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İnsan Vücut Titreşim Modelinin Model İndirgenmesi

Murat BALCI[1], Ömer GÜNDOĞDU[2*]

Öne Çıkanlar:

- ISO 7962 standart modelinin yerini almak üzere insan vücudunun indirgenmiş mertebeli biyomekanik modeli önerilmiştir.
- Genetik algoritmalar, dinamik davranışı korurken indirgenmiş modelin parametrelerini optimize eder.
- Frekans tepkisi karşılaştırmaları, özellikle rezonans davranışını tahmin etmede indirgenmiş ve orijinal
- modeller arasında güçlü bir uyum göstermektedir.
- Model, araç dinamikleri ve insan-makine etkileşimi çalışmalarında düşey yönlü titreşim analizlerinde
- kullanılmaya uygundur.

ÖZET:

İnsan vücudunun biyomekanik modelleri genellikle karmaşıktır ve davranışının modelleri birçok diferansiyel denklemin yazılmasını ve çözülmesini gerektirir. Zaman alan bu süreç yerine sistemin ana davranışlarını koruyan daha küçük modellerin kurulumu daha pratik bir süreç olarak değerlendirilmektedir. Bu çalışmada ISO 7962'nin önerdiği insan vücudu modeli yerine analitik çözümü olan daha küçük bir model önerilmiştir. İstenilen model indirgemesi yapılırken genetik algoritmalar kullanılmış ve orijinal sistemin davranışını kopyalayan yeni sistemin parametreleri oluşturulmuştur. Daha sonra hem orijinal sistemin hem de indirgenmiş sistemin davranışları grafiksel olarak karşılaştırılmıştır. Karşılaştırmalar indirgenen modelin hesaplamalarda da kullanılabileceğini ve düşük frekans rezonansları gibi noktalarda çok iyi sonuçlar alınabileceğini gösterdi.

Anahtar Kelimeler:

- Model İndirgeme
- İnsan Vücut Titreşimi
- ISO 7962

Model Order Reduction of a Human Body Vibration Model

Highlights:

- A reduced-order biomechanical model of the human body is proposed to replace the ISO 7962 standard model.
- Genetic algorithms optimize the reduced model's parameters while preserving dynamic behavior.
- Frequency response comparisons show strong agreement between the reduced and original models,
- particularly in predicting resonance behavior.
- The model is suitable for use in vertical-direction vibration analyses within vehicle dynamics and
- human-machine interaction studies.

ABSTRACT:

Biomechanical models of the human body are generally complex, and models of its behavior require writing and solving many differential equations. Instead of this time-consuming process, it is considered a more practical process to install smaller models that preserve the main behaviors of the system. In this study, instead of the human body model proposed by ISO 7962, a smaller model with an analytical solution has been proposed. While performing the desired model reduction, genetic algorithms were used and the parameters of the new system that replicated the behavior of the original system were created. Then, the behaviors of both the original system and the reduced-order system were compared graphically. Comparisons have shown that this small model can also be used in calculations and that very good results can be achieved on points such as low-frequency resonances.

Keywords:

- Model Reduction
- Human Body Vibration
- ISO 7962

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INTRODUCTION

In many areas such as vehicle designs, it is necessary to know the constants that determine the body's dynamic properties to predict the human body's behavior against mechanical vibrations and impacts. One way to estimate these parameters is by measuring the vibration transmissibility of the human body. Transmissibility of the human body depends on posture, type of excitation, and physical characteristics of the subject. Although measurements can be made at many points in the human body, the most important points are the head, neck, shoulders, and waist (ISO 7962, 1987). This standard was created to enable transmissibility measurements to obtain the low-frequency responses of a high-order system. Mechanical impedance and seat-to-head transmissibility values for a seated subject were updated with a later standard (See ISO 5982, 2001).

While examining vehicle vibrations, one of the first examples of modeling vehicles together with the human body and examining system vibrations as a whole was created by adding the driver to the quarter car model. This problem has a mechanical system model with four degrees of freedom. System parameters were computed for different objective functions by applying genetic algorithms (Gündoğdu, 2007). Subsequently, an increase in the number of similar problems was observed. For example, Papaioannou and Koulocheris (2018) added a human model with eight degrees of freedom to a half-car model with four degrees of freedom and performed parameter optimization using genetic algorithms against different objective functions. Zhao et al. (2023) established a five-degree-of-freedom model to examine the vibrations transmissibility from a commercial vehicle seat to the head and made predictions using the response surface method and genetic algorithms.

The problem later became the subject of active control applications using different control techniques (Al-Ashmori and Wang, 2020). Additionally, similar approaches have been applied to vehicle seat designs (Fai et al., 2007).

The bio-vibration models are also applied to driver comfort problems such as the study performed by Usanmaz (2020), where a half car model was established together with a four degrees of freedom driver model and simulated for head accelerations. Another application area of bio-vibration models of the human body is the problem of detecting the forces acting on the neck and lower back regions of drivers. For example, Yanıkören et al. (2023) established a vibration model of an eleven-degree-of-freedom driver with a five-degree-of-freedom vehicle and simulated how bumper dimensions and car speed affect neck and lower back forces.

Due to its practical significance, numerous model order reduction techniques have been proposed in the literature over the past several decades and continue to be favored by researchers (Chinesta et al., 2004; Kumar and Sikander, 2024; Scarciotti and Astolfi, 2024). While the earlier methods, such as Pade and Routh (Shamash, 1975) approach and aggregation methods (Arbel and Tse, 1979; Kwong, 1982), did not assure any performance, other methods like Wilson (1970, 1974), Hyland and Bernstein (1985), and Bernstein and Haddad (1987) were based on the optimization of some performance criteria. These later methods are computationally expensive and do not guarantee to find the global optimum. Therefore, in this study, genetic algorithms are used in optimizations because they have a better chance to provide global optimum solutions.

Using genetic algorithms, this work suggests a new lower-order model for the human body that retains the majority of its bio-vibrational features. In addition to vehicle dynamics studies and ergonomic designs, many biodynamic studies on human-machine interactions are expected to incorporate such a lower-order model.

MATERIALS AND METHODS

Modeling Human Body

ISO 7962 (1987) suggests a physical model composed of four lumped masses, and some linear springs and dampers as shown in Figure 1. The parameter values given in the standard are listed in Table 1.

Transmissibility depends on posture and changes from one activity to another. Basic postures are considered to be sitting, standing in an upright position, and lying. Sitting and standing present similar transmissibility in the vertical axis direction, depending on whether the excitation is given from the body alone or body and feet together. Therefore, the model is provided to make vibration analysis in such a way as to perform analysis in either sitting or standing upright position.

The physical model does not serve as a one-to-one anatomical representation of the human body; instead, it is designed to mathematically replicate human body dynamics to an acceptable degree. The system's response is the response of the mass m_1, which can be imagined as the human head, to base excitations.

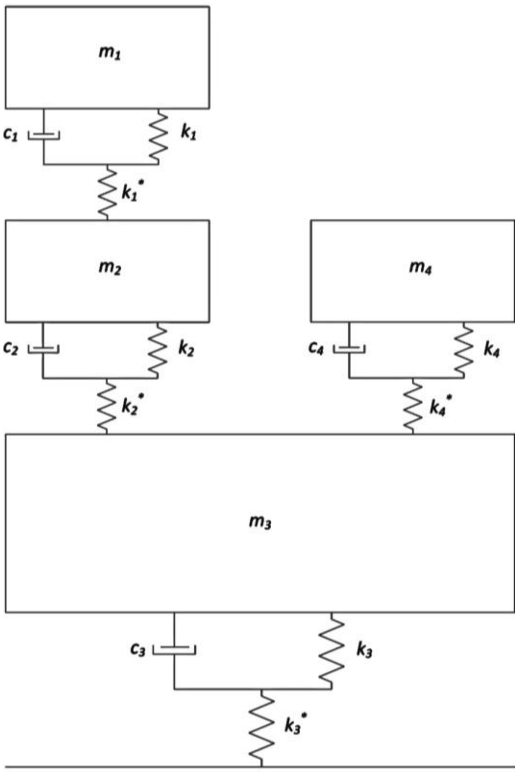

Figure 1. The model suggested by ISO 7962 (1987) for human body vibrations

Table 1. Parameter values provided by ISO 7962 (1987) for higher-order model

Masses **[kg]**		***Spring Constants*** **[N./m]**				***Damping Constants*** **[N.s./m]**	
m_1	8.24	k_1	22×10^8	k_1^*	36×10^7	c_1	748.1
m_2	8.05	k_2	20.13×10^4	k_2^*	66×10^9	c_2	578.0
m_3	44.85	k_3	88.56×10^3	k_3^*	52.34×10^4	c_3	2964.0
m_4	13.86	k_4	36.47×10^3	k_4^*	69.30×10^3	c_4	901.8

The mathematical model of the system given in Figure 1. can be developed from the use of Newton's second law of motion. Then, they can be expressed in terms of state space as

$$\dot{x}=Ax+Bu \tag{1}$$

$$y=Cx+Du \tag{2}$$

where the matrix A is the state matrix, B input matrix, C output matrix, and D direct transition matrix while the vector x is the state vector, y output vector, and u input vector (Ogata, 2002).
The standard presents experimental and model-based data for transmissibility modulus and phase angle in the frequency range of 0.5 Hz to 31.5 Hz. Two peaks and their shapes observed in the transmissibility plots lead to a conclusion that the lower-order model to be proposed should have at least one real and one complex conjugate pole in its characteristic equation. For this purpose, a lower-order model with three degrees of freedom is proposed as in Fig. 2, and its compatibility with both experimental and theoretical results obtained for the higher-order model is investigated.

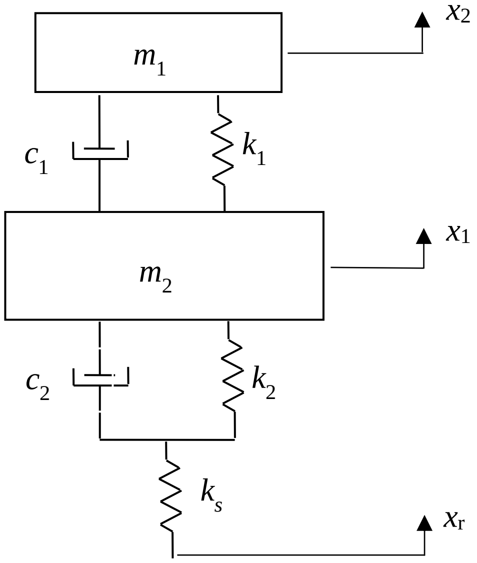

Figure 2. Lower order model proposed for the human body

In the determination of parameter values, an objective function is proposed to minimize the square of the difference between the impulse responses of higher and lower-order models in the form of

$$J = min\ \sum(x\_high - x\_low)^2 \tag{3}$$

The objective function used in the optimization minimizes the sums of the differences between the higher order model and lower order model responses in positions of the masses, where *x_high* represents the impulse responses of higher-order models, and *x_low* represents those of lower-order models. The objective function calculates the squared difference between *x_high* and *x_low* to prevent differences in different signs from simplifying each other and causing errors. The objective function offered here may have more than one local optimum, and since genetic algorithms have a better chance to catch the global minimum (Michalewicz, 1996), they are chosen as the optimization means in this study. While other methods mostly proceed from one point to another by obeying some transmission rule, genetic algorithms work with a large range of the population of the solution set, which gives a higher probability of catching the global minimum. Hence, methods other than genetic algorithms have a higher chance of being trapped in a local optimum close to the starting point of the optimization process (Goldberg, 1989). The parameters obtained from this optimization are used to obtain the frequency response of the lower-order model of the human body.

RESULTS AND DISCUSSION

In the standard, transmissibility plots are provided for low-frequency measurements in the range of 0.5 Hz and 31.5 Hz. Although there is no data out of this frequency range, the reliability of these data is still in question. Since the current study is based on the model and measurements given in the standard, the results of this study are also given in the same range. The parameter values obtained from the genetic optimization for the proposed lower-order model are presented in Table 2.

Frequency responses are especially important as they show resonance frequencies and give vibration amplitudes in a undimensional way. In this article, the performance of the study has been tried to be shown, especially through frequency responses.

In Figure 3, the experimental results given in the ISO7962 standard and the frequency response of the model recommended by the standard are plotted together with that of the reduced model proposed in this article. At first glance, it seems that the predictions of the reduced model are closer to the experimental results than those of the model proposed by the standard. It is obvious that the proposed reduced model at low frequencies proceeds in parallel with the standard's proposal, but at resonance frequencies the reduced model performs better. It is very important to both predict the resonance frequency correctly and approach it in terms of amplitude at the resonance frequency of this superiority. In addition to improved performance in prediction, the reduced model has an analytical solution see app. and also gives researchers the option to obtain results for desired variety of inputs. This is presented to researchers in this article as a separate advantage.

Table 2. The parameter values computed for the proposed lower order model

Masses (kg)		*Spring Constants* (N/m)		*Damping Constants* [N.s/m]	
m_1	4.88	k_1	6.18×10^4	c_1	333
m_2	65	k_2	6.41×10^4	c_2	2935
		k_s	8×10^5 N/m		

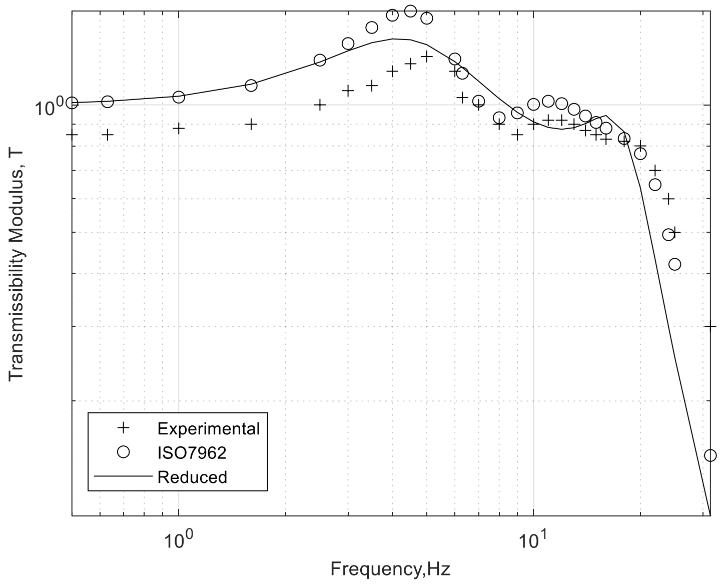

Figure 3. Frequency response of the human body for lower-order and higher-order models

The transfer functions associated with the system given in Fig. 2 is given below. $X_1(s)$ and $X_2(s)$ are the deflection of the first and second masses, respectively, while $Y(s)$ is the deflection of the massless platform connecting k_2 and c_2 to k_s. The parameter in the denominator $X_r(s)$ is the disturbance coming from bottom.

$$\frac{X_1(s)}{X_r(s)} = -\frac{k_s(k_1+c_1 s)(k_2+c_2 s)}{\Delta(s)} \tag{4}$$

$$\frac{X_2(s)}{X_r(s)} = -\frac{k_s(m_1 s^2+c_1 s+k_1)(k_2+c_2 s)}{\Delta(s)} \tag{5}$$

$$\frac{Y(s)}{X_r(s)} = -\frac{k_s m_1 s^2 (k_1 + c_1 s)(m_1 s^2 + c_1 s + k_1)(m_2 s^2 + c_2 s + k_2)}{\Delta(s)} \tag{6}$$

where the characteristic equation is given as

$$\Delta(s) = A_0 + A_1 s + A_2 s^2 + A_3 s^3 + A_4 s^4 + A_5 s^5 \tag{7}$$

and

$$A_0 = -k_1 k_2 k_s \tag{8}$$

$$A_1 = -c_1 k_2 k_s - c_2 k_1 k_s \tag{9}$$

$$A_2 = -c_1 c_2 k_s - k_1 k_2 m_1 - k_1 k_2 m_2 - k_1 k_s m_1 - k_1 k_s m_2 - k_2 k_s m_1 \tag{10}$$

$$A_3 = -c_1 k_2 m_1 - c_2 k_1 m_1 - c_1 k_2 m_2 - c_2 k_1 m_2 - c_1 k_s m_1 - c_1 k_s m_2 - c_2 k_s m_1 \tag{11}$$

$$A_4 = -c_1 c_2 m_1 - c_1 c_2 m_2 - k_2 m_1 m_2 - k_s m_1 m_2 \tag{12}$$

$$A_5 = -c_2 m_1 m_2 \tag{13}$$

CONCLUSION

This study aims to develop a human-body physical model that can be used together with vehicle dynamics and human-machine interaction problems. For this purpose, a lower-order model is obtained from a higher-order model proposed in the international standard using model order reduction and genetic algorithms. While the original model has eight degrees of freedom, the model proposed in this study has three degrees of freedom. When the frequency responses for the original and reduced order models are compared, a very good correspondence is observed.

Although the proposed model presents very close results to the original one, some model simplifications are performed and the model is established in such a way as to give a dynamic response in the vertical direction only, i.e. it does not consider any motion in the horizontal direction. Furthermore, the model lacks extra constraints introduced by the effects of driver belts, back and arm supports, etc. Thus, a more complicated model including these interactions can be developed in a future study.

Another simplification in the model is done by performing a linear vibration analysis although the human body represents a nonlinear behavior against vibration excitations.

Also, the head is modeled in the vertical direction although it is possible to move in both vertical and horizontal direction in response to vertical excitations.

In summary, a model with these simplifications can be used especially together with a vehicle or a machine model for a human body vibration analysis in the vertical direction. Such a simple model can be used to predict accelerations that specifically affect the driver's head. More detailed models can of course be built, but the extent to which the internal organs and musculoskeletal system are affected by vibration can be estimated by analyzing them numerically rather than analytically. However, the purpose of this article was to find a reduced order system that would of course have an acceptable analytical approach. It has been shown that this aim can also be achieved through a reduced order model such as the one proposed in this article.

Conflict of Interest

The article authors declare that there is no conflict of interest between them.

Author's Contributions

The authors declare that they have contributed equally to the article.

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