Available online at www.sciencedirect.com

SCIENCE DIRECT®

Journal of Sound and Vibration 286 (2005) 382–394

JOURNAL OF
SOUND AND
VIBRATION

www.elsevier.com/locate/jsvi

Short Communication

# System design for isolation of a neonatal transport unit using passive and semi-active control strategies

Michael Bailey-Van Kuren*, Amit Shukla

*Department of Manufacturing and Mechanical Engineering, Miami University, 142 Kreger Hall, Oxford, OH 45056, USA*

Received 29 March 2004; received in revised form 5 November 2004; accepted 18 November 2004
Available online 25 January 2005

## Abstract

A need for vibration isolation in neonatal transport cart is recognized by the medical community. This study is a first step in the feasibility analysis and design of such vibration isolation system. For this application, an effective system can be defined as an isolation unit that reduces the level of vibration and mechanical shock experienced by the patient. A goal of this work is to provide the patient with a higher quality level of care relative to the existing neonatal transport system. Insight into the design of a vibration isolation system for a neonatal transport cart is presented with a simple 2 dof system model. The vibration isolation is done by adding air-spring-based passive and active systems. The air springs stiffness is a nonlinear function of pressure. Parametric studies performed with these models show that a passive isolation system provides stable dynamic behavior without sufficient damping. It is shown that with suitable combination of these parameters an effective vibration isolation of the neonatal transport cart is possible thus providing better quality of care.

## 1. Introduction

This study performs characterization and initial design of a vibrations isolation and/or shock suppression system to be included in a neonatal transport cart. In this application, an effective system can be defined as an isolation unit that reduces the level of vibration and mechanical shock

---

*Corresponding author. Fax: +1 513 529 1454.
*E-mail address:* baileym@muohio.edu (M. Bailey-Van Kuren).

doi:10.1016/j.jsv.2004.11.005

experienced by the patient. Acceptable vibration levels for neonatal transportation have not been defined within the medical or engineering literature. Therefore, the goal of this work is to provide the patient with a higher quality level of care relative to the existing system.

In order to meet this goal, there are several design objectives. The system design should prevent topping and bottoming out during which high amplitude impulses may be transmitted. Furthermore, the isolation system must be able to support a fully loaded neonatal transport cart. The vertical profile of the isolation system must be minimized as an ergonomic consideration to facilitate the work activities of the transport team. In order to characterize the existing system, the elements of neonatal transport and the relationship to previous transportation vibration research were explored.

### 1.1. Neonatal transport

Neonatal transport is the transport of newborn infants to a medical facility to provide critical care. Although transportation is accomplished via ground (ambulance) and air (airplane or helicopter), this project is focused on cart redesign for ground transportation. The neonatal transport cart utilized in this study is a standard cart utilized by children's hospitals. The cart is an adult stretcher with approximately 200 kg of instrumentation and equipment mounted on the platform as shown in Fig. 1. The neonatal equipment includes a TI500 Globe Trotter incubator (also referred to as the isolette), temperature-monitoring instruments, and vital sign indicators. In all, the value of this system is approximately $500,000. Transport teams utilize these carts for

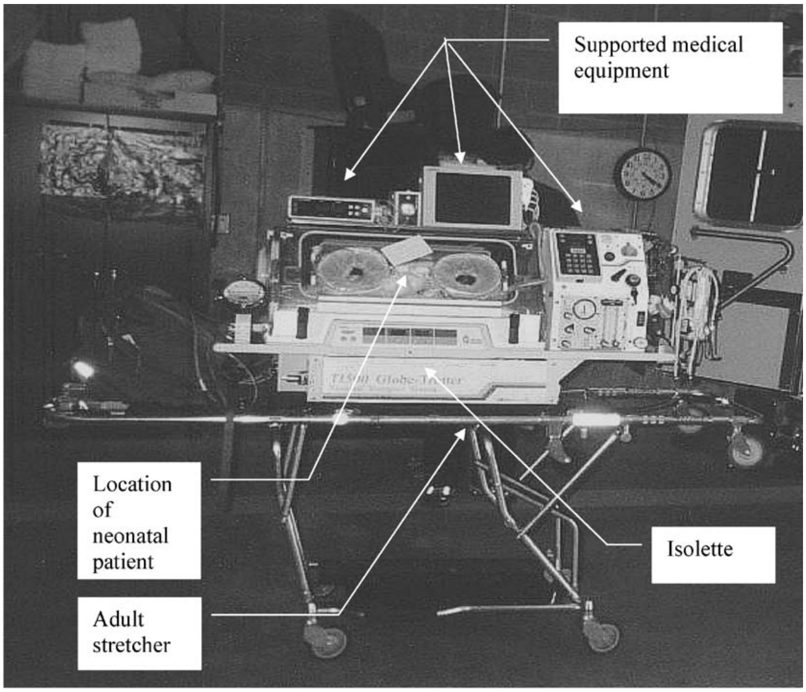

Fig. 1. Existing neonatal transport cart.

moving critical patients within a 300 km radius of the hospital on approximately 1000 runs/year. This existing system does not include a system for shock suppression and/or vibration isolation.

Neonatal patients often exhibit extreme sensitivity to external stimuli including physical manipulation. The result of external stimuli is often manifested by a change in heart rate or breathing rate ultimately affecting the oxygenation rate (% oxygen) in the bloodstream.

Many researchers have documented the adverse effects of transportation on neonatal patients. In reference to ground transportation, Powers [1] states, "Poor rear suspension with a narrow wheel base and high center of gravity, as well as poor road conditions, can lead to uncomfortable bouncing. This may be detrimental to some patients, especially those with orthopedic injuries."

Relating to air transport, Woodward and Vernon [2] noted that gravitational forces can lead to variations in cardiac output, "shifting of the patient with motion or vibration could be disastrous for one who has a cervical spine injury", and "Vibration and noise can be disconcerting to the patient, lead to increased anxiety, and be manifested physiologically by increased blood pressure, heart rate, diaphoresis, and combativeness." They state that vibration dampening should be provided.

Hawkins and Noah [3] also note that transportation can increase the stress of the infant. Iyer and Vidyasagar [4] state that "some conditions … may worsen during transport due to the vibrations and bumps of the ride" and that chest tubes "may move and get dislodged with the movement or vibrations of the ambulance." Furthermore, Ackerman [5] summarized that noise and vibration have a greater effect on neonates and that medical equipment may also be adversely affected.

Another benefit that may be realized from reducing vibration on the neonatal transport cart is that the medical equipment may be further isolated from the external vibrations. To address this problem, Wu et al. [6] developed an FEA model of printed circuit board-based medical devices to determine the effects of transportation-based vibration. However, no vibration levels measurements in actual transportation were acquired.

### 1.2. Transportation vibration analysis

Although little research has been performed in the area of neonatal transport, vibration analysis regarding vehicle passengers is well documented. Vehicle vibration research focuses on reducing passenger vibration levels within the vehicle. ISO 2631-1:1997 [7] defines discomfort levels for *whole body vibrations* (WBV). Several measures of WBV are presented with the weighted root-mean-square (rms) acceleration, $a_w$, as the primary quantity of vibration magnitude.

In order to determine the relationship to lower back pain, Chen et al. [8] studied the vibration levels in taxis and found that the mean WBV magnitude ranged from 0.17 to 0.55 m/s$^2$. Paddan and Griffin [9] studied 100 vehicles for WBV levels and found that almost all vehicles exceeded 0.47 m/s$^2$ rms which according to ISO 2631 requires "caution with respect to potential health risks" if the duration of exposure is 8 h within a 24 h period. In terms of duration of exposure, the neonatal transport problem differs from vehicle transportation since health-related effects result from a ride that is typically 1 h or less.

Donati [10] reviewed different solutions to reduce WBV in mobile machinery in order to reduce operator back injuries. Some of the solutions in mobile machinery include suspension devices between the operator and the vibration source at the tires, vehicle body, the cab and the seat. It is found that the suspension solution depends greatly on the system under consideration. Therefore, there are no direct solutions that can be applied to the neonatal transport problem.

Another possible damping solution is to use magnetorheological (MR) fluid-based systems. McManus et al. [11] studied the effects of a semi-active MR fluid damper on suspension seat performance, finding increased damping near the free travel end limits. The MR damper provided improved performance under high-magnitude excitations and when the suspension ride height was adjusted closer to the end-stops. This possible solution does address the end stop considerations required for the neonatal system. However, this can be an expensive and complex solution. The applicability of MR dampers will be a focus of future research.

This paper is organized as follows: a system model is presented to describe the neonatal transport cart and an air-spring-based suspension in Section 2. Design considerations for a neonatal transport vibration isolation system are presented in Section 3. Passive and active isolation strategies are compared. The results from these parametric studies are presented in Section 4. Some conclusions and recommendations for future work are given in Sections 5 and 6, respectively.

## 2. Neonatal cart system model

This paper focuses on modeling the transport cart dynamics for design of an air-spring-based isolation system. Design constraints for developing a suspension for a neonatal transport cart follow typical suspension design constraints. Patient sensitivity to external stimuli requires the elimination of transmitted shock when the suspension tops or bottoms out near its travel limits. Neonatal patients may experience fatigue resulting from the vibration during much shorter travel durations.

There are also unique elements of the system design. Modeling of a neonatal transport cart can facilitate suspension design-related to the suspension travel. Opposing constraints related to the suspension travel include that sufficient travel is required to avoid hitting travel end stops while limiting the travel range is needed within the cart assembly is necessary to maintain the stability of the transport cart as the center of mass is displaced vertically. Furthermore, a suspension with large travel introduces new ergonomic concerns by moving the isolette unit up and creating an uncomfortable work height for the medics.

Initial work to modify a neonatal transport cart sought to reduce the transmission of vibration to the patient during ground transportation. After evaluating other options, the shock suppression system designs were constrained to fit between the isolette and the stretcher platform. This location facilitates the use of an existing quick disconnect mechanism and minimizes the ergonomic implications on the transport team personnel. In order to identify the domain for this design, information regarding the behavior of the existing system is needed.

### 2.1. Characterization of vibration isolation for neonatal transport

Experimental studies were performed to characterize the neonatal transport system by determining dominant modes and system behavior under typical excitation. Data was collected during loading into the ambulance and during transport within the ambulance on city streets and highways. Acceleration data was obtained at the neonatal isolette and the adult stretcher frame during typical transport. Signals from piezo-electric accelerometers with appropriate signal conditioning were acquired with a Measurement Computing DAS16/16-AO with 16-bit resolution on a laptop computer. ISO 2631 [7] stresses a frequency range of 1–80 Hz for health, comfort, and perception. Thus, this initial data for system characterization was sampled at a rate of 175 Hz.

The neonatal transport cart system behavior during ambulance runs resulted in dominant frequency response between 10.25 and 17.09 Hz. Thus, the designed isolation system should attenuate above 10 Hz. Acceleration data from the transport cart while the cart was being transported by ambulance showed that the maximum vertical acceleration experienced in the system is approximately 128 m/s$^2$.

ISO 2631-1:1997 [7] relates WBV to comfort levels for a seated position with WBV between 1.25 and 2.5 m/s$^2$ defined as very uncomfortable and levels above 2 m/s$^2$ defined as extremely uncomfortable. However, the standard states “the effects of vibration on the health of persons standing, reclining or recumbent are not known”. In neonatal transport, the patient is in a recumbent position. Although WBV values cannot be directly applied to neonatal transport, the extreme sensitivity of neonatal patients would suggest that WBV levels should be maintained below levels of WBV found in other studies. Furthermore, the WBV values provide a metric for relative comparison of design alternatives.

ISO 2631 [7] defines the primary quantity of vibration magnitude as the *weighted rms acceleration*, $a_w$, which is given in Eq. (1) for translational systems. For systems with occasional shocks, the running *rms* evaluation method (Eq. (2)) resulting in a *maximum transient vibration value* (MTVV) is recommended. Since the initial data acquired during transport cart use shows that occasional shocks are experienced by the system, an alternate method to measure WBV that increases sensitivity to peaks is the fourth power *vibration dose value* (VDV) as given in Eq. (3). In these equations, $T$ represents the duration of measurement in seconds

$$a_w = \left[\frac{1}{T}\int_0^T a_w^2(t)\,\mathrm{d}t\right]^{112} \frac{\mathrm{m}}{\mathrm{s}^2}, \tag{1}$$

$$\mathrm{MTVV} = \max[a_w(t_0)]$$

where

$$a_w(t_0) = \left[\frac{1}{\tau}\int_{t_0-\tau}^{t_0} a_w^2(t)\,\mathrm{d}t\right]^{112} \frac{\mathrm{m}}{\mathrm{s}^2}, \tag{2}$$

$$\mathrm{VDV} = \left[\int_0^T a_w^4(t)\,\mathrm{d}t\right]^{1/4} \frac{\mathrm{m}}{\mathrm{s}^{1.75}}. \tag{3}$$

In order to characterize the system in terms of WBV, the sample data obtained during the ambulance ride was analyzed for a case with occasional shocks and a VDV of 0.36 m/s$^{1.75}$ was obtained. This provides a baseline for comparison as system designs are evaluated.

### 2.2. Air-spring-based vibration isolation model

The ride acceleration data was utilized to assemble a prototype air-spring-based isolation system (Fig. 2). The vibration isolation is achieved by using air springs in between the cart and the neonatal transport. Air springs are widely used for vibration isolation due to their low system natural frequencies ($<5.0\,\mathrm{Hz}$) which can be reduced even further by use of a reservoir. Further, the system natural frequencies do not change significantly with the change in load. The prototype system which included one large air spring in parallel with four small air springs was designed to support a load of approximately 2000 N. Pressure selection is essential for isolation performance. The pressure directly determines the height of the air spring and these heights change at different rates under load. The resulting challenge in the physical design of the isolation system is that the mounting plates must be able to accommodate for the variation in height between the two models of air springs. A system model facilitates the analysis of the variation in component height.

Although this air-spring-based prototype demonstrated the feasibility of an air-spring-based system for this problem, the prototype also pointed out a need for further study to investigate the damping and isolation behavior of the neonatal transport system. The neonatal transport is modeled as a 2 dof system (Fig. 3). The nominal system parameters are given in Table 1. The system model for passive isolation is

$$\begin{bmatrix} M_1 & 0 \\ 0 & M_2 \end{bmatrix}\begin{bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{bmatrix} + \begin{bmatrix} C_1 + C_2 & -C_2 \\ -C_2 & C_2 \end{bmatrix}\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} + \begin{bmatrix} K_1 + K_2 & -K_2 \\ -K_2 & K_2 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} F \\ 0 \end{bmatrix}, \tag{4}$$

where $K_2$ is the stiffness of the vibration isolator (air spring) system and is a function of the pressure in the spring as well as the configuration used. The spring rate of an air spring is not constant and is a function of the change in effective area, volume, and pressure. This stiffness of the air springs is related to two factors: the variation in volume, and the variation of effective area. This relationship was documented by Quaglia and Sorli [12] to express the

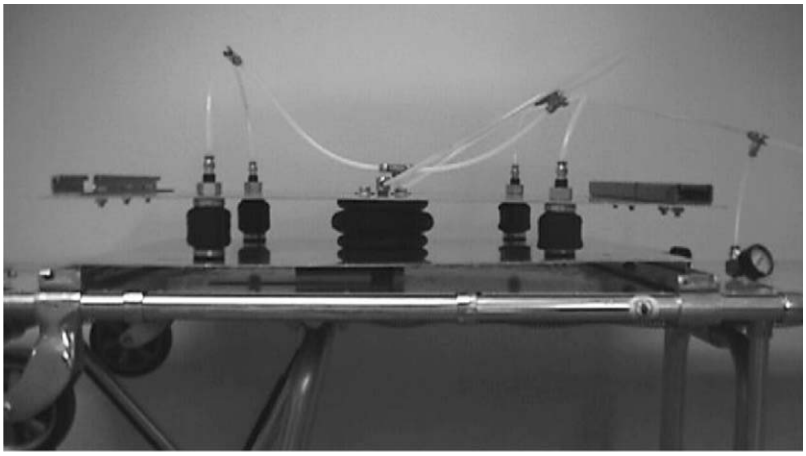

Fig. 2. Side view of prototype air-spring-based system.

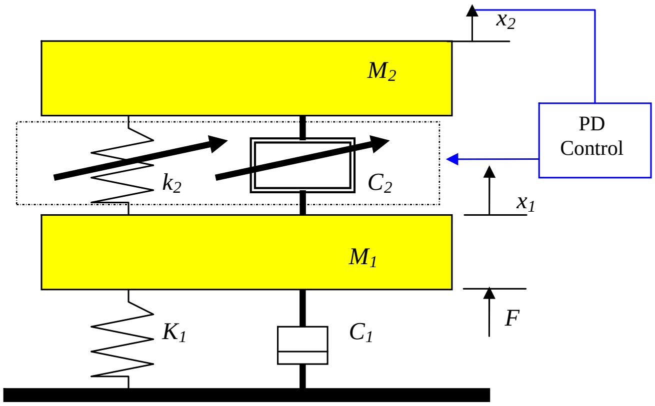

Fig. 3. Model schematic for the neonatal transport with the vibration isolator.

Table 1
Nominal system parameters

| Parameter | Symbol | Nominal value |
|---|---|---|
| Mass of the transporter | $M_2$ | 200 kg |
| Mass of the cart | $M_1$ | 22 kg |
| Stiffness of the cart | $K_1$ | 2100 kN/m |
| Stiffness of the vibration isolator | $k_2$ | 140 kN/m |
| Structural damping of the cart | $C_1$ | 2% |
| Viscous damping of the vibration isolator | $C_2$ | 4% |

Table 2
Air-spring stiffness equation parameters

| Equation parameter | Description |
|---|---|
| $N$ | 1.38 for adiabatic expansion |
| $P_1$ | Pressure in the spring |
| $V_1$ | Volume of the spring |
| $A$ | Cross-section area of the spring |
| $H$ | Height of the spring |
| $P_a$ | Ambient pressure |

overall stiffness as

$$K_2 = \frac{nP_1 V_1^n A}{V_1^{n+1}} \frac{\mathrm{d}V_1}{\mathrm{d}h} - (P_1 - P_a) \frac{\mathrm{d}A}{\mathrm{d}h}, \tag{5}$$

where $K_2$ is the stiffness of the air-spring system, the equation parameters are defined in Table 2. The damping of the air spring, $C_2$, is 4% based on the air spring product literature. This nonlinear model is utilized for evaluating the resultant stiffness of the air spring.

## 3. Vibration isolation system design

### 3.1. System design strategies

The isolation of vibrations generated during the ride of a neonatal transport can be limited or altered by using passive or active control strategies. As proposed in this work the original neonatal transport system prototype design is a pneumatic air-spring-based passive vibration isolation system. It is shown that some tuning of system parameters (stiffness) is possible by adjusting the nominal air-pressure in these air-spring-based isolators. However, the damping associated with the air-spring-based isolation/suspension systems is negligible. To enhance damping behavior of the air-spring-based suspension systems an active system configuration is also investigated.

In a vibration isolation and/or control system, the amount of external power (energy) required to achieve the desired operation dictates if the system is passive or active. Passive vibration isolator systems only utilize passive stiffness and damping elements. On the other hand, if either the stiffness or the damping element is active in nature then the vibration isolation system is active. The neonatal system input excitation signals are of a broad band nature since they are generated by the ambulance riding on a variety of road conditions. Furthermore, the neonatal isolette is configurable (depending on the requirements of the patient being transported) which can lead to changes in system properties (mass, etc.) at different times of operation. Furthermore, damping in the air-spring-based system can only be controlled by employing an active control mechanism.

Although, in this study, the prototype passive system performed well in terms of shock suppression, the vibration isolation capabilities need to be determined. In some systems, passive isolators can lead to poor vibration isolation characteristics or even vibration enhancement. In our application, $M_2$ may vary due to different configurations of medical equipment attached to the cart. Therefore, a single passive system design cannot address all possible configurations. An active vibration isolation/control system can be an alternative. However, the active system must exhibit a substantial increase in performance to justify implementation over the simpler and less costly passive system.

The active system is based on an active controlling force that is used to modify the stiffness and damping properties of the isolation system actively in response to the external vibration. This active controlling force is generated using a control strategy or algorithm that produces the desired system response. However, active control and isolation systems may suffer from control-induced instabilities [13].

In the design of vibration isolation and control systems much emphasis is placed on design simplicity, overall stability, low-cost and low-energy requirements. An active vibration control strategy is investigated which utilizes a proportional and derivative controller gains to achieve an active restoring force by modifying the pneumatic pressure in the air springs. The output of interest to this study is the position of the neonatal transport cart. The mathematical models and the appropriate passive–active control theory used in this work are widely known to the research community. However, the goal of this work is to demonstrate the simple use of vibration isolation for a medical application of interest namely, a neonatal transport.

### 3.2. Isolation system design criteria

The design criteria for any vibration isolation system are to improve the transmissibility of the associated system by providing a modification to the characteristic parameters such as mass, damping and/or stiffness. The transport cart problem is concerned with force transmissibility as opposed to displacement transmissibility. In addition to transmissibility requirements, there is a need for stability of the overall system in the design of vibration isolation for a neonatal transport. In light of these objectives this work explores the parameters of the vibration isolation system to develop the best-possible design option for both a passive as well as an active control strategy.

### *3.3. Suggested designs*

The passive isolation system model is studied for three configurations of air springs for vibration isolation:

Configuration 1: One 11.43 cm diameter spring at the center.
Configuration 2: Four 3.4 cm diameter springs around the edges.
Configuration 3: One 11.43 cm diameter spring at the center and four 3.4 cm diameter springs around the edges.

These configurations explore the differences between using a single large air spring versus a set of smaller air springs. The nominal stiffness of the large diameter air spring is approximately equivalent to the nominal stiffness of the four small diameter air springs in parallel. Configuration 2 provides additional lateral stability to the system as compared to Configuration 1. The final configuration is a redundant system with a resulting increase in stiffness which has some reliability advantages in case of air-spring failure in the field.

The active control system model uses proportional and derivative (PD) control to actively modify the air-spring stiffness by changing the air-spring pressure and thus directly effecting the restoring force due to the air-spring-based suspension system. Fig. 3 shows a schematic of the proposed approach. The parameters of interest are air-spring stiffness ($K_2$), proportional gain ($K_p$) and derivative gain ($K_d$). The nominal system parameters are $K_2 = 800$, $K_p = 800$ and $K_d = 400$. This model is further investigated to study the stability behavior and enhanced damping characteristics.

## 4. System design analysis

The design of isolation system requires a thorough understanding of the system dynamics and response to external vibrations on the parametric space. The parameters of interest to this study include the stiffness of the air-spring isolator and the controller parameters. The aim of the following studies is to investigate the effect of parametric change (pressure of air spring, mass, configuration, etc.) on the ability of the air springs to isolate vibration of the neonatal transporter.

Configuration 1 is utilized as the baseline case in this paper and corresponds to a single 11.43 cm diameter air spring. The transfer function of the position output over the force input for configuration 1 is shown in Fig. 4. The first natural frequency due to the inclusion of air springs is close to 2 Hz. The second natural frequency of the system is close to 18 Hz. It is also shown that effective attenuation of the vibrations is achieved by the air springs. Fig. 4 further shows the difference in the transfer function at the nominal pressure in air springs for the three different configurations. At higher frequencies ($>10\,\mathrm{Hz}$) the attenuation obtained for the three different configurations is practically same, however at lower frequencies the response amplitude is considerably affected by the choice of configuration. Further, as the stiffness of an air spring is a nonlinear function of the pressure (Eq. (5)) an increase in air pressure results in a higher stiffness of the air spring. Configurations 1 and 3 display a similar decrease in transmission at low frequency but to a lesser degree. The differences in the high frequency ranges of all three configurations do not correspond to any detrimental behavior of the system at high frequency due to the change in pressure.

It is expected that as the pressure in the air springs is increased, the amplification of the input at the damped natural frequency of the system increases. Furthermore, an increase in air-spring pressure increases the stiffness associated with the spring which increases the natural frequency. The effective stiffness for each configuration differs due to the contributions of the individual springs and the corresponding pressure. The effect of variation of several parameters including the air-spring stiffness (due to variation in air pressure), and controller parameters (proportional gain and derivative gain) on the eigenvalues of the closed loop system (Fig. 5) is essential in the design of the isolator. Fig. 5(a) clearly shows that the dynamic stability of the neonatal transport is robustly preserved by addition of a passive element. Only configuration 1 is analyzed as the trends in eigenvalue analysis will be similar for the other two configurations. It can be concluded that some limited control over isolator frequency can be achieved by changing the pneumatic pressure of air-spring isolators.

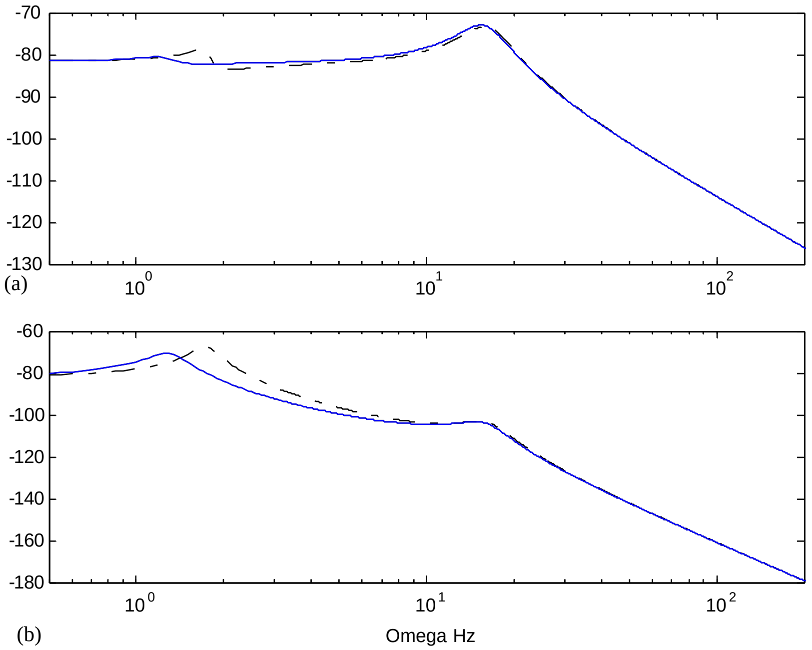

Fig. 4. Transfer function of the (a) stretcher ($M_1$) (stretcher position/input force) and (b) incubator ($M_2$) (incubator position/input force). The three configurations are: configuration 1 (-·-·-); configuration 2 (- - - -) and configuration 3 (——).

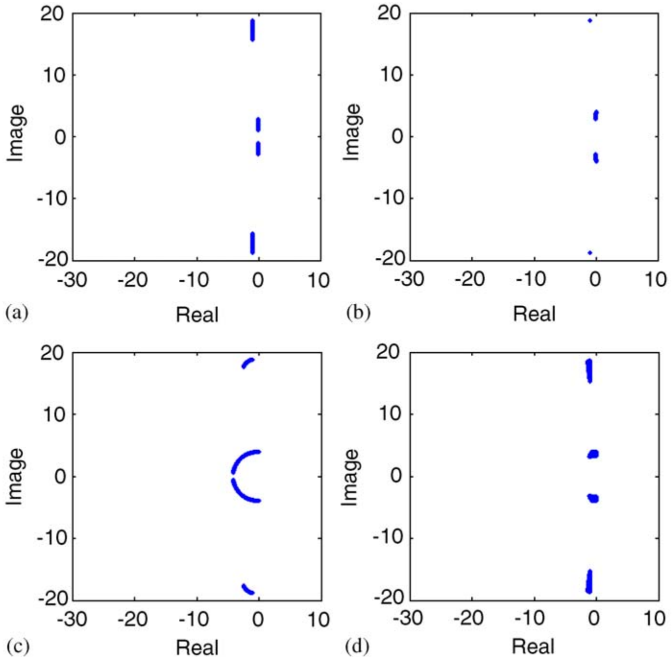

Fig. 5. The effect on the system eigenvalues due to varying (a) air-spring stiffness, (b) proportional gain, (c) derivative gain, and (d) both air-spring stiffness and derivative gain.

The parameters of interest for the active PD controller are air-spring stiffness ($K_2$), proportional gain ($K_p$) and derivative gain ($K_d$). The nominal system parameters are air-spring stiffness of 140 kN/m, proportional gain of 800 and derivative gain of 400. Fig. 5(b) and (c) show the variation in the frequency and damping characteristics of the system as represented by the eigenvalues as the controller parameters are varied. The effect of increasing proportional gain is to result in increase in the frequency of the first mode. The effect of derivative gain is more significant on the damping of each of the system modes. As we vary both air-spring stiffness and derivative gain some variation in the frequency of each mode is possible which can be utilized to design appropriate isolator for the neonatal transport application. A key motivation for using the active strategy for vibration isolation using air springs is the ability to control damping behavior. However, it is well known that active control strategies can lead to loss of stability. Hence control parameters will need to be carefully tuned to enhance damping.

Another issue of relevance in the design of an isolator is the concept of reactivity, which is the maximum amplification rate, over all initial perturbations, immediately following a perturbation from an equilibrium state. Reactivity can be evaluated as the norm of the *Hermitian* matrix of the system evaluated at the equilibrium state [14]. A positive value of the reactivity indicates that no matter how small a perturbation the response will initially grow in magnitude. The greater the reactivity the larger is this initial growth to a perturbation. Fig. 6 shows the reactivity of this system as a function of the vibration isolator stiffness and the controller parameters (gains). It is shown that the isolator stiffness has the least reactivity as compared to the controller gains. Also, with in the range of parameters the reactivity is always a positive number for this system. So for

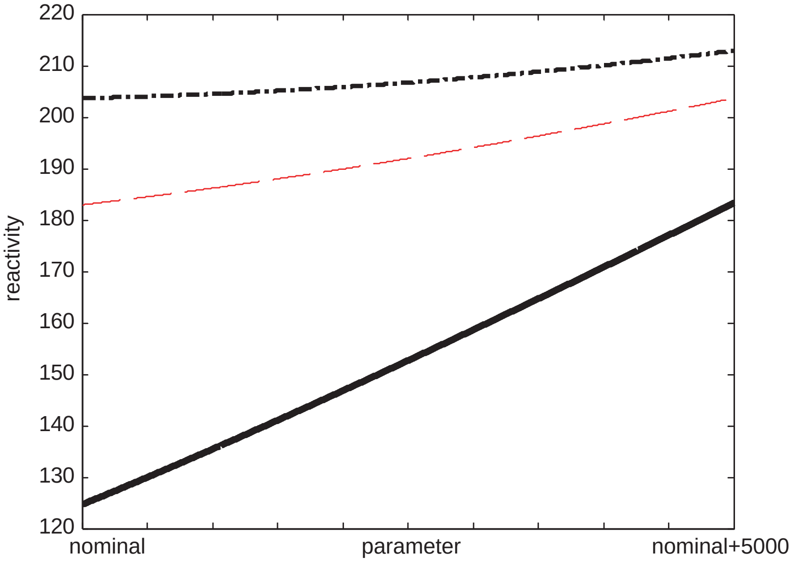

Fig. 6. Reactivity as a variation in vibration isolator stiffness (——), proportional gain (- - -) and derivative gain (-·-·). The parameters were varied from a nominal value linearly in unit increments up to nominal + 5000. The nominal values for this study are air-spring stiffness (400 lb/in), proportional gain (10) and derivative gain (1).

isolator design the smaller values of isolator stiffness, proportional gain and derivative gain will be advantageous and recommended.

## 5. Conclusions

Insight into the design of a vibration isolation system for a neonatal transport cart is presented with a simple 2 dof system model. Parametric studies performed with these models show that a passive isolation system provides stable dynamic behavior without sufficient damping. It was also found that some limited control over isolator frequency can be achieved by changing the pneumatic pressure of air-spring isolators. The passive system configuration can greatly affects the response amplitude at lower frequencies ($<10$ Hz). It was found that the configuration 2 provided the best isolation characteristics for a passive system among the test cases.

In terms of active control, the effect of varying both air-spring stiffness and derivative gain results in a trade-off in the damping associated with the first and second modes. Although a loss of stability occurs it is not in the range of operation for the system. Varying air-spring stiffness and the proportional gain produced similar results.

Based on this study, a prototype system developed for passive isolation will be further implemented, tested to confirm system behavior and tested in clinical trials. A vibration isolation system with a lower vertical profile than the current passive solution would be beneficial in terms of ergonomics for medical personnel. The stability of the isolette in tipping during braking is to be further investigated. One damping solution of interest is to apply magneto-rheological (MR) fluid-based dampers for vibration isolation in the neonatal transport system and is a matter of future research interest to the authors.

## Acknowledgements

This work was made possible with a grant from the American Society of Quality Biomedical Division, donated air springs from Firestone Industrial, resources of the Ohio Supercomputing Center, and the transport team from Cincinnati Children's Hospital.

## References

[1] K.S. Powers, Organization of a pediatric–neonatal transport program, in: *Handbook of Pediatric and Neonatal Transport Medicine*, Hanley & Belfus, Philadelphia, 1996.

[2] G.A. Woodward, D.D. Vernon, Aviation physiology in pediatric transport, in: *Handbook of Pediatric and Neonatal Transport Medicine*, Hanley & Belfus, Philadelphia, 1996.

[3] H. Hawkins, Z. Noah, Equipment, in: *Pediatric Transport Medicine*, Mosby, St.Louis, MO, 1995.

[4] R.S. Iyer, D. Vidyasagar, Transport issues in neonates with respiratory problems, in: *Handbook of Pediatric and Neonatal Transport Medicine*, Hanley & Belfus, Philadelphia, 1996.

[5] N. Ackerman, Aeromedical physiology, in: *Pediatric Transport Medicine*, Mosby, St. Louis, MO, 1995.

[6] J. Wu, R.R. Zhang, S. Radons, X. Long, K.K. Stevens, Vibration analysis of medical devices with a calibrated FEA model, *Computers and Structures* 80 (12) (2002) 1081–1086.

[7] International Organization for Standardization, ISO 2631-1: Mechanical vibration and shock—Evaluation of human exposure to whole-body vibration—part 1: general requirements, 1997.

[8] J.C. Chen, W.R. Chang, T.S. Shih, C.J. Chen, W.P. Chang, J.T. Dennerlein, L.M. Ryan, D.C. Christiani, Predictors of whole-body vibration levels among urban taxi drivers, *Ergonomics* 46 (11) (2003) 1075–1090.

[9] G.S. Paddan, M.J. Griffin, Evaluation of whole-body vibration in vehicles, *Journal of Sound and Vibration* 253 (2002) 195–213.

[10] P. Donati, Survey of technical preventative measures to reduce whole-body vibration effects when designing mobile machinery, *Journal of Sound and Vibration* 253 (1) (2002) 169–183.

[11] S.J. McManus, K.A.St. Clair, P.Ed. Boileau, J. Boutin, S. Rakheja, Evaluation of vibration and shock attenuation performance of a suspension seat with semi-active magnetorheological fluid damper, *Journal of Sound and Vibration* 253 (1) (2002) 313–327.

[12] G. Quaglia, M. Sorli, Experimental and theoretical analysis of an airspring with auxiliary reservoir, in: *Proceedings of the Sixth International Symposium on Fluid Control*, *Measurement and Visualization*, Sherbrooke, Canada, August 2000.

[13] A. Shukla, M. Bailey-Van Kuren, Nonlinear dynamics of a magneto-rheological-fluid-based active suspension system for a neonatal transport, in: *Proceedings of the SPIE Smart Structures and Non Destructive Evaluation Conference*, San Diego, March 2004.

[14] R.A. Horn, C.R. Johnson, *Matrix Analysis*, Cambridge University Press, Cambridge, 1985.