THE HUMAN HEAD NECK SYSTEM: A REVIEW OF MODELLING APPROACHES

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We present a review of the modelling approaches for the human head - neck system. The models address two major problems, related to the three - dimensional description and second with the material properties which are largely unknown. All the models converge to a layered description where each component corresponds to a different material of the system. The models can be classified to systems that solve the free - vibration problem as well as those which solve the external stimulus problem.

1 Description of the Problem

The human head - neck system is a difficult structure to model. Many researchers have tried to create models in the past, but to our knoweledge no complete modelling approach to the system exist. There are two difficulties: the first is related to the complex model which often requires three - dimensional computation, and second the lack of experimental data since *in vivo* experiments are rare due to the problem of finding volunteers and the difficulties encountered in the experiments themselves.

The major problems related to the system under discussion are classified in two categories. The first is related to the determination of the dynamic characteristics of the system and the second one to the response of the system to an external or internal stimulus.

The dynamic characteristics of the human head - neck system consist of the eigefrequencies as well as the corresponding eigenmodes under the regime of elastic vibrations. It is well known that the dynamic characteristics knowledge should be exploited suitably in order to identify through non - invasive methods the evolution of usually undesirable alterations (i.e., intracranial pressure) in the cranial cavity.

Many interesting research problems arise when the response of the system under examination to a stimulus is considered. This is the case when the car accident or an unlucky blow in boxing occurs. In addition, the same problem arises when someone tries to apply a measurement process in order to determine the dynamic characteristics. We note that the cardiac pulse can also be considered as internal stimulus.

Thus, detailed models must be developed to account for structural and material properties of the system to predict accurately the behavior of the system. Most of the works published converge to a layered structure of the system, with a neck support, which is shown in Fig. 1.

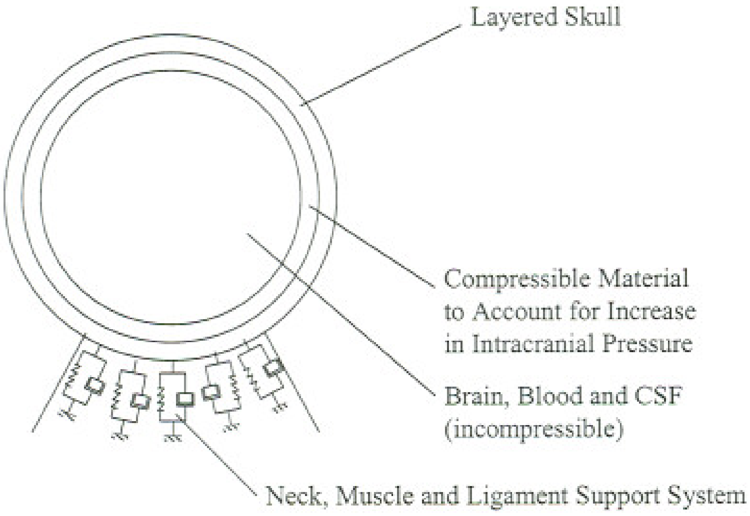

Figure 1. The Layered Structure of the Human Head - Neck System.

2 General Statements

It is not easy to propose a straightforward classification for the models proposed for the human head - neck system. We can distinguish among the earliest stages, from 1965 - 1975, to the period from 1975 - 1990 and the latest attempts after 1990. Three factors can be used for the classification:

geometry, materials and method of solution. The thin shell approaches even they provided with a very good understanding of the layered structure they were limited to skull descriptions for spherical geometries and they provided insight only for the structure of the eigenfrequency spectrum. Finite element solutions can address difficult geometries, but in the case of the skull the first approaches addressed only two - dimensional geometries which do not provide any knowledge for the three - dimensional approach. It is possible to take into account geometrical characteristics, but those which are of importance (e.g. facial bones) were ignored in most of the approaches. Finite element modelling also does not provide in the refererences listed below with generic understanding of the various components entering the system. The three - dimensional approaches, even they are limited to some geometries, they can be used for the prediction of the dynamic characteristics of the system and to describe the neck support. The latter also is a matter of classification, since the neck constitutes a fundamental component of the whole structure participating jointly in the elastic vibrations of the system. However, due to the involved complexity, the neck behavior is addressed in only a few publications. In the early stages of work Goldsmith [23] provided with an extensive review from the engineering and medical point of view. A classification of the published works by 1976 is given by King and Chou [29] in a review article on the mathematical modelling and simulation of the system crash response.

The early models are characterised by their referring to simplified and regular geometry. At the beginning knowledge from the shell theory was used leading to the major assumption according to which the skull (outer layer) is considered very thin compared with the head radius.

3 The Models

The first modelling attempt is due to Engin[17] and to Engin and Liu[18] who adopted a model consisting of a thin homogeneous isotropic and spherical shell containing an inviscid irrotational fluid. This approach provided with useful insight in the understanding of the problem but the limitation of the thin skull introduced certain problems. This was proved by Charalambopoulos *et. al.*[4] in an attempt to solve the problem of a spherical skull and compare the solution with those obtained from the thin shell approximations. They proved that such a model can easily predict the eigefrequencies measured in experiments. This was the first indication that models can predict well the eigefrequencies, even the geometry chosen is not the realistic one. The model was extended[6] to include the viscoelastic behavior of the skull. This gave rise to the understanding of the dissipative behavior of the skull.

Akkas [2] extended the thin shell approach using a sandwich spherical shell model. He again considered that the shell was thin and elastic and the brain as inviscid and compressible fluid. He performed free as well as forced vibrational analysis using finite differences. Kenner and Goldsmith [27] considered an axi - symmetric thin spherical shell model.

Advani and Owings [1] considered the structural modelling of the human head consisting of a uniform elastic spherical layer (skull) containing an elastic core (brain). Talhouni and DiMaggio[44] introduced the modelling of the head as a prolate spheroidal shell filled with an inviscid fluid. At the same time the viscoelastic behavior of the brain is addressed by Liu *et. al.* as a Kelvin material[32] and the analysis was based on finite differences. Chan[3] proposed a visco - elastic prolate ellipsoid shell model using finite elements for the solution of the problem. Misra[34] studied the steady vibration of the human skull - brain system due to an axisymmetric impact varying harmonically with time. He modelled the skull as a prolate spheroidal shell made of a linear viscoelastic material representing the skull enclosing a linear viscoelastic material representing the brain. Misra and Chakravarty[35] studied the free vibrations problem by taking into account the dissipative material behavior of both the skull and the brain. Nanda[39] presented a work on the effect of viscoelastic behavior of the cranial bone on the vibration chracteristics of the skull - brain system. An analysis in depth of the viscoelastic behavior of the brain tissues was presented by Charalambopoulos *et. al.*[7]. They found that the model can predict the eigenfrequencies of the system and in some cases the damping coefficients. They claimed that such a discrepancy in the damping coefficients is due to the viscoelastic behavior of the neck.

Guarino and Elger [24] adopted the modelling of the human head by a fluid - filled elastic shell containing a concentrically located elastic sphere. The major assumptions are that the fluid is inviscid, the spherical shell is thin and the modes of the physical system are axisymmetric. However, it was proved that a three - dimensional analysis[5] introduced an extra pattern of eigenfrequencies. In [5] two other models were discussed, the case of having a fluid - filled hollow sphere and the case of three elastic layers.

3.1 Modelling the Geometry

The geometry itself remains a significant complexity factor and even in the finite element models, major assumptions have been introduced. Within this framework some researchers lately have presented studies on the geometry generation and discretisation of the human head with its various consituents[30]. However, the method has been used from the beginning stages. Hardy and

Marcal[19] performed an elastic analysis of the human skull. Shugar and Katona[42] presented a three - dimensional model for the head injury. The skull has been discretized in three layers and both elastic and viscoelastic materials have been considered. Khalil and Hubbard[28] proposed three models to study the head response to axisymmetric impact loading. The first model consists of a single layer spherical shell covered by another layer (scalp). The second differs in the geometry which is now comprised of segments of two spheres and a cone and in the third model a more detailed approach to the skull, considering three layers, has been taken into account. In all models the skull and scalp were elastic and the cavity filled with inviscid fluid corresponding to brain.

Ward *et al.*[45] performed finite element analysis to predict the intracranial pressure in head injury. Hosey and Liu[21] described the fundamentals of using finite elements in modelling the human head - neck system. Ruan *et. al.* used three - dimensional finite element approaches to study the behavior of the human head to an impact [41]. Zhou *et. al.*[48] extended the approach and in the two latest works we meet efforts to propose a first approach of accident simulation [48] in order to estimate the human head tolerance threshold. Willinger *et. al.*[46] validated a finite element human head model [26] under different impact conditions by considering intracranial compressibility.

A review of the finite element models for the biomechanics of human head injury up to 1996 is given by Voo *et. al.*[47].

The small deviation from the spherical geometry was proved that does not contribute significantly to the dynamic characteristics problem, since small changes have been observed in the eigenfrequency spectrum [8]. Large deviations from the spherical geometry to spheroidal prolates affects significantly the frequency spectrum and a new mathematical method for its treatment is needed [13]. To this direction the formulation of the problem through the spheroidal Navier eigenvectors has been proved very efficient [14]. The existence of the facial bones as well as non - uniformities observed in the thickness of the skull alter significantly the eigenfrequency spectrum giving rise to new eigenfrequencies. This is accomplished by simulating the system using bispherical coordinates [9].

Nagashima *et. al.*[38] and Tada and Nagashima[43] studied the brain lesions by the finite element method. They considered the pressure increase in cerebral oedema and examined the distribution of pore pressure and fluid flow in the brain tissue. They offered another point of view to the modelling of brain, examining another problem describing the brain as a porous media with flow of CSF in the pores.

3.2 Modelling the Neck Support

Some other researchers addressed directly the neck support. Landkoff *et. al.*[31] analysed the axisymmetric impact on the spherical human head which is rigidly constrained at its bottom point by an artificial viscoelastic cylindrical neck which is clamped at its distal end to a rigid support. The parameters of the proposed viscoelastic model were determined by least squares fitting of data. The potential deleterious effects of the helmet mass and inertia through increased head rotations during high acceleration periods were studied by Huston and Sears[22]. Merill *et. al.*[33] presented a three - dimensional model of the head - neck system and developed a numerical method that permits the evaluation of the load kinematic and load distribution response of the model to any head impact or base impulsive loading. Misra and Chakravarty [36] adopted a mathematical model of the human head, which was supposed to be connected to a linear viscoelastic cantilever beam, representing the neck.

However, it was not possible to simulate all the motions of the human head by simply imposing idealised boundary conditions. Hosey and Liu[21] included in the finite element description the neck. DiMasi *et. al.*[16] developed an anatomically simplified model to study the head impact with a vehicle's interior under crash conditions. Charalambopoulos *et. al.*[10] developed a model where the neck support was simulated as three dimensional continuously and uniformly distributed elastic strings simulating a mixed type boundary condition. This led to another model where the neck support corresponds to three dimensional elements which include viscoelastic components. The three - parameter model parameters were obtained from fitting to experimental data. The viscoelastic model for the neck was selected among models existing in the literature to best fit experimental observations for the frequencies. The last two models gave insight to the understanding of the behavior of the system in the presence of the neck, with the appearance of two modes at the beginning of the spectrum, which correspond to rotation and translation of the system, and a shifting of the other eigenfrequencies. The viscoelasticity introduced in the second model gave the opportunity to better predict experimental data.

3.3 The Response to an External Stimulus

The issue of the dynamic response of the system to an external stimulus addressed in most of the studies. However, this required a separate solution and no unique approach was reported. This is presented by Charalambopoulos *et. al.*[12]. They describe an approach which uses the previously obtained solutions for the free vibration problem and adapts it to the external or internal problem, which is now considered as the non - homogeneous replica of the homogeneous vibration models. In such a way the previously reported solutions can be easily used to treat such problems. The external stimulus is the major diagnostic tool for human head abnormalities and a mean to understand the system behavior under an external unexpected impact (e.g., car accident, etc.).

4 Concluding Remarks

We have given an extensive description of the work that has presented in the modelling of the human head - neck system. Researchers have used thin shell theory, three dimensional description of simplified and more realistic geometries to address both the free - vibrations and the external impact problem of the head - neck system. It has been shown that simplified geometries can predict accurately the dynamic characteristics of the system if a realistic material behavior is included. More realistic geometries can be realised with finite element modelling and can provide with useful insight for the effect of the facial bones and abnormalities in the layers or the positioning of an abnormality. All those models can significantly contribute to the development of new non -invasive methods for the monitoring of patients suffering from head diseases.

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