Stiffness-based Spring Design Optimization using Taguchi Method to reduce Low-Frequency Vibration

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Abstrak

Getaran frekuensi rendah telah menjadi salah satu masalah utama dalam sistem mekanis. Selain sulit untuk dikontrol dan diukur, getaran frekuensi rendah juga dapat mengakibatkan dampak lain di bidang lingkungan seperti timbulnya kebisingan dalam level yang cukup tinggi yang berbahaya untuk tubuh manusia. Salah satu metode yang efektif untuk mengurangi getaran adalah dengan menggunakan isolator getaran seperti pegas dan peredam. Meski demikian, penggunaan peredam ternyata hanya efektif untuk mengurangi getaran pada frekuensi menengah dan tinggi. Oleh karena itu, penelitian ini memberikan sebuah metode optimasi pegas atau konstanta pegas untuk mengurangi getaran frekuensi rendah. Metode Taguchi digunakan dalam penelitian ini karena sederhana dan bisa diaplikasikan di dalam berbagai kegunaan dalam bidang teknik. Dua parameter utama dari geometri pegas digunakan sebagai variabel dalam metode taguchi and dievaluasi menggunakan konsep transmisibilitas. Dari hasil yang didapatkan, metode taguchi sangat sesuai dan efektif untuk mendapatkan nilai optimum geometri pegas untuk mengurangi getaran frekuensi rendah.

Kata kunci*—Getaran, taguchi, transmisibilitas, pegas, optimisasi*

Abstract

Low-frequency vibration has been troublesome for a mechanical system. Despite the measurement difficulties, low-frequency vibration also creates several environmental effects such as high noise level that is harmful to the human body. One of the methods to reduce vibration is tuning the vibration isolation i.e. spring and damping coefficient. However, the latter method is found to be effective only for the mid-high frequency range. Therefore, this paper proposes an optimization of the spring a.k.a. stiffness coefficient in order to reduce the low-frequency vibration. The Taguchi method is used as an optimization tool since it offers simplicity yet powerful for any field of application, particularly in engineering. Two significant parameters in the spring geometry were selected as the optimization variable in the Taguchi method and evaluated using vibration transmissibility concept. The result shows that the Taguchi method has been successfully obtained the optimum value for the spring geometry purposely to reduce the vibration transmissibility.

Keywords—*Vibration, Taguchi, transmissibility, spring, optimization,*

1. INTRODUCTION

Vibration is one of the most important factors in engineering. It does not only affects the mechanical system performance but also relates closely to failure. Therefore, researchers put much attention on the vibrational behavior of a mechanical system.

Spring is a key component in vibration. It determines how big the vibration oscillations would be and therefore often of interest. The vibration oscillations can be tuned by either controlling the stiffness of the spring or employing damping to the system. This paper focuses on the latter strategy since studies on vibration damper has been massively conducted.

Previous works on spring have been known to be done purposely to improve their performance in vibration. Pattar et. al. [1] analyze the static performance of a helical spring under compression load. The result of the works provides stress distribution throughout the spring that is very useful for future development. Visave and Mahajan [2] investigate the performance of mono-suspension spring by an experimental study. This can be said that the research is more-likely an application of the research from Pattar et. al. in a practical application. The result shows that the stress distribution pattern from the numerical study quite agrees with the result from experimental.

From previous researches above, one can note that the transmissibility of the system is very important to be observed and used as one of the main vibration parameters. Transmissibility is actually a ration between vibrational output over input energy. It can be a force or displacement transmissibility. Lage et. al. [3] explain and show a very detail study of the use of both types of transmissibility. Lu et. al. [4] investigate the transmissibility of a nonlinear vibration isolation system. Joo and Kang [5] propose the transmissibility for their relative response sensitivity analysis. Moreover, transmissibility is also very effective for studying human-body vibration or the effect of vibration on muscle. Govindan and Sharsa [6] analyze the low-frequency vibration of the human body exposed to vertical excitation. Here, the vibration transmissibility is used as the main parameter. Deboli et. al. [7] measure the horizontal and vertical transmissibility of an agricultural tractor seat. This indicates that the transmissibility is very important also in the ergonomic seat design. Similarly, Adam and Jalil [8] also investigate the vertical suspension seat transmissibility in the agricultural tractor seat. Yan et. al. [9] even make a particular study of transmissibility-based system identification for structural health monitoring, which shows the importance of vibration transmissibility.

As an effort to improve the performance of spring in terms of transmissibility, this paper, therefore, proposes an optimization strategy using the Taguchi method. It is a well-known easy, simple and applicable optimization method in any application field i.e. in the tribology performances [10], materials [11], geothermal [12] and nano-technology recently [13]. This method is implemented for the helical spring design which is explained in detail in the next section.

2. METHODOLOGY

2.1 Helical spring design parameter

Figure 1 is a 3-Dimensional model of a helical spring. The geometry of the spring is obtained from the approximate geometry of a commercially available spring. However, to conduct a numerical study, the geometry has been simplified into a continuous round circle model and neglecting the end tips as seen in the figure.

2. 1.1 Stiffness Equation

The stiffness of the helical spring can be calculated by [14]

$$k = \frac{Gd^4}{64nR^3} \quad (1)$$

where G is Shear Modulus or known as Modulus Rigidity, d is the spring wire diameter, n is the number of turns and R is spring radius.

From here, two parameters were selected as the optimization variables i.e the Modulus of Rigidity G and wire diameter d. The reason for this choose was due to the significant effect of materials on the stiffness that is represented by the modulus of the rigidity. Meanwhile, the spring wire diameter d is the simplest and most possible parameter to be modified during manufacture among other parameters. Therefore, these two were selected.

These variables were then calculated using the Taguchi method which is discussed in the following sub-section. Meanwhile, the other parameters are kept having constant values as n is 5 and the radius R to be 0.05 m.

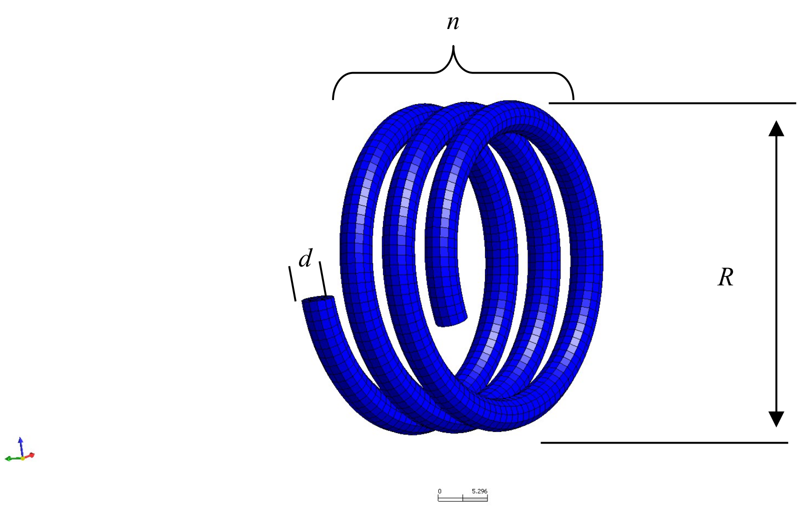

Figure 1. A 3-Dimensional Model of Helical Spring

2. 2 Taguchi Method

The initial step of the Taguchi method is defining the performance variables which have been mentioned in the previous sub-section. Next, defining the control factors and level of factors. The parameter design is given in Table 1 below

Tabel 1. Parameter Design

No	Process Variables	Level		
		1	2	3
1	Aluminum Alloy	0.1 mm	0.15 mm	0.2 mm
2	Carbon Steel	0.1 mm	0.15 mm	0.2 mm
3	Titanium Alloy	0.1 mm	0.15 mm	0.2 mm

The Taguchi L9 orthogonal array containing nine experiments was utilized corresponds tp the number of process variables and the levels. The summary for the nine experiments is given in Table 2 below

Tabel 2. Factors levels of each experiment condition.

Experiment No	Parameter 1	2
1	Aluminum Alloy	0.1 mm
2	Aluminum Alloy	0.1 mm
3	Aluminum Alloy	0.1 mm
4	Carbon Steel	0.15 mm
5	Carbon Steel	0.15 mm
6	Carbon Steel	0.15 mm
7	Titanium Alloy	0.2 mm
8	Titanium Alloy	0.2 mm
9	Titanium Alloy	0.2 mm

The effect of all studied parameters was analyzed by Analysis of Means (ANOM) to examine whether the parameters significantly influence the Transmissibility ratio. Based on the equation by Rao, the transmissibility ratio can be calculated by [14]:

$$T = \sqrt{\frac{k^2 + (\omega c)^2}{(k - \omega^2 m)^2 + (\omega c)^2}} \tag{2}$$

Where *k* is the spring stiffness coefficient, which in this case, is observed for optimization objective, *w* is the angular frequency of the vibration, *c* is the damping factor of 50000 N/m.s and *m* is the mass of the system. For the numerical study purpose, the mass is assumed as 500 kg.

3. RESULT AND DISCUSSIONS

The L9 Taguchi result is presented in table 3. It shows the result for the nine numerical studies with several repetitions is also presented. The Signal-to-Noise (S/N) ratio with the concept of "the smaller-the-better" is also presented from the 1^{st} to 9^{th} experiment which is calculated using Eq. 3. From here, a calculation analysis can be made.

$$S / N = -10 \log_{10}\left(\Sigma \frac{y^n}{n} \right) \tag{3}$$

Tabel 3. Results for Taguchi trials for stiffness and S/N ratio.

Exp No	1	2	3	S/N ratio
1	182250000	182250000	182250000	82.60667537
2	16000000	16000000	16000000	72.04119983
3	2847656.25	2847656.25	2847656.25	64.54487563
4	1482250000	1482250000	1482250000	91.70921459
5	130119649	130119649	130119649	81.14342883

6	23155344	23155344	23155344	73.64651237
7	420250000	420250000	420250000	86.23507722
8	36893476	36893476	36893476	75.66949575
9	6563844	6563844	6563844	68.17158251

The data is then used to plot the S/N graph for both optimization variables i.e. the materials and spring wire diameter, which can be seen in Figure 2. From the material result, it can be seen that the Aluminum shows the minimum result compared to Carbon Steel and Titanium. It only has around 73 S/N ratio, while Carbon Steel has 82 S/N ratio and Titanium has 76.5 S/N Ratio. From the spring wire diameter result, it is seen that increasing the diameter reduces the transmissibility ratio. It can also be said that the bigger the wire diameter, with the same number of turns spring radius, the transmissibility can be reduced. The minimum S/N value for this radius is obtained by a 0.2 mm radius with a 69 S/N ratio. Meanwhile, the other two diameters of 0.1 and 0.15 mm give a higher S/N ratio of 87 and 76, respectively.

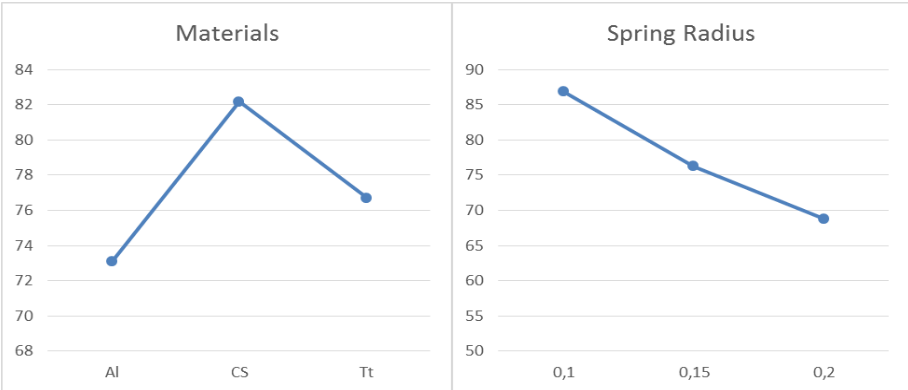

Figure 2. Taguchi mean S/N ratio analysis for given parameter design.

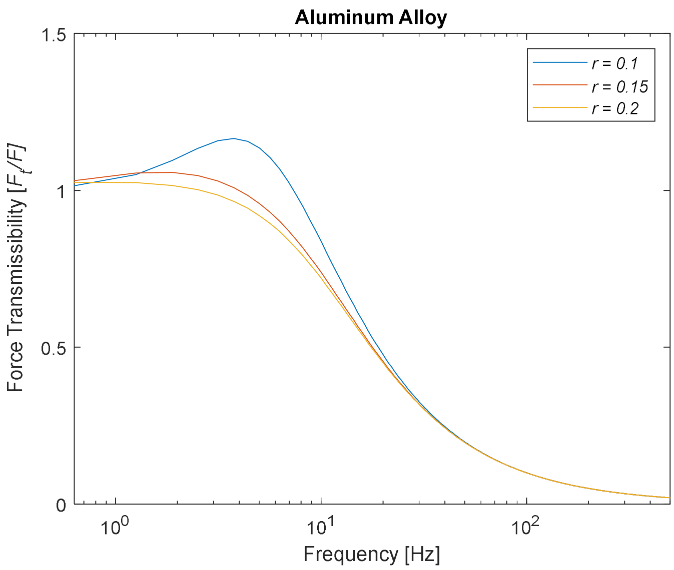

Figure 3. Transmissibility result of Aluminum Alloy sample

To show more clearly of the minimum obtained value, the transmissibility graph is depicted in Figure 3 to 5, while the comparison between all results is depicted in Figure 6.

Figure 3 shows the transmissibility result for the aluminum alloy with spring wire diameter variations from 0.1 to 0.2 mm. the spring with 0.1 mm wire diameter gives the highest transmissibility of 1.2 around 50 Hz frequency. Increasing the wire diameter into 0.15 mm apparently reduces the transmissibility into 1.1 at 50 Hz. Moreover, increasing again into 0.2 mm gives lower transmissibility up to 1 at 50 Hz. This is important information since around this low-frequency, many troublesome failures occur due to resonance or other causes, as well as body health issues subject to low-frequency vibration [6]. As a conclusion for Aluminum alloy, the optimum wire diameter value is obtained by 0.2 mm size.

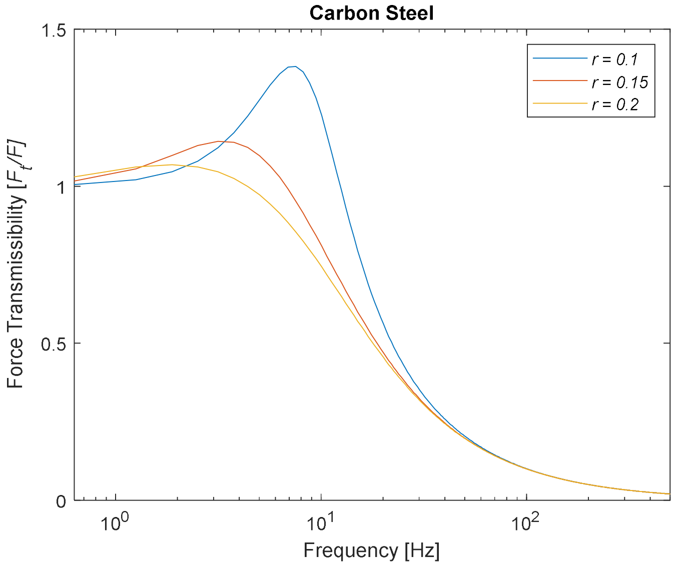

Figure 4. Transmissibility result of Carbon Steel sample

The transmissibility result for Carbon Steel material is depicted in Figure 4. Similarly, the spring wire diameter is varied from 0.1 to 0.2 mm as designed in the Taguchi before. It is seen that the spring with 0.1 mm wire diameter gives the highest transmissibility up to 1.4 around 100 Hz frequency. It is considerably higher than the previous Aluminum material. Again, by increasing the wire diameter into 0.15 mm from Taguchi design of experiment, reduces the transmissibility significantly into 1.2 and shift the frequency to 50 Hz. Once again, increasing the wire diameter into 0.2 mm gives much lower transmissibility up to 1.1 at 50 Hz. This is very similar to the previous Aluminum result and provides similar best wire diameter size for obtaining the minimum transmissibility.

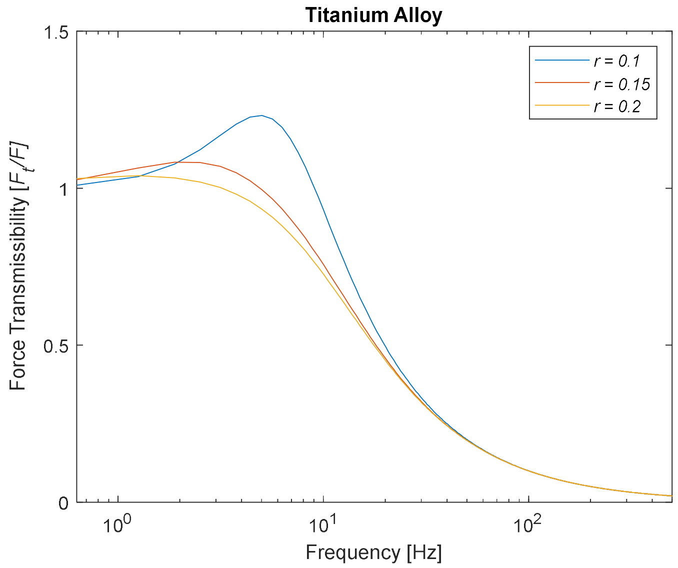

Figure 5. Transmissibility result of Titanium Alloy sample

Figure 5 shows the transmissibility result for titanium alloy with, again, different spring wire diameter variations from 0.1 to 0.2 mm. Generally, the result shows similarities with the result of Aluminum alloy where the spring with 0.1 mm wire diameter has the highest transmissibility of 1.2, but here, around 80 Hz frequency. Increasing the wire diameter into 0.15 mm apparently reduces the transmissibility into 1.1 at 50 Hz. Increasing again into 0.2 mm gives more slight lower transmissibility up to 1.0 at 50 Hz.

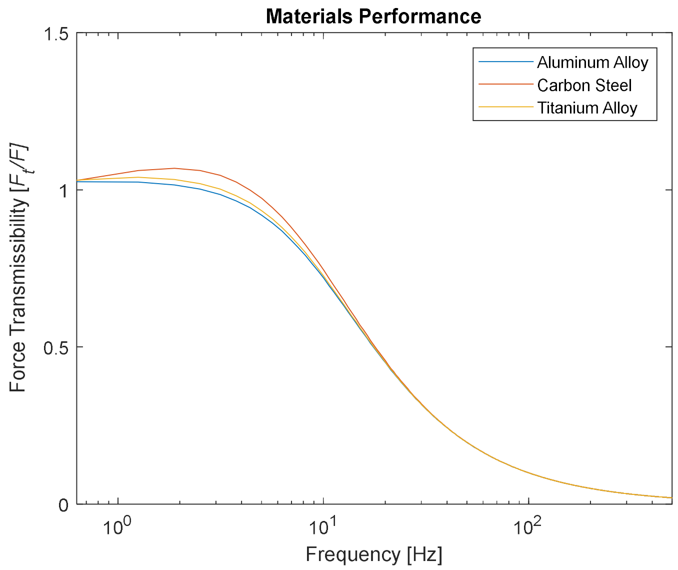

Figure 6. Transmissibility comparison for all sample materials.

For comparison, Figure 6 shows the transmissibility comparison for all sample materials. The differences between all materials at low frequency seems to be very slight. At around 30 - 50 Hz, the difference is only around 0.05 to 0.1. The highest transmissibility is obtained by Carbon Steel with 1.1 transmissibility, followed by Titanium alloy with roughly 1.05 and lastly Aluminum alloy with 1.0 transmissibility. This result confirms the result of the S/N ratio obtained from the Taguchi method result in the previous section.

4. CONCLUSION

A numerical study on the helical spring design optimization has been conducted using Taguchi method. From the result, several conclusion can be made:

1. Taguchi is an old yet simple and useful method to optimize the commercial helical spring design.
2. The spring with Aluminum shows the superiority of transmissibility reduction performance among Carbon Steel and Titanium.
3. Increasing the spring wire diameter into 0.2 mm apparently effective to improve the transmissibility performance.
4. The result can be further improved by designing more spring wire diameter and spring materials.

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