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HAVS and HAV-nots: Investigating Resonance in the Human Arm Caused by Contact with Machinery

Irina Viktorova¹, Matthew Fleck¹ and Muhammed Kose¹

1 – Department of Mathematical Sciences, Clemson University, Clemson, South Carolina



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ABSTRACT. Mechanical vibration is a vast field composed of thousands of studies and experiments regarding individual systems and structures' vibrations and oscillations. In this paper a special and complex case regarding hand-arm vibration will be studied and analyzed mathematically. The human hand-arm system is affected by vibrations caused by contact with vibrating objects. In order to understand the effect on the hand-arm system, a mathematical model of the system as two viscoelastic rods connected by a hinge was derived. Using this model, it was possible to derive the propagation of both the longitudinal and bending vibrations of the arm, and find the resonance frequencies of the system from the elbow to the shoulder. The harmful effect of these frequencies is discussed with regards to Hand-Arm Vibration Syndrome, a disease stemming from repeated contact with vibrating objects. Hand-Arm Vibration Syndrome is found to be a pervasive issue among physical laborers who use vibrating machinery. A sample set of construction tools is analyzed and compared with the modeled resonance frequencies of the arm. Considering the resonance frequencies of the arm is significant for tools manufacturers. Research on the frequencies at which tools function may be overly dangerous to workers who are required to handle such tools frequently.

Introduction. Vibration is a common byproduct of mechanical technology. Construction and contract workers typically are in contact with such technology on a daily basis. This interaction has been found to lead to a disease known as Hand-Arm Vibration Syndrome (HAVS). The disease causes intensive damage to the hand and arm and can be debilitating. Individual machines emit vibration at a specific frequency, and if it is at the natural frequency of the material in the human arm or hand, can cause devastating damage and more quickly lead to the development of HAVS. Therefore it is important to know accurately the resonance frequencies in the arm and compare them to the individual frequencies emitted by construction technology. Due to the extreme difficulty of gathering data on the human arm from a living subject, models of the arm are a practical solution to the resonance problem. An investigation of the arm modeled and analyzed as two viscoelastic rods is conducted below.

Resonance. Resonance is the phenomenon at which an externally forced frequency coincides with the natural frequency, defined by a ratio close to one between the two frequencies. When damping is present, pseudo resonance will occur with the maximum amplitude of the vibrating object. In general, amplitude is not linearly dependent on frequency. An important case of resonance, including the hand-arm system, relates amplitude A to the square of the frequency ω [1]. The case of resonance in the hand-arm system will be examined later.

The Hand-Arm System and Vibration. It is difficult to envision the human body, or any living organism, as a structure that can be mathematically modeled. The vast complexity of the body makes it incredibly difficult to predict, record, or analyze information about bones or organs, despite the large variety of stresses they undergo. Vibration is one such stress; it enters the body when an organ makes contact with a vibrating object, such as a jackhammer. An instance of whole body vibration would be sitting in a car when driving on a gravel road. A very common tremor experienced by humans is hand-arm vibration. When exposed repeatedly over long periods of time, there is risk to the nerves in the fingers, hand, and arm. This condition is known as hand-arm vibration syndrome

(HAVS). HAVS symptoms include, but are not limited to, loss of feeling in the hand or arm, recurrent pain, and blanching [2]. The National Institute of Occupational Safety and Health estimates over 1.2 million workers are subject to hand-arm vibration and are at risk for HAVS. This is seen below in Fig. 1. Clearly, HAVS is a pervasive issue for many physical laborers. Prolonged exposure to vibrating machinery increases the severity of the syndrome. This means that by decreasing the number of machines and tools that operate at a resonant frequency of the hand or arm, long term damage to the hand-arm system can be drastically lessened.

No. of Workers	Industry	Type of Tool
500,000	Construction	Handtools
200,000	Farming	Gasoline chain saws
14,000	Metal working	Handtools
54,000	Steel	Furnace cleaning using powered handtools
30,000	Lumber and wood	Gasoline chain saws
34,000	Furniture manufacturing	Handtools
100,000	Mining	Pneumatic drills
250,000	Truck and auto manufacturing	Handtools
64,000	Foundries	Handtools
Total	1,246,000	

Fig. 1. Hand-arm vibration exposure statistics by occupation [2]

Viscoelastic Modeling of the Hand-Arm System: The problems of vibrosafety are connected with considering the human reaction to various mechanical inputs and traditionally is sorted as a mechanical system with concentrated, undistributed parameters.

This is a simple and effective approach, but with an obvious drawback; setting up a system similar to the actual human arm is possible only if an experimental subject is available. However, analyzing the human body and its parts as a solid mechanical body presents of a lot of challenges. Human organs have a complicated shape and the biomaterial of human tissue is not fully researched. There is plenty of data on the experimental study of bone structures, but it is difficult to compare due to the different conditions of testing, the different animal species they belong to, et cetera. Similarly, the available data on mechanical properties of human muscle tissue is contradictive and unreliable. Thus the methods of mechanics of solids has not been applied to analysis of the hand-arm vibration. The same reasoning is applied to the problem of the vibrations propagation in the human tissue. The objective of this model is to show how to generalize the analysis of the harmonic wave propagation along the human arm.

The human arm is modeled as the system of two homogeneous viscoelastic rods of λ_1 and λ_2 lengths each, joined by a hinge [3]. The modality of the muscle and bone tissue as a homogeneous and viscoelastic solid is based on the experimental mechanical testing data on the bone structure which shows that the bone tissue does behave as the linear viscoelastic material. The material surrounding the bone muscle tissue causes the increase in viscoelasticity and accounts for the parameters of the model equation. The rods are considered homogeneous since the wavelengths, at lengths of tens of meters, at the frequencies considered are overwhelmingly greater than the maximum cross-sectional measurements for the human arm, which the results in the propagation solely in a two dimensional front plane. This allows nonhomogeneity to be neglected [3].

Mathematical Analysis: The problem of vibrations propagating along the human arm is divided into two parts. The first is related to longitudinal oscillations propagating from the hand to the elbow. The second is related to propagation of the superposition of longitudinal and bending vibrations from the elbow to the shoulder, with the action ratio being defined by the angle of bending for the elbow joint. Thus, if the arm is straight and the bending angle is 0, there is no bending mode involved. On the contrary, if the angle is 90 degrees, then only the bending component is important to account for [3]. In the following equations, W is the amplitude; ω is the vibrational frequency; λ is the length of the rod; and x is the position of the cross section of the rod in relation to $\lambda=0$. k is a constant equal to $\frac{r}{2}$ where r is the radius of the cylinder. The amplitude of the bending vibrations is then given by the formula:

$$W = \frac{\omega}{2} \left[\frac{S_1 \sin(kx) - S_2 \sinh(kx)}{\sin(k\lambda) \cosh(k\lambda) - \cos(k\lambda) \sinh(k\lambda)} \right] + \cos(kx) + \cosh(kx) \quad (1)$$

where

$$S_1 = 1 - \cos(k\lambda) \cosh(k\lambda) - \sin(k\lambda) \sinh(k\lambda) \quad (2)$$

$$S_2 = 1 - \cos(k\lambda) \cosh(k\lambda) + \sin(k\lambda) \sinh(k\lambda) \quad (3)$$

The propagation of longitudinal and bending vibrations along a viscoelastic rod of finite length can be modeled by the combined theory of wave propagation in viscoelastic solids. [4][5]. It should be stressed that the combination of longitudinal and bending vibrations along the second rod between the elbow and the shoulder are characterized by the amplitude value, which depends on the angle of the bent elbow. The amplitude of longitudinal vibrations that have reached the shoulder joint decreases due to the viscosity of the body tissue and the distribution into the bending and longitudinal modes. The simplified amplitude of the bending vibrations at $x = \lambda_2$, where λ_2 is the length of the rod between the elbow and the shoulder, is defined by the expression:

$$W(x = \lambda) = \omega * \left[\frac{\sin(k\lambda) - \sinh(k\lambda)}{\sin(k\lambda) \cosh(k\lambda) - \cos(k\lambda) \sinh(k\lambda)} \right] \quad (4)$$

Equation (4) models the amplitude W as a function of ω and λ , where k is a constant. In addition, there is an amplification factor ρ that relates the amplitude of displacement and the frequency ω of bending vibrations [3]. The relationship is represented by the equation:

$$\rho = \frac{(\cosh(\omega) - \cos(\omega) - \sin(\omega) \sinh(\omega))^{\frac{1}{2}}}{\sqrt{2}(\sinh(\omega) - \sin(\omega))} \quad (5)$$

It is important to note that equations (1) and (4) only characterize the bending vibrations in the arm, while (5) encompasses the complex vibrations in the hand-arm system. Differentiating equation 5 with respect to ω and setting it equal to zero obtains the values of ω that produce the minimum and maximum amplitudes of vibration. Setting the derivative equal to zero and solving gives the first extremum at $\omega=3\pi$ [3]. Simplifying the first derivative of (5) with $\omega = 3\pi$ gives:

$$\frac{d\rho}{d\omega} = \sinh(\omega)^2 * [\sin(\omega) - \cos(\omega) - 1] = 0 \quad (6)$$

This solution shows that maximum and minimum amplitudes occur at frequency intervals $\omega = \frac{\pi}{2} + n\pi$ and $\omega = \pi + n\pi$ for all n . By differentiating ρ again, it is possible to find whether the extremum frequency is a maximum or a minimum value. Plugging in 3π to the second derivative of (5) produces a negative value. This means that the frequencies at $\omega = 3\pi, 5\pi, 7\pi \dots$ are where the maximum values of amplitude occur. These values are the resonance frequencies.

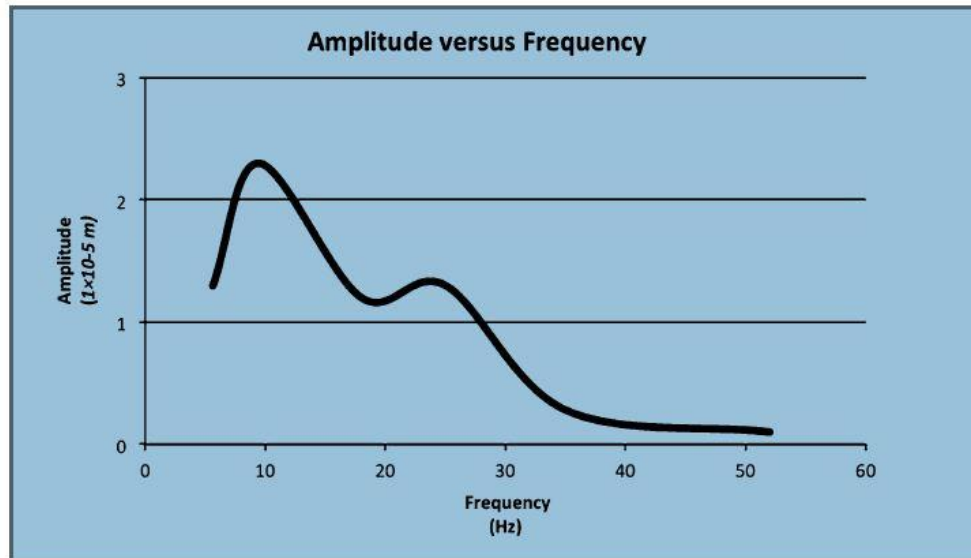


Fig. 2. Relationship between Frequency and Bending Amplitude for human arm vibration [3]

Fig. 2 shows that the amplitude of a propagating wave along the human arm is a function of the frequency. Equation (5) also demonstrated that the ratio of the amplitudes is proportional to the squares of the frequency ratios [3]. By plugging in the frequencies at which the first maximum amplitudes occur, 3π and 5π , and using the relationship between the amplitude and frequency ratios, it can be determined that the first ratio of maximum amplitudes is $\frac{(3\pi)^2}{(5\pi)^2} = \frac{9}{25}$. This ratio, $\frac{9}{25}$, matches the data shown in Fig. 2, which contains experimental data collected from an external study [3]. This confirms the theoretical results of the resonance frequencies in the human arm. The amplitude increases significantly when a piece of equipment vibrates at a resonant frequency. For example, the amplitude at the frequency 3π Hz is approximately 2.4×10^{-5} meters, compared to about 1.3×10^{-5} meters at 6 Hz and 15 Hz. Fig. 2 illustrates this spike in amplitude. The increased amplitude means that a larger amount of energy is being transferred into the hand-arm system because the energy is proportional to the square of the vibrational amplitude.

Constructional Tool Data: Clearly, the vibration of a handheld tool vibrating at a resonance frequency will lead to a great amount of energy propagating through the arm. This higher amplitude resulting from resonance also means the hand-arm system undergoes larger displacements. The vibrations from work equipment displace the arm repeatedly, damaging the tissue and bone. When a piece of equipment vibrates at one of the arm's resonance frequencies, the amplitude is increased along with the amount of energy surging through the arm. This displacement of the arm is one of the central causes of HAVS.

TABLE II
Summary of Dominant Frequency and Corresponding Individual Axis Acceleration
Magnitude for Tools Tested

Tool Description	Handle	No. of Hands	Abrasive	Frequency (Hz)	Magnitude (m/s ²)		
					X	Y	Z
Hand grip orbital sander	main	1	100 grit	90	50	60	190
		2	100 grit	90	30	70	220
	body	1	80 grit	90	70	50	120
		2	80 grit	90	40	90	110
		2	100 grit	90	90	110	140
		2	80 grit	90	60	80	90
Palm grip orbital sander	body	1	320 grit	150	120	70	40
	body	1	100 grit	150	120	70	170
	body	1	80 grit	150	115	60	120
Impact wrench	body	2	locked spindle	50	10	10	10
Heavy duty right angle sander	main	2	80 grit	45	5	2	2
	dead	2	80 grit	45	5	6	6
	main	2	grinding disc	80	90	70	40
	dead	2	grinding disc	80	40	50	80
Trimming shear	main	1	blade	35	6	15	10
Light duty right angle sander	main	2	fine disc	70	3	2	1
	dead	2	fine disc	70	2	6	7
Jitterbug sander	body	1	230 grit	100	290	110	130
Vertical polisher	right	2	polishing pad	100	20	20	20
	left	2	pad	100	30	20	150

Fig. 3: Frequencies and Directional Accelerations of Various Tools used in an Automotive Assembly [6]

It is crucial then to know the frequencies at which tools typically operate. A list of frequencies specific to certain tools in an automotive assembly plant is shown in Fig. 3.

In the example set of tools above, the dominant frequencies of all tools measured were greater than the theoretically calculated resonance frequencies of 3π and 5π hertz. These resonance frequencies apply to the region of the arm beyond the elbow and extending to the shoulder. According to research done by the Center for Disease Control, most mathematical models find that vibration energy propagating at frequencies lower than 80 hertz affects the arm, while tools with vibrating frequencies greater than 100 hertz typically are limited to transferring energy just into the hand [2]. This agrees with what was found in the mathematical analysis for the viscoelastic rod model.

Fig. 4 demonstrates a model done by an external study that agrees with this above trend. Vibrations at lower frequencies transfer more energy per unit time to the shoulder, while higher frequencies transfer much less. There is also a spike in absorbed power at approximately 3π Hz, which concurs with the resonance frequency found using the viscoelastic rod model [3]. The tools included in the study shown in Fig. 3 would not cause resonance in the shoulder region of the arm. However, this sample set is clearly not enough data to conclude that a majority of power and construction tools do not vibrate at a frequency to cause resonance and therefore increase the amplitude of stress waves propagating across the human arm. It is recommended that all tools manufacturers list the dominant frequencies at which their products operate and attempt to minimize the production of tools that operate near the resonance frequencies of the arm.

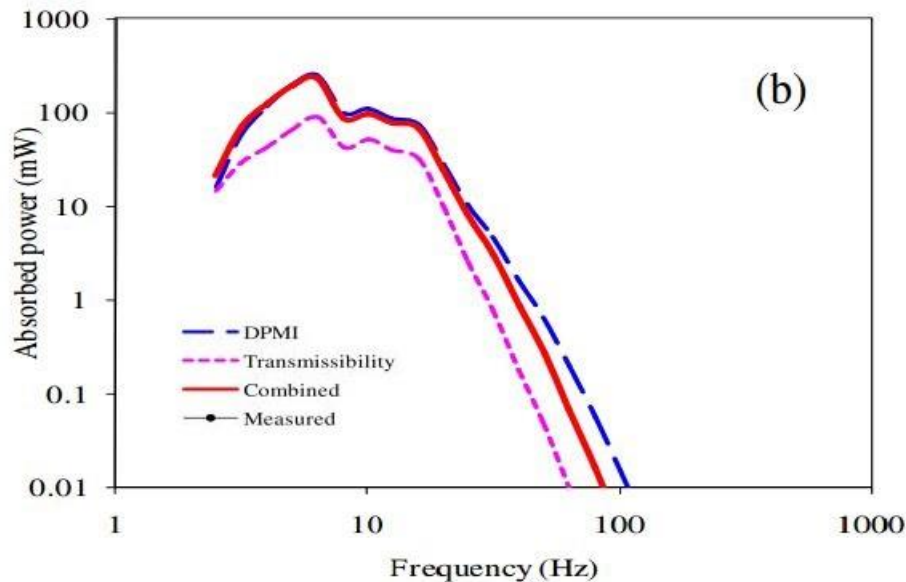


Fig. 4. Vibrational power absorbed at the shoulder of an extender arm as a function of frequency [7]

HAVS Prevention Methods: It may be recommended that the workers invest in anti-vibration gloves. Manufacturers produce the protective characteristics of the gloves in several ways. They may increase the thickness of the contact patch on the glove in order to absorb vibration with the extra padding. This is the most commonly used technique. They may also use an anti-vibrational polymer such as Vibrastop Nylon. Adding such a polymer to the fabric increases glove's vibrational absorption. This method maintains a slimmer sized glove. Another method, patented by the worker safety firm Impacto©, is to insert small air bubbles into the glove. The glove acts similarly to bubble wrap and protects the hand [8][9]. These types of gloves can be purchased at a price close to non-protection construction gloves and are an inexpensive and effective way to lower the risk of damage to the hand-arm system due to contact with vibrating machinery.

It may also be recommended that the construction companies invest in anti-vibrational machinery for the long-term health and safety of their workers. Unfortunately anti-vibrational mechanisms in machinery are only built into the high cost brands. In some instances, like the Bosch jackhammer, manufacturers claim a reduction of the vibrational transmission to the hand-arm system by up to 40% [10].

Summary It is clear that the hand-arm system has been greatly simplified for analysis. However, the model system of two linear viscoelastic rods and a hinge allows the study of resonance using the relationship between amplitude and frequency. The model also determines the viscoelastic parameters of the hand-arm system. This model ultimately allows for a fair representation of the hand-arm system and at what frequencies external vibration will cause resonance and do the most damage to a living human arm. Since it is dangerous and difficult to obtain data regarding the response of bones to vibration from human subjects, the viscoelastic rod model is a valuable alternative. Information obtained from the analysis of this model should be used by manufacturers of vibrating equipment, specifically construction machinery, to limit the risk to those operating the equipment. Based on all the information provided and the side effects that HAVS produce in the long-term, it is highly recommended that companies invest in anti-vibrational gloves and machinery with anti-vibrational mechanisms built in. These precautions are likely to decrease the probability of the onset of HAVS in a worker and continued progress in the field of anti-vibration may further eliminate the risk. Effective application of this information may be able to prevent damage to the hand-arm system and HAVS.

References

- [1] Pieter, Den Hartog Jacob. *Mechanical Vibrations*. New York: Dover Publications, 1985. Print.
- [2] "Vibration Syndrome." Centers for Disease Control and Prevention. Centers for Disease Control and Prevention, 06 June 2014. Web. 15 Jan. 2016.
- [3] Viktorova, Irina, Lauren Holden, and Sara Bailey Stocks. "Analysis of Resonance Frequencies for the Problem of Induced Vibrations Along the Human Arm." *Collaborative Mathematics and Statistics Research Springer Proceedings in Mathematics and Statistics* (2014): 67-73. Web.
- [4] Christensen, R. M. *Theory of Viscoelasticity: An Introduction*. New York: Academic, 1971. Print.
- [5] Coleman, Bernard D. *Wave Propagation in Dissipative Materials*. Berlin: Springer, 1965. Print.
- [6] Radwin, Robert G., Thomas J. Armstrong, and Ernst Vanbergeijk. "Vibration Exposure for Selected Power Hand Tools Used in Automobile Assembly." *American Industrial Hygiene Association Journal* 51.9 (1990): 510-18. Web.
- [7] Adewusi, S., S. Rakheja, P. Marcotte, and M. Thomas. "Distributed Vibration Power Absorption of the Human Hand-arm System in Different Postures Coupled with Vibrating Handle and Power Tools." *International Journal of Industrial Ergonomics* 43.4 (2013): 363-74. Web.
- [8] "Anti-Vibration Gloves Are Worth Every Penny." *Chainsaw Journal*. N.p., 27 Feb. 2015. Web. 29 Feb. 2016.
- [9] "Impacto BG40840 Anti-Vibration Mechanic's Air Glove, Black." *Anti Vibration Safety Gloves*. N.p., n.d. Web. 29 Feb. 2016.
- [10] "Robot Check." *Robot Check*. N.p., n.d. Web. 29 Feb. 2016.