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

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ABSTRACT

The Vibration transmitted to helicopter aircrew is the main risk factor for health. In this paper, a seat suspension based on negative stiffness structure is proposed to improve the vibration environment for 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. Here after 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 vibration 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" that represent promotion of ride quality and improvement of vibration environment for pilot. Furthermore, the results indicate that no frequency modulation happens in vibration transfer path from cabin floor to pilot's head.

KEYWORDS

Vibration damping, Negative Stiffness Structure (NSS), Seat suspension system, Whole body vibration (WBV), Pilot seat

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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 studied 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 is limited by loading capacity. In current study, a seat suspension based on NSS is presents so that it can reduce the vibration transmissibility and at the same time keep loading capacity of the system. In most previous works, pilot body has been assumed as a lumped mass and whole body vibration (WBV) issue have been neglected. In 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 of the 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 cause that total dynamic stiffness of the system in vertical direction is reduced while the system loading capacity is kept. 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.

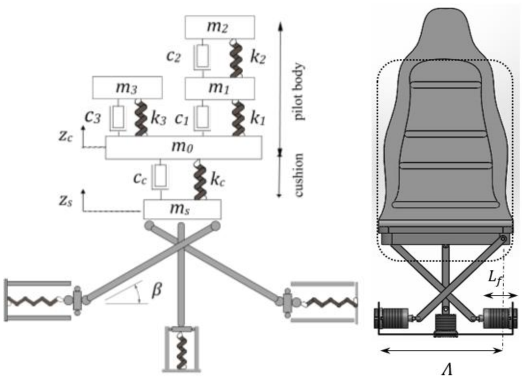

Figure 1. The integrated model of suspension-seat-pilot

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

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

The system evaluation in dimensionless mode has advantages such as ease of analysis, ability to use in scaled system and 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:

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

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.

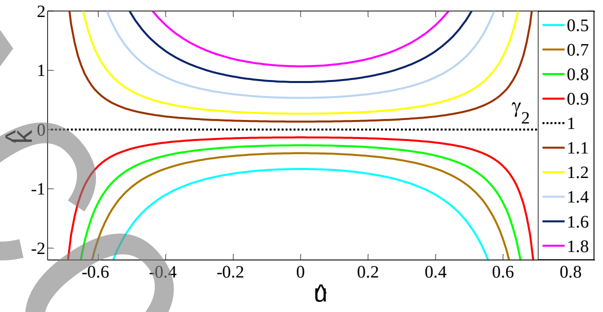

Figure 2. Dimensionless dynamic stiffness with respect to $\hat{u}$ and γ_2 for $\gamma_1 = 0.76, \alpha = 0.5$

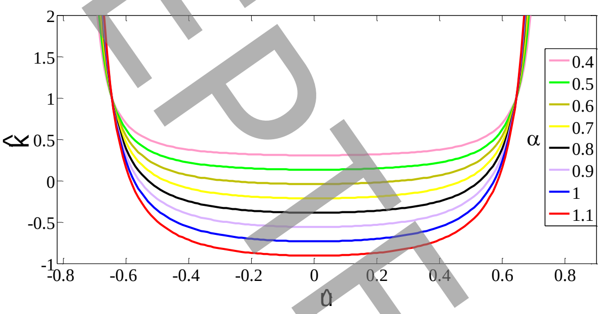

Figure 3. Dimensionless dynamic stiffness with respect to $\hat{u}$ and α for $\gamma_1 = 0.76, \gamma_2 = 1.1$

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.

3. Results and discussion

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

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)		

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

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

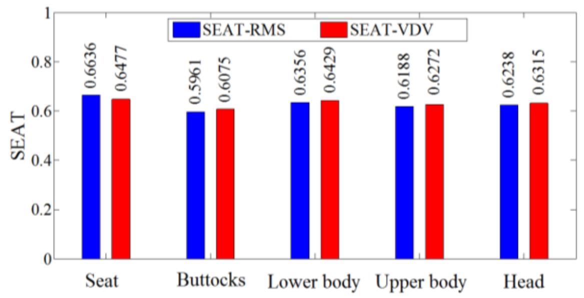

Figure 4. The suspension performance according to SEAT

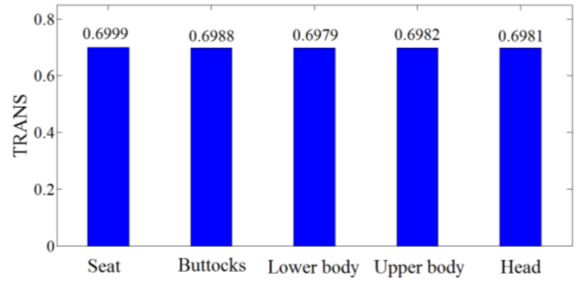

Figure 5. The suspension performance according to the TRANSMISSIBILITY

The results demonstrate that the suspension system based on NSS decrease the vibration transmitted to body 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. Conclusion

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.

5. References

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