Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech. Eng., 53(Special Issue 4) (2021) 593-596
DOI: 10.22060/mej.2020.18125.6743

Modeling, design and investigation of seat suspension based on negative stiffness structure to improve the vibration environment for helicopter pilots

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ABSTRACT: The vibration transmitted to helicopter aircrew is the main risk factor for their health. In this paper, a seat suspension based on a negative stiffness structure is proposed to improve the vibration environment for the aircrew. The main advantage of the proposed seat suspension is mitigation of vibration transmitted to occupant in the same time keeping the system payload capacity. Hereafter deriving the dynamic model of the proposed system, the occupant model is attached to achieve an integrated occupant-seat-suspension model. Next, the design procedure of suspension parameters is presented to reduce the vibration transmission. In order to reach realistic results, the simulations are performed using the measured data on Bell-412 helicopter cabin floor. Then, the level of vibrations transmitted to seat and pilot body parts are evaluated using ISO-2631 and common criteria. The results show the performance of system based on negative stiffness structure is good in terms of vibration reduction so that root mean square and vibration dose value of vertical vibration for pilot's body parts are mitigated about 40% in comparison with cabin floor vibration. Also, according to ISO-2631, comfort level is upgraded from uncomfortable to a little uncomfortable which represents promotion of ride quality and improvement of vibration environment for the pilot. Furthermore, the results indicate that no frequency modulation happens in the vibration transfer path from the cabin floor to the pilot's head.

Review History:

Received: Mar. 17, 2020
Revised: Jul. 04, 2020
Accepted: Nov. 14, 2020
Available Online: Nov. 28, 2020

Keywords:

Vibration damping
Negative stiffness structure
Seat suspension system
Whole body vibration
Pilot seat

1- Introduction

A high level of undesired vibration transmitted to the pilot could lead to health problems such as fatigue, discomfort, neck strain and back pain injuries. Various reports verify high prevalence of neck and back pain among helicopter pilots regardless of the helicopter type [1]. Since redesign of helicopter structure is complex, expensive, and time-consuming, the design of high efficient novel suspension seats can be a suitable alternative to decrease the vibration transmission to the pilot. Various studies have been done on nonlinear suspension systems to reach high efficient suspension structures. Virgin et al. [2] studied a thin bent strip that behaves as a nonlinear spring to reduce the vertical vibration transmissibility. Sun et al. [3] evaluated a nonlinear isolator based on an n-layer Scissor-Like Structure (SLS) with a tunable anti-resonance frequency band. In addition, Carrella [4] proposed a useful isolation system that merges the negative and positive stiffness structures to each other.

Although traditional isolators have usually high loading capacity, their efficiency is low in terms of vibration reduction for low frequency excitation. On the other hand, new isolators with ultra-low dynamic stiffness are limited by loading capacity. In the current study, a seat suspension based on NSS is presented so that it can reduce the vibration transmissibility and at the same time keep the loading capacity of the system. In most previous works, pilot body has been assumed as a lumped mass and Whole Body Vibration (WBV) issue has been neglected. In the current study, a lumped-mass model based on ISO-5982 is considered for the pilot body to evaluate the effect of the vibration on occupant body parts. In addition, in order to achieve results closer to reality and validate high efficiency of the system under real conditions, the real vibration data of Bell-412 helicopter cabin floor is measured and applied as excitation signal.

2- Parametric Analysis Suspension System

The proposed suspension structure is such that lateral side plays a negative stiffness role for the system in vertical direction. Regarding definition of dynamic stiffness ($k = \partial F / \partial z$), if $\partial F / \partial z < 0$, it means the negative stiffness. In other words, lateral sides reduces the total dynamic stiffness of the system in vertical direction while the system loading capacity is preserved. The integrated model of suspension-seat-occupant is shown in Fig. 1. The occupant model used in the current study is according to ISO-5982, which is widely used to design, test and evaluate the seat suspension systems.

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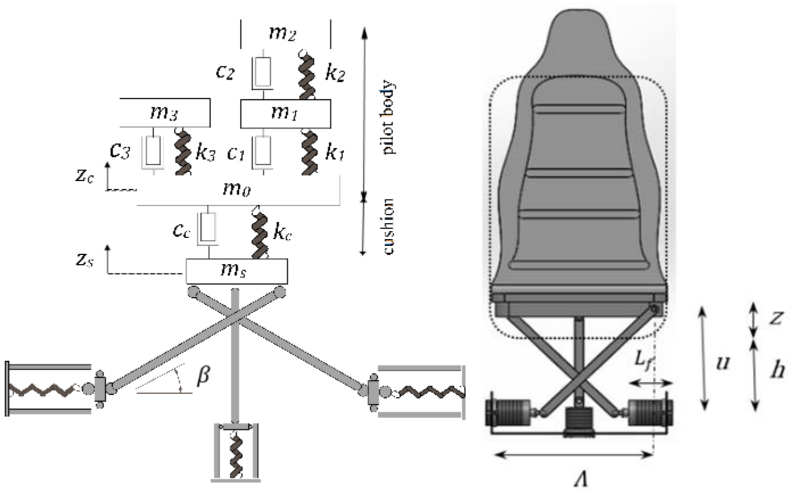

Fig. 1. The integrated model of suspension-seat-pilot

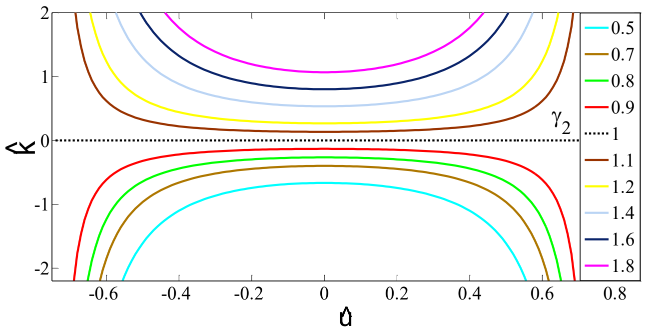

Fig. 2. Dimensionless dynamic stiffness with respect to $\hat{u}$ and γ_2 for $\gamma_1 = 0.76, \alpha = 0.5$

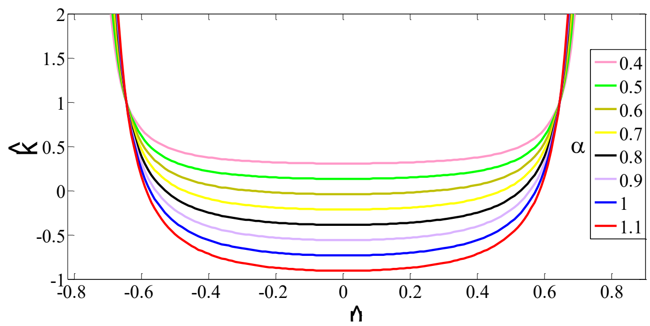

Fig. 3. Dimensionless dynamic stiffness with respect to $\hat{u}$ and α for $\gamma_1 = 0.76, \gamma_2 = 1.1$

(1)

Assume that the seat frame is displaced an amount z by force F. the relation between z and F can be calculated by the principle of virtual work.

$$F = 2k_h\left\{\frac{-L_o}{\sqrt{L_h^2-\left(\sqrt{L_h^2-(\Lambda-L_o)^2}+z\right)^2}}+\frac{\Lambda}{\sqrt{L_h^2-\left(\sqrt{L_h^2-(\Lambda-L_o)^2}+z\right)^2}}-1\right\}\left(\sqrt{L_h^2-(\Lambda-L_o)^2}+z\right)+k_v z \quad (1)$$

n dimensionless mode has advantages such as ease of analysis, ability to use in scaled system, etc. considering $u = h + z$ and the dimensionless parameters defined in Eq. (2).

$$\hat{F} = \frac{F}{k_v L_o}, \hat{z} = \frac{z}{L_o}, \gamma_1 = \frac{L_h}{L_o}, \gamma_2 = \frac{\Lambda}{L_o}, \alpha = \frac{k_h}{k_v} \quad (2)$$

The dimensionless dynamic stiffness of system can be derived using $\hat{k} = \partial\hat{F}/\partial\hat{z}$ as follows:

$$\hat{k} = 1 + 2\alpha\left(\frac{\hat{u}^2(\gamma_2-1)}{(\gamma_1^2-\hat{u}^2)^{3/2}} - \frac{(1-\gamma_2)+\sqrt{\gamma_1^2-\hat{u}^2}}{\sqrt{\gamma_1^2-\hat{u}^2}}\right) \quad (3)$$

From Eq. (3), it can be seen that $\hat{k}$ is only function of α and is independent of the seat displacement for $\gamma_2 = 1$. In Figs. 2 and 3, changes of the dimensionless dynamic stiffness $(\hat{k})$ with respect to the dimensionless displacement of the seat $(\hat{u})$ are shown. As shown in Fig. 2, $\gamma_2 < 1$ causes the system instability problem because of negative stiffness. Also, Fig. 3 shows that large value of α can lead to the same problem of instability.

Regarding $\hat{k} = k/k_d$, the lateral springs play a negative stiffness role for vertical direction only if $\hat{k} < 1$. The smaller $\hat{k}$, the greater the vibration reduction. $\alpha = 0.5, \gamma_1 = 0.76, \gamma_2 = 1.1$ can be a proper candidate according to Figs. 2 and 3.

Table 1. The values of design parameters

parameter	value	parameter	value
γ_1	0.76	L_h	30 (cm)
γ_2	1.1	$^*k_h$	4.31 (KN/m)
α	0.5	k_v	8.62 (KN/m)
Λ	20.02 (cm)	$^*c_h$	73.17 (N.s/m)
L_0	40 (cm)	c_v	731.7 (N.s/m)
L_v	20 (cm)		

$*\ k_l = k_r = k_h\ ,\ c_l = c_r = c_h$

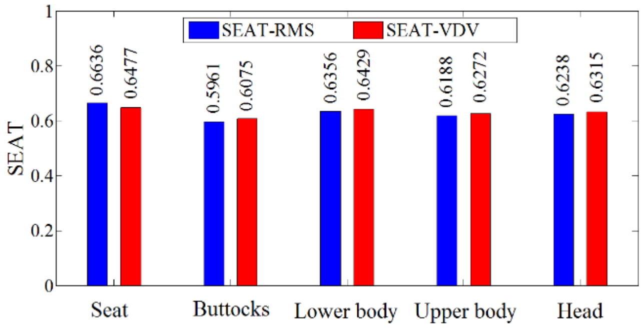

Fig. 4. The suspension performance according to SEAT

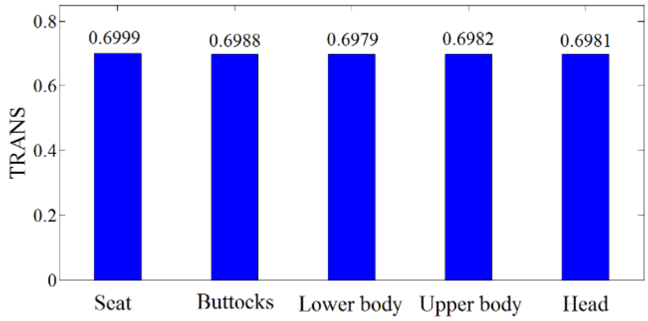

Fig. 5. The suspension performance according to the TRANSMISSIBILITY

3- Results and Discussion

Evaluation of the system dynamic stiffness, the impacts of design parameters on the dynamic stiffness and loading capacity lead to a group of suitable values for the system design parameters (Table 1).

In order to investigate the system efficiency in terms of vibration reduction, the amount of the vibrations transmitted to the seat and pilot body parts are assessed according to SEAT and TRANSMISSIBILITY.

The results demonstrate that the suspension system based on NSS decreases the vibration transmitted to body by about 40%. According to ISO-2631, comfort level of the pilot is promoted to “a bit uncomfortable”. The system response in frequency domain reveals that the vibration amplitude for the primary frequency of helicopter cabin floor (5.4 Hz) is reduced by about 80% in presence of the suspension based on NSS.

4- Conclusions

As shown by the results, the seat suspension based on negative stiffness can present significant efficiency in terms of the vibration reduction if its design parameters are chosen carefully. It seems that there is no modulation phenomenon along the vibration path. Also, it seems that suspension performance can be promoted using active control.

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HOW TO CITE THIS ARTICLE

E. Davoodi, P. Safarpour, M. Pourgholi, M. Khazaee, Modeling, design and investigation of seat suspension based on negative stiffness structure to improve the vibration environment for helicopter pilots, Amirkabir J. Mech. Eng., 53(Special Issue 4) (2021) 593-596.

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