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MODELLING OF OVERHEAD TRANSMISSION LINES TO SUPPRESS ITS VIBRATION USING MASS DAMPER

نمذجة خطوط النقل الهوائية لكبح اهتزازها باستخدام مخمدات ديناميكية

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ملخص البحث :

لقد تم تسجيل العديد من حالات الانهيار المفاجئ للكابلات الكهربية خلال العقدين الماضيين في مصر والخارج، وقد ثبت بتحليل أسباب تلك الانهيارات أنها ترجع غالبا إلى الاجهادات المتكررة الناجمة عن الاهتزاز الميكانيكى للكابلات، وقد تم تعليق العديد من مسجلات الاهتزاز على طول خط نقل الطاقة الكهربية من سمالوط وحتي القاهرة لتسجيل مستوى الاهتزاز والتنبؤ بالعمر المفترض لذلك الخط. وقد تم اختيار أماكن القياس بناء على قياسات لسرعة الرياح فى تلك المناطق على مدى ثلاث سنوات وقد وجدأن العمر الافتراضى فى العديد من مواقع القياس أقل من عشرين عاما.

وحتى يمكن إطالة عمر تلك الكابلات فلابد من خفض مستوى الاجهادات الديناميكية وعليه فقد تم اقتراح تعليق مخمدات اهتزاز ديناميكية حتى يمكن خفض سعة اهتزاز الخط ومن ثم الاجهادات الديناميكية.

ويحتوى هذا البحث على دراسة لمحاكاة اهتزاز الخط فى ظروف تشغيله وبمحاكاة استجابة الخط وجد أن سعة الاهتزازة عالية نسبيا ويتقارب القيم المقاسة فى المواقع محل الدراسة، وبعد ذلك تم دراسة تعليق مخمدات اهتزاز ديناميكية لكبح الاهتزاز بالخط وتحديد افضل مكان للتثبيت, وبمحاكاة المنظومة الجديدة وجد أن أكبر سعة اهتزاز تبلغ حوالى خمس قيمها قبل تعليق الفواصل وعليه فإن العمر الافتراضى قد تخطى ١٥٠ عاما.

ABSTRACT

A study of the sudden failure of conductors in overhead transmission lines has been developed, using field data. It is found that the failure can be attributed to the excessive vibration of conductors under the stochastic wind excitation. By analyzing the field data, the maximum amplitude of vibration, and consequently the dynamic stress in the conductor, is calculated, and conductor's life is estimated to be less than 20 years for several sites.

In this work, mass-damper "which acts as dynamic absorber" is introduced to reduce the vibration of overhead transmission lines, such that the sudden failure of the conductors can be avoided. The effect of clamping mass damper on the vibration of the conductor, and consequently on the dynamic stresses, has been investigated. The estimated life of the conductor is found to increase to more than 150 years by the implementation of this scheme.

Keywords: Vibration of Overhead Transmission lines, Mass-damper, Dynamic Stresses, Life Time

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1. INTRODUCTION

During the last two decades, several failures of the overhead transmission lines have been recorded. The failure analysis of the damaged conductors illustrated that several mechanical factors have major effects on the conductor failure. These factors could be mentioned as the conductor tension, type of clamps, damping devices and the stochastic vibrations induced by wind [1-10]. Wind-induced conductor vibrations, for instance, are unavoidable. They may cause wire fractures, mainly in the inner layers of the conductor. This is discovered after several years of service, which, in most cases, is too late.

According to the failure analysis of the damaged lines, and the comprehensive studies of *CIGRE' (Confe'rence Internationale des Grands Re'seaux Electriques a' Haute Tension)* [2-3], several vibration recorders have been manufactured [8]. These vibration recorders are clamped to the tower wing to measure, and record, the line vibration as illustrated in Fig.(1). The recorded results illustrate that the vibration is relatively high and consequently the estimated life-time of the line may be uneconomic.

In order to reduce the vibration, it is proposed to clamp mass dampers to the line. Mass dampers may be tuned to the main natural frequency of the system, and may be not. The spring-mass system of the mass damper may have a considerable damping coefficient and may not [4]. Tuned mass dampers have been extensively studied and applied to reduce wind-induced vibration of building structures since the 1970s. Much of those efforts were devoted to develop the design procedure and optimizing the parameters for improved performance [11-12].

The mass dampers are clamped to the line to reduce the vibration level, according to general recommendations [1-9]. However, farther investigations are needed to explore the effect of the line dynamics and damper parameters on the vibration.

In this paper, the effect of the parameters of the mass damper and its location, on the line vibration has been investigated. The vibration of the line without mass damper is studied. The effect of clamping mass damper on the vibration of the conductor, and consequently on the dynamic stresses, has been investigated. The estimated life of the conductor is found to increase to more than 150 years by the implementation of this scheme.

This paper is organized as follows; in Section 2, the vibration of the line is derived. The effect of mass damper is investigated in Section 3. In Section 4, the results of Section 3 are implemented to one of the most dangerous portions of the 500 kV overhead transmission line from Assiut to Cairo. The results and discussions are presented in Section 5, and the conclusions are summerized in Section 6.

2. VIBRATION OF THE LINE

The wire is vibrating in the vertical direction, about its static equilibrium curve, under the stochastic wind excitation, as illustrated in the free body diagram Fig. 2. The equation of motion can be written as:

$$m(x)dx\frac{\partial^2 y(x,t)}{\partial t^2} = \left[T(x) + \frac{\partial T(x)}{\partial x}dx\right]\left[\frac{\partial y(x,t)}{\partial x} + \frac{\partial^2 y(x,t)}{\partial x^2}dx\right] + p(x,t)Ddx - T(x)\frac{\partial y(x,t)}{\partial x}$$

(5)

where; $m(x)$ = mass per unit length of the wire,

$T(x)$ = tension in the wire,

D = diameter of the wire,

$p(x,t)$ = the stochastic pressure induced by the wind.

The above equation can be reduced to:

$$m(x)\frac{\partial^2 y(x,t)}{\partial t^2} = \frac{\partial}{\partial x}\left[T(x)\frac{\partial y(x,t)}{\partial x}\right] + p(x,t)D$$

(6)

From a practical point of view, the wire tension, the wire mass per unit length of the wire and the wind pressure can be considered constant throughout the wire span. Now, equation 6 can be written as follows:

$$m\frac{\partial^2 y(x,t)}{\partial t^2} = \frac{\partial}{\partial x}\left[T\frac{\partial y(x,t)}{\partial x}\right] + p(t)D$$

(7)

The above equation is a non-homogenous partial differential equation with stochastic excitation. The homogenous partial differential equation associated with this equation:

$$m\frac{\partial^2 y(x,t)}{\partial t^2}=\frac{\partial}{\partial x}\left[T\frac{\partial y(x,t)}{\partial x}\right]$$
(8)

This equation is a reducible homogenous partial differential equation, which has the solution;

$$y(x,t)=\sum_{n=1}^{\infty}\sqrt{\frac{2}{ml}}\sin\left(\frac{\Omega_n x}{V}\right)(C_i\sin\Omega_n t+D_i\cos\Omega_n t)$$
(9)

where $V=\sqrt{T/m}$,

Ω_n = the frequency of vibration, of the nth mode = $n\pi V/l$,

l = the length of the span of the line.

The stochastic vibration is a function of the wind velocity and the wire diameter. The frequency of vibration in such a case is:

$$f=\alpha_s\left(\frac{v}{D}\right),$$
(10)

Where α_s = Strouhal number, which equals 0.22 for cylindrical shapes [2],

v = the stochastic wind velocity.

The most dangerous conditions is encountered when frequency "f" coincides with one of the line natural frequencies.

The dynamic stochastic pressure of the wind, $p(t)$, can be written as:

$$p(t)=0.5\,\rho\,F_w(v,t)$$
(11)

Where ρ = the density of air at the working conditions,

$F_w(v,t)$ = the stochastic function describing the vertical aerodynamic force on the wire due to the wind.

Equations (5) to (11), together with the recorded data of the wind velocity and the data of the line (Table 2), can be used to calculate the spectral density function of the line response. The spectral density curve for the response is presented in Fig. 3.

3. Passive Design Modifications

In the field of system dynamics, several passive design modifications have been introduced to reduce the system response, and consequently the dynamic stresses. These modifications are the use of dynamic absorbers or dampers. Regarding the vibration of the overhead lines single absorber is introduced without the accurate placement of it for the different lines and wind excitation conditions.

Here, mass-damper has been considered.The damper is assumed to be clamped to the wire to suppress its vibration. The effect of the parameters of the damper and its location, on the line vibration is investigated. Thus, the proper absorber can be selected and its optimum location can be determined in order to achieve a longer lifetime of the wire.

The most dangerous harmonic component of the excitation is that which has the frequency defined in equation (10). Therefore, the dynamic absorber is designed to reduce the effect of this excitation. This harmonic force may be considered uniformly distributed along the line and it may be expressed as:

$$F(t)=F_o\sin\omega t,$$
(12)

Where $\omega=2\pi f$

In order to calculate the response of the line to the above component, the following forcing integral term has to be introduced:

$$N_n(t)=\int_0^l\sqrt{\frac{2}{ml}}\sin\left(\frac{\Omega_n x}{V}\right)F_o\sin\omega t\,dx$$
(13)

This integral will be used to calculate the generalized coordinate, $\gamma_n(t)$, which is defined as:

$$\gamma_n(t)=\frac{1}{\Omega_n}\int_0^t N_n(\tau)\sin\Omega_n(t-\tau)d\tau$$
(14)

Now, the response of the line can be written as:

$$y(x,t) = \sum_{n=0}^{\infty} C_n \sqrt{\frac{2}{ml}} \sin\left(\frac{\Omega_n x}{V}\right) \gamma_n(t),$$

(15)

Where $C_n = 1$, for $n = 1, 3, 5, \ldots$

$C_n = 0$, for $n = 0, 2, 4, \ldots$

After taking the boundary conditions into consideration, the response can be written as:

$$y(x,t) = \sum_{n=0}^{\infty} C_n A \sin\left(\frac{\Omega_n x}{V}\right) B(\Omega_n \sin\omega t - \omega \sin\Omega_n t)$$

(16)

Where A and B are constants to be determined by the boundary conditions.

If the internal damping of the line is considered, this equation can be reduced to:

$$y(x,t) = \sum_{n=0}^{\infty} C_n A \sin\left(\frac{\Omega_n x}{V}\right) B\, \Omega_n \sin(\omega t - \phi)$$

(17)

Therefore, the constants, A and B can be written as

$$A = \frac{2F_o}{ml} \cdot 2 \cdot \left(\frac{l}{\pi}\right)^3 \left(\frac{m}{T}\right) = \frac{4F_o}{\pi^3} \cdot \frac{l^2}{T}, \quad \text{and}$$

$$B = \frac{1}{\pi^3} \frac{1}{\sqrt{(1 - r_n^2)^2 + (2\xi_n r_n)^2}}$$

A typical response of the system is represented by the solid curve (Fig. 4). It is clear that the response is generally high near the system eigen-frequencies.

3.1. Line Response with Mass-Damper

Now, a dynamic absorber is assumed to be attached to the line at a distance x_a in order to reduce the system response and the model in this case is shown in Fig. 7. In order to calculate the response of the line to the above excitation, in the presence of the dynamic absorber, the following forcing integral terms are introduced:

$$N_{n1}^*(t) = \int_0^l \sqrt{\frac{2}{ml}} \sin\left(\frac{\Omega_n x}{V}\right) F_o \sin\omega t \, dx$$

(18)

$$N_{n2}^*(t) = \int_0^l \sqrt{\frac{2}{ml}} \sin\left(\frac{\Omega_n x}{V}\right) F_1 \sin(\omega t + \varepsilon) \, dx$$

(19)

where ε = phase angle due to the damping of the absorber.

The above term will be used to calculate following generalized coordinate;

$$\gamma_n^*(t) = \frac{1}{\Omega_n} \int_0^t \left(N_{n1}^*(\tau) + N_{n2}^*(\tau)\right) \sin\Omega_n (t - \tau) d\tau$$

Now, the response of the line can be written as follows:

$$y_1(x,t) = \sum_{n=0}^{\infty} C_n \sqrt{\frac{2}{ml}} \sin\left(\frac{\Omega_n x_a}{V}\right) \gamma_n^*(t)$$

(21)

The response can be expressed as:

$$y_1(x,t) = \sum_{n=0}^{\infty} C_n A_1 \sin\left(\frac{\Omega_n x}{V}\right) \gamma_n(t)\, B_1 (\Omega_n \sin\omega t - \phi_1) \quad (22)$$

where:

$$A_1 = \frac{4F_o}{\pi^3} \cdot \frac{l^2}{T},$$

$$B_1 = \frac{1}{\pi^3} \sqrt{\frac{(2\xi_{an} r_n)^2 + (r_n^2 - r_{an}^2)^2}{(2\xi_{an} r_n)^2 \left[r_n^2 - 1 + \mu_n r_n^2\right]^2 + \left[\mu_n r_{an}^2 r_n^2 - (r_n^2 - 1)(r_n^2 - r_{an}^2)\right]^2}}$$

$$r_n = \frac{\omega_f}{\Omega_n}, \quad r_{an}^2 = \frac{\omega_d^2}{\Omega_n^2}, \quad \mu_n = \frac{m_d}{m_{n_{eq}}},$$

$$\xi_n = \frac{c_d}{2m_d \Omega_n}, \quad \omega_d^2 = \frac{k_d}{m_d}, \quad \Omega_n = \frac{n\pi}{l} \sqrt{\frac{T}{m}}$$

By the proper selection of the absorber parameters and its location, the maximum amplitude of vibration can be minimized. This has been achieved by applying Powell's method [10]. It is clear that the amplitude of vibrations has been considerably reduced, (the dotted curve of Fig. 4).

4. PRACTICAL APPLICATION OF A DYNAMIC ABSORBER

The analysis presented in Section 3 is applied to one of the most dangerous portions of the 500 kV overhead transmission line from Assiut to Cairo. Analysis of the recorded vibration revealed that the lifetime of the wire, at this portion, could be as low as two years. Therefore, this portion of the line was chosen for the application of the absorbers. The absorber was selected, from the available absorbers, and its optimum location was determined, using the analysis of Section 3. The vibration of the line with the selected absorber at the optimum location was recorded, and analyzed. The results showed that the estimated lifetime of the wire could be increased to more than 150 years by the use of the absorbers.

4.1. Measured Data

Due to failure problems in the 500 kV line, several vibration recorders have been located on the towers to measure the vibration of the line, at different sites for 60 days. The measuring sites have been selected according to the direction and the velocity of wind over two years. A sample of the data, for the life of the line, is given in Table. 1. The vibration records, which have been used in this work, are VIBRAC100 and VIBRAC300 [9]. Figure 1 illustrates the mounting of the recorder. After the end of the recording time, the recorded data is analyzed to construct the amplitude-frequency matrix for the measurements. Figure 2 represents a sample of this data matrix. It is clear that the maximum amplitude of vibration occurs between 15 Hz and 25 Hz.

In this Section, the analysis presented in section 3.2 is applied to one of the most dangerous portions of the 500 kV overhead transmission line from Assiut to Cairo. Analysis of the recorded vibration revealed that the lifetime of the wire, at this portion, could be as low as two years. Therefore, this portion of the line was chosen for the application of the absorbers. The absorber was selected, from the available absorbers, and its optimum location was determined, using the analysis of Section 4. The vibration of the line with the selected absorber at the optimum location was recorded, and analyzed.

4.2. Recording and Analyzing of Vibration

The vibration recorder VIBRAC 300, which is produced by SEFAG [8], has been used in this work. It was mounted on the wing boat. A displacement transducer was used to measure the wire vibration at a sampling frequency of 2 kHz. A microprocessor is included in order to measure and record the peaks of the vibrations, which are confirmed by a bandwidth filter. The recorder, also, had a built in storage to store the measured data. At the end of the data collection, the recorder was removed from the line, and connected to a personal computer. Using this computer, much information was obtained. This information included: frequency spectrum, Amplitude frequency matrix and estimated lifetime.

4.3. Estimation of the Wire Lifetime

As mentioned above, wire fracture always occurs very close to its point of fixation to the tower wing. Therefore, a vibration recorder is provided in order to measure the vertical displacement of the wire very close to the point of fixation; namely at 3.5 inch (89 mms) from the wing. The displacement measured at such a small distance is proportional to the stress on the wire. The manufacturer of the vibration recorder, also, provides tables which give an estimate for the maximum number of cycles, which the wire can afford during its lifetime, for different amplitudes and different frequencies of the measuring point, assuming that the wire experiences simple harmonic vibration. These tables are used for estimating the wire lifetime, when the measuring point experiences periodic vibration as explained below.

Let us assume that the measuring point experiences periodic motion whose harmonic component is expressed in the form "$E_i \sin(2\pi f_i t + \phi_i)$". According to the tables provided by the manufacturers, each of these harmonics gives an estimate for the maximum number of cycles which the wire can afford, N_i, assuming that this harmonic displacement exists alone. Obviously, in the case of this single harmonic, the wire lifetime, T_i (in years), is obtained from the relation:

$$T_i = \frac{N_i}{n_i},$$

where n_i is the number of cycles, which the wire experience per year. In order to get an estimate for the wire in the case of periodic vibrations, the manufacturers recommended the expression:

$$\frac{1}{T_e} = \sum \frac{1}{T_i}.$$

where T_e is the estimated lifetime, and summation is for the different harmonics included in the analysis. This expression may be written as:

$$T_e = \frac{1}{\sum_i (n_i / N_i)}$$

(24)

5. Results and Discussion

The results obtained by analyzing the vibration of the wire before clamping the absorber are depicted in Fig.8 and Table 2. Table 2, indicates that the frequency 20 Hz has the greatest contribution in the reciprocal of the wire lifetime $(1/T_e)$, which was 36.8%. Fig. 8 and Table 3 represent the analysis of the vibration of the wire after clamping the absorber. Comparison between (Fig. 8 and Table 2) and (Fig. 9 and Table 3) indicates that the number of cycles per year, n, corresponding the frequency 20 Hz has been reduced from (145.552×10^6) cycles per year to (9.77×10^6) cycles per year, i.e. to 6.7% of its value before clamping the absorber. Regarding the lifetime of the wire, it can be seen from Tables 2 and 3 that lifetime has been increased from 2.11 years to more than 150 years, which was the main objective of this work.

6. CONCLUSION

The excessive vibrations of the 500 kV overhead transmission line, coming from Assiut to Cairo, has been considered. The vibration of the line, at different sites, has been recorded, and the lifetime of different portions of the line has been estimated. It was found that the amplitude of vibration at several portions was so high that the estimated lifetime was less than 20 years. The dynamic study of the line showed that it was vibrating under the compound effect of tension and stochastic wind load.

Dynamic absorbers were clamped to the line in order to suppress the vibration. Partial differential equation of the wire motion, before and after clamping the dynamic absorber, has been solved. By dynamic analysis of the wire vibrations, with the dynamic absorber clamped to it, the proper absorber was selected and its optimum location was determined. It was found that the use of the proper absorber at the optimum location could reduce the amplitude of vibration at the measured point to one third of its original values. This result was checked experimentally and the reduction of the amplitude was found to be reasonably close to the theoretical result. According to the tables provided by the manufacturer of the vibration recorder, the estimated lifetime of the wire, with the absorber clamped to it, may be increased to more than 150 ye

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APPENDIX A

In order to calculate the response of the line, the following generalized coordinate, $y_n(t)$, can be calculated as follows;

$$\Re_n(t) = \frac{1}{\Omega_n}\int_0^t I_t \sin\Omega_n(t-\tau)\,d\tau$$

(A1)

Where $I_t = \left\{\int_0^l \sqrt{\frac{2}{ml}}\, \sin\left(\frac{\Omega_n x}{V}\right) P_o \sin\Omega t\, dx\right\}$

The response of the line can be written as;

$$y(x,t) = \sum_{n=0}^{\infty} C_n \sqrt{\frac{2}{ml}}\, \sin\left(\frac{\Omega_n x}{V}\right) \Re_n(t) \; ,$$

(A2)

Where $C_n = 1$, for $n = 1, 3, 5, \ldots$

$C_n = 0$, for $n = 0, 2, 4, \ldots$

After taking the boundary conditions into consideration, the response can be written as;

$$y(x,t) = \sum_{n=0}^{\infty} C_n \; A_n \sin\left(\frac{\Omega_n x}{V}\right)$$
$$(\Omega_n \sin\Omega t - \Omega \sin\Omega_n t)$$

(A3)

Where A_n is a constant to be determined by the boundary conditions. If the internal damping of the line is considered, this equation can be reduced as;

$$y(x,t) = \sum_{n=0}^{\infty} C_n A_n \sin\left(\frac{\Omega_n x}{V}\right)\; \Omega_n \sin(\omega t - \phi)$$

(A4)

Hence, the constant A_n can be derived as;

$$A_n = \frac{1}{n^3}\frac{F_o l(\pi^3 T/4l^2)}{\sqrt{(1-r_n^{\,2})^2 + (2\xi_n r_n)^2}}$$

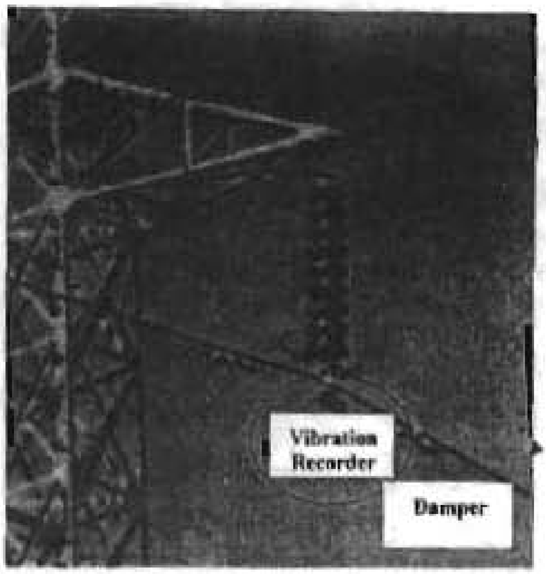

Fig. 1.a. Vibration recorder clamped to the wing (Two Mass-Dampers are clamped to the line).

Fig 1.b. Vibration recorder clamped to the wing

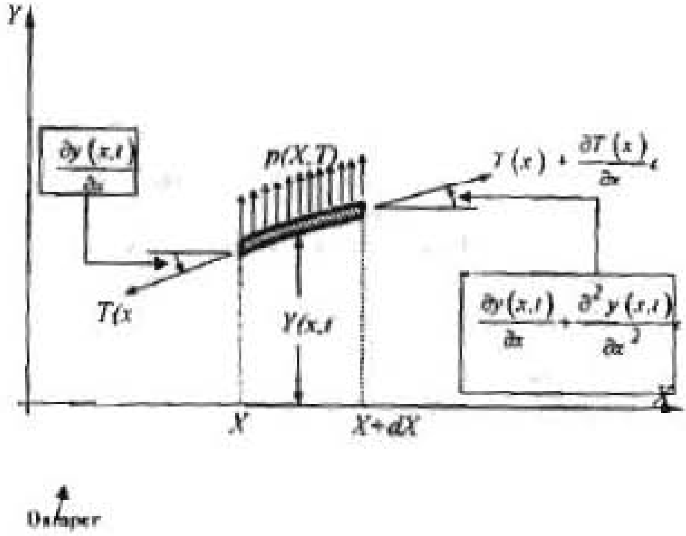

Fig. 2. Free body diagram of a portion of the considered line.

Table 1 The data of the 500 kV line.

Outer diameter	2R	30.2	mm
Mass/unit length	m	1.8	kg/m
Span of the line	l	400	m
Rated strength	T_{max}	146	kN
Aluminum layers			
	Number of strands	54	
	Strand diameter	2	mm
Steel layers			
	Number of strands	19	
	Strand diameter	2	mm
Bundles "at equal spaces"			
No. of Bundles	6x3		

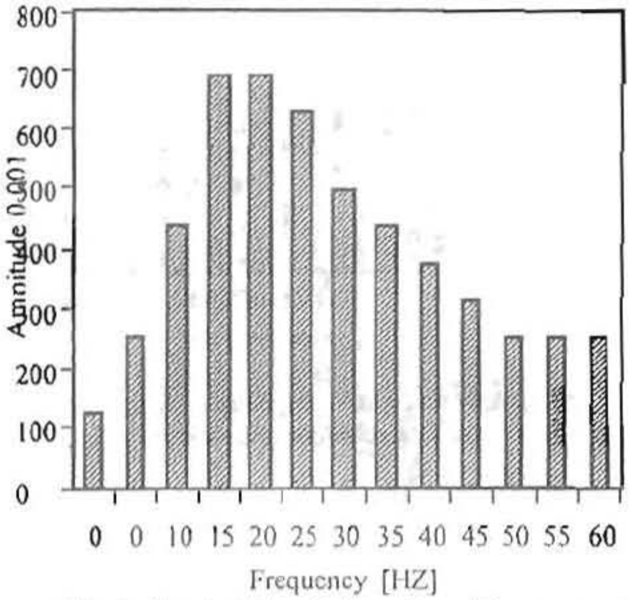

Fig. 3. Spectral density function of the response.

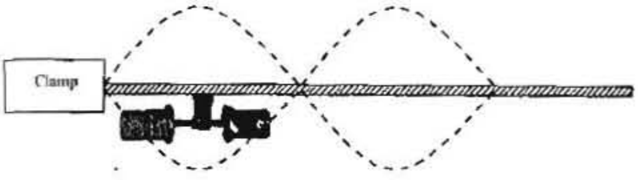

Fig.5. Clamping of the mass damper to the line

Fig. 6. Selected mass damper (Stockbridge).

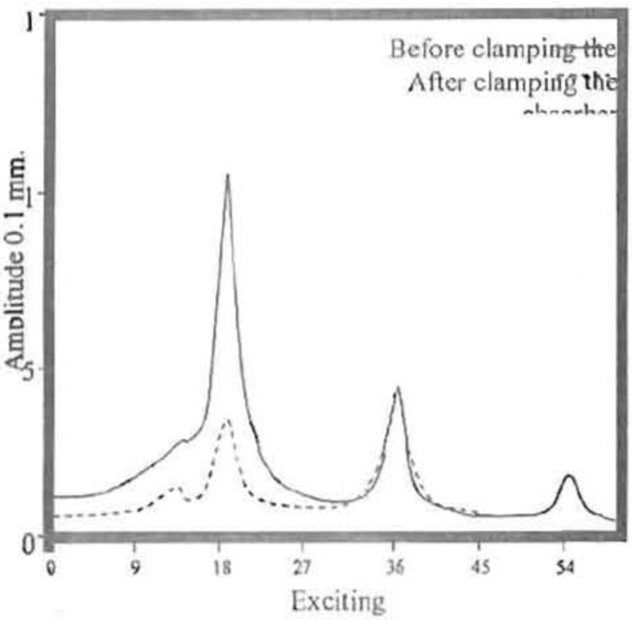

Fig.4. Amplitude-frequency curve before and after clamping the mass damper.

Table 2. A sample of the lifetime data before clamping the damper.

Frequency [Hz]	n=No. Cy. * 10^{-6}	(n/N) p. class	%
2	1.794	0.0000	0.0
5	4.238	0.0000	0.0
10	17.510	0.0050	1.1
15	61.430	0.0941	19.8
20	145.552	0.1745	36.8
25	137.423	0.1503	31.7
30	68.293	0.0470	9.9
34	16.130	0.0024	0.5
40	10.408	0.0006	0.1
45	5.715	0.0001	0.0
50	3.101	0.0000	0.0
59	3.476	0.0000	0.0
83	2.822	0.0000	0.0
100	0.369	0.0000	0.0
143	0.204	0.0000	0.0
200	0.020	0.0000	0.0

S (n/N) = 0.47411 / (S (n/N)) =
estimated lifetime = 2.11 Years

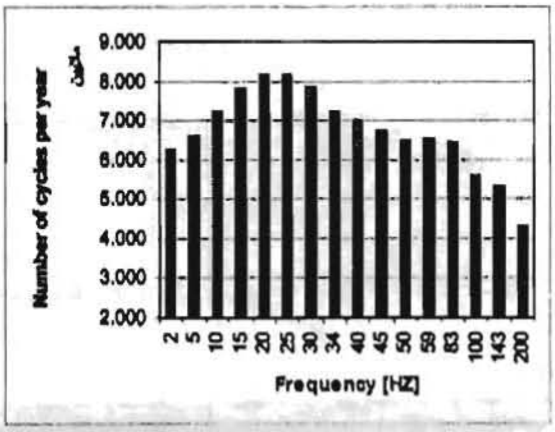

Fig. 7. A sample of the amplitude –frequency curve before clamping the damper

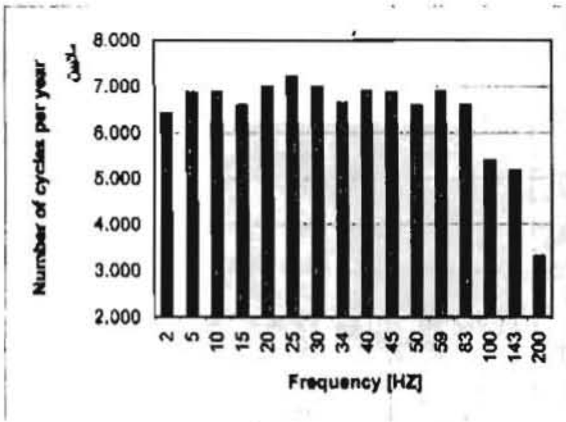

Fig .8.Asample of the amplitude – frequency curve after clamping the damper

Table 3. A sample of the lifetime data after clamping the damper.

Frequency [Hz]	n=No. Cy. * 10^{-6}	(n/N) p. class	%
2	2.597	0.0000	6.0
5	7.299	0.0000	1.1
10	7.758	0.0000	1.1
15	3.965	0.0000	1.4
20	9.770	0.0000	10.8
25	15.879	0.0000	19.8
30	9.553	0.0000	14.2
34	4.375	0.0000	7.9
40	7.800	0.0000	9.5
45	7.405	0.0000	8.5
50	3.772	0.0000	6.2
59	7.632	0.0000	9.1
83	3.971	0.0000	4.2
100	0.235	0.0000	0.0
143	0.142	0.0000	0.0
200	0.0020	0.0000	0.0

s (n/N) = 0.00001 / (S (n/N)) = estimated lifetime > 150 Years