for anticipating a significant effect of the periodical inhomogeneity on the system stability can be formulated as follows. The parameters of a periodically-inhomogeneous elastic system at the contact point with the moving oscillator vary periodically in time provided that the oscillator’s velocity is constant. The period of this variation equals d/v, where d is the spatial period of inhomogeneity and v is the oscillator’s velocity. Obviously, one may expect parametric resonance if one of the natural frequencies of the oscillator on the elastic system equals $nd/2v$.

To explore the effect of the periodical inhomogeneity, the stability is studied of the moving oscillator on a string supported by periodically spaced discrete supports as shown in Figure 1(b). This model mimics simplistically the dynamic interaction of overhead power line with the current collector of a train. It is shown that, as expected, parametric instability zones exist in the parameter space of the system. The size of these zones strongly depends on the stiffness and viscous damping in the supports of the string. The stiffer the supports, the wider are the zones. The effect of the damping is ambiguous. The higher-order zones become narrower as the damping increases, whereas the main zone widens. The latter effect can be explained by the fact that a higher damping in the supports increases their dynamic stiffness thereby causing a larger energy input into the system by the force that maintains the uniform motion of the oscillator along the string.

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Lifts and Environment

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The present high levels of energy consumption are causing important changes in the Earth climate. This fact can be seen in the progressive environmental degradation caused, among other agents, by the global warming.

To try to minimise the problem the possible alternatives are to stop the countries development (nearly impossible), to decrease the level of life in the developed world (not accepted), to increase the use of “green energies” (very complicated), or to reduce the energy consumption by increasing the energetic efficiency of the general means and equipment (possible and feasible).

The world is looking for solutions and different sectors as plants, buildings, traffic, transportation, heating and air conditioned, lighting, isolation, etc. are always considered. Nevertheless lifts, that suppose a significant rate of energy consumption, are not taken into consideration in the regulations in force.

The lecture makes a fast overview of:

- The history of lifts.
- General aspects and key statistics’.
- Main differences between the conventional and the “Green or New Generation Lifts”.
- Economical study of the total lifts or modernisation packages change (definition of Green equipment, savings and over costs).
- Regulation on going.
- A vision of the lifts of the future.