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Vibration Measurement and Analysis Using Heterodyne Laser Detection

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Abstract:

An experimental Michelson interferometer arrangement has been implemented utilizing the principle of laser Doppler vibrometry. He-Ne laser has been used as a coherent light source. The circuit for heterodyne detection has been built to detect and record Doppler signals. Two types of materials have been used as vibrating panel, which are excited by acoustic waves applied from a loudspeaker connected to a function generator. The applied waves were in frequency range of 10-100Hz. The recorded results of the experimental work demonstrate that the vibration frequency of the panel conforms to the applied frequency when the ratio between the applied and natural frequencies is greater than two (or less than one half).

Keywords: *Vibration Measurement, laser heterodyne detection*

1. Introduction

Lasers are widely used today in vibrometers, since the measurements are performed in a contactless manner, i.e., the laser vibrometer does not affect the dynamic behavior of the system under measurement [1].

Laser Doppler Vibrometer "LDV" is one of the most important methods to detect object vibration frequency, object velocity and acceleration [2]. The first trial of measuring fluid speed using Doppler phenomenon and laser was in 1964 using He-Ne laser [3].

2. Fundamentals of Panel's Vibration

There are two general kinds of vibration, free and forced vibration. Free vibration takes place when a system oscillates under the action of forces inherent in the system itself, and when external impressed forces are absent. The system under free vibration will vibrate at one or more of its natural frequencies, which are properties of the dynamic system established by its mass and stiffness distribution [4].

Vibration that takes place under the excitation of external force is called forced vibration, which is represented by the pressure of acoustic waves over the two vibrating panels [4].

It is important to know if the vibrating system is linear or not. If the vibrating system is linear, the system is forced to vibrate at the excitation frequency. If the vibrating frequency is not equal to excitation frequency of applied force, the system is non-linear [5].

Mechanical systems tend to behave as linear if excitation frequency of applied force is far from natural frequencies of those systems. If applied excitation frequencies occur in the region of natural frequency, the system will be unstable and vibrate with a frequency different from that of the excitation frequency [5].

Natural frequency of materials having a panel shape can be obtained using the following equation [6].

$$f_n = \frac{\psi_{ij}^2}{2\pi a^2}\left[\frac{E h^3}{12\gamma(1-\nu^2)}\right]^{1/2} \qquad (1)$$

where

Ψ_{ij} is a dimensionless frequency,
a is plate's height,
h is plate's thickness,
i is the number of half-waves in mode shape along the horizontal axis,
j is the number of half-waves in mode shape along the vertical axis,
E is the modulus of elasticity,
γ is the mass per unit area, and

ν is a poisson's ratio.

3. Heterodyne Detection

The technique often referred to as "optical beating" is the heterodyning or time dependent interference of two optical beams. Heterodyning is a well known technique in radio waves in which two signals are added and passed through a non-linear circuit element or "detector". The, mixed, output then contains the sum and difference frequencies and harmonics. If the original frequencies are close, the difference will be low and may be readily separated by a low pass filter (usually incorporated in the detector circuit) [7].

The same principle can be applied in optics. The beating can be observed by illuminating an optical detector simultaneously by light of two different frequencies. A normal optical detector is non-linear in the electrical sense since its output is proportional to the intensity of the incident light, i.e. the square of the optical electric field [2]. Thus, the addition of the two optical fields at the detector, results in an output containing the difference frequency as shown in figure 1 [8].

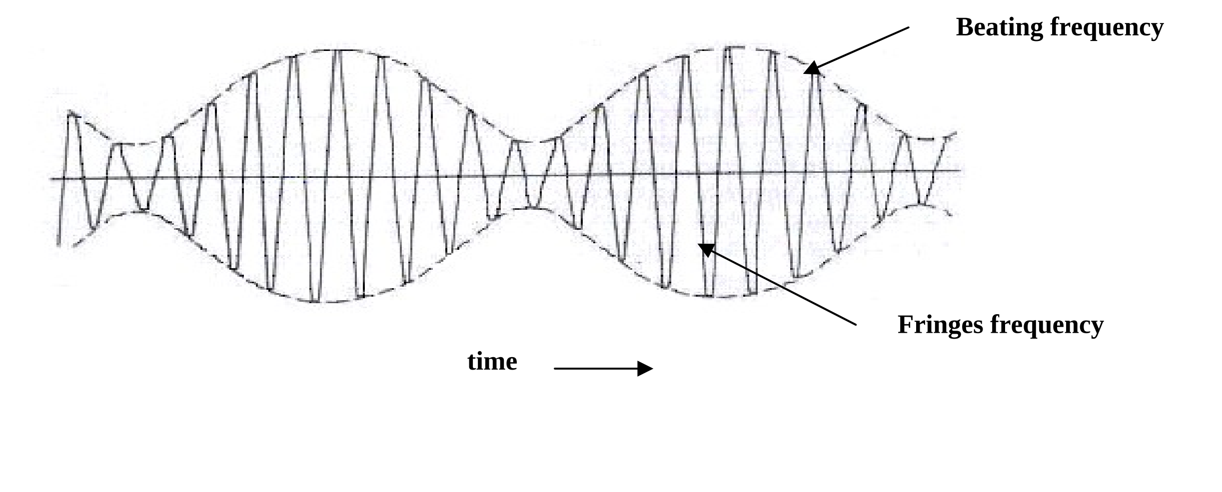


Figure (1) Waveform of output signal

Expressing the two fields at time t by [8]:

$$\mathbf{E_R = E_{oR} \cos (2 \pi f_1 t + \Phi_1)} \qquad (2)$$

$$E_T = E_{oT} \cos (2 \pi f_2 t + \Phi_2) \qquad (3)$$

where

ER is the wave front amplitude of the reference laser beam at the detector,

EoR is the wave front amplitude of the laser beam as reflected from the fixed mirror,

ET is the wave front amplitude of the signal laser beam at the detector,

EoT is the wave front amplitude of the laser beam as reflected from the vibrated mirror,

f1 is the reference laser frequency, which is equal to fL,

f2 is the modulated laser frequency, which is equal to (fL±fD),

Φ1 and Φ2 are phases of laser waves frequency.

The output i (t) of the detector is equal to the square of the total electric field. Thus:

$$i (t) = [EoR \cos (2 \pi f1\ t + \Phi1) + EoT \cos (2 \pi f2\ t + \Phi_2)]^2 \qquad (4)$$

Transforming this trigonometrically and neglecting terms of optical frequency which clearly cannot be observed at the output of the detector (for its high frequency), then [8]:

$$i (t) = 1/2(EoR2+EoT2) + EoREoT \cos [2 \pi (f1- f2)t +(\Phi1 - \Phi2)] \qquad (5)$$

The output thus contains a d.c term proportional to the total intensity and a beat frequency (f1-f2) term proportional to the product of the amplitudes EoREoT or (IL1IL2)1/2 , where IL1 and IL2 are the intensities of the two beams [9]. The output signal, of equation (5), is illustrated graphically in figure 1 [7].

4. Experimental work

An Experimental arrangement based on Michelson interferometer (figure 2) has been implemented for heterodyne detection to measure panel vibration. A photograph of this arrangement is shown in figure 5. The apparatus which has been used in this arrangement consists of:

He-Ne laser source.
Beam splitter coated for 50% reflection.
Fixed mirror.

- Detection circuit.
- Two vibrating panels; a circular aluminum foil of 6cm diameter and 0.004cm thickness, and an X-ray film 30*40cm^2 area and 0.1cm thickness.

Michelson interferometer arrangement has been implemented in this experimental work. The laser beam which is emitted from He-Ne source splits into two beams through the beam splitter. One is directly aimed toward the target, which is called measured beam. The other is aimed toward the fixed mirror, which is called reference beam. The distance from the beam splitter to the target and to the fixed mirror are equal, and is adjusted to 30 cm. The distance between beam splitter and the laser source is 15 cm.

The two reflections of beams have been mixed together by beam splitter. The mixing output which departs from beam splitter has been aligned to be incident on the detector surface as shown in figures 2 and 3. The distance from the beam splitter to the detection circuit was adjusted to be 5m.

A detection circuit has been fabricated, it consists of a detection unit "semiconductor phototransistor" followed by a low noise amplifier (figure 4w) with a gain factor equal to 35.

A range of frequencies was applied through a loudspeaker connected to a function generator in order to vibrate the object. This range begins from frequencies far from object natural frequency to frequencies in the range of the object's natural frequency. This is to evaluate the response of the vibrating targets for frequencies which are near or far from their natural frequencies.

The calculated natural frequencies and relevant physical properties of target panels are presented in table 1. The calculation method of the natural frequency for these panels is detailed in reference [10].

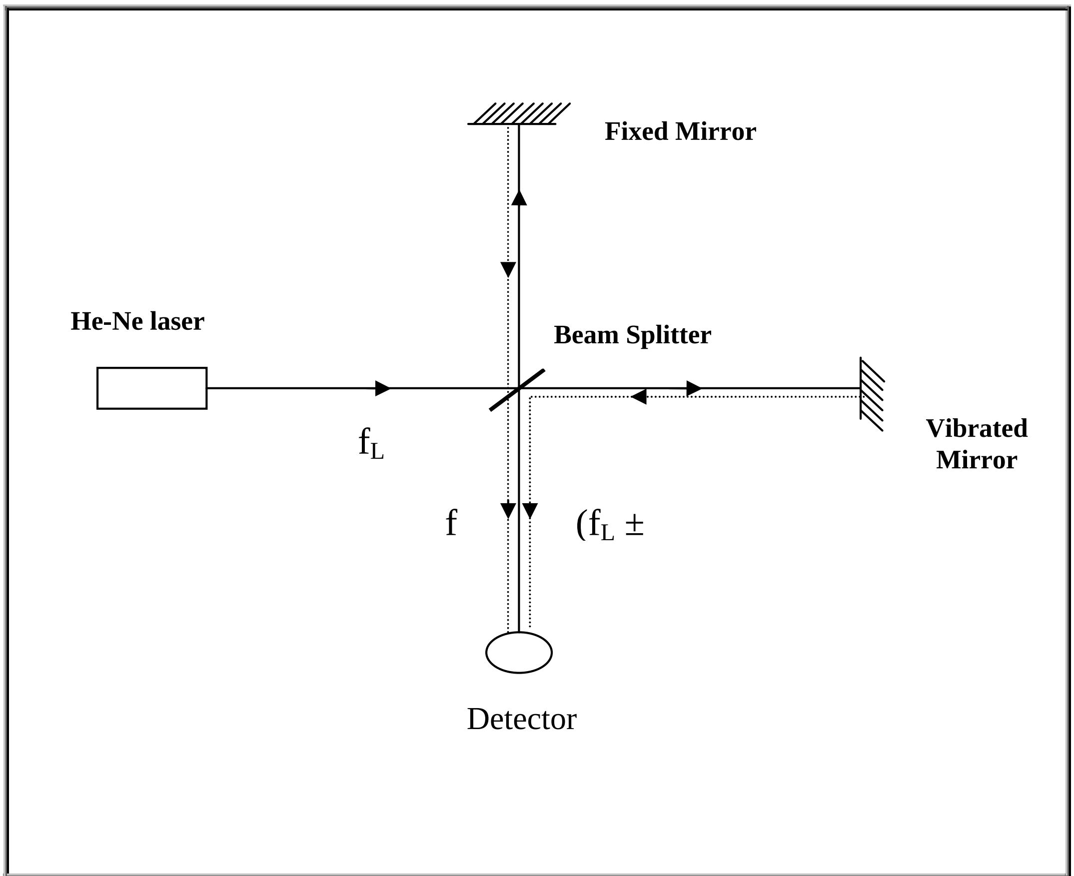


Figure (2) Principle of heterodyne detection arrangement

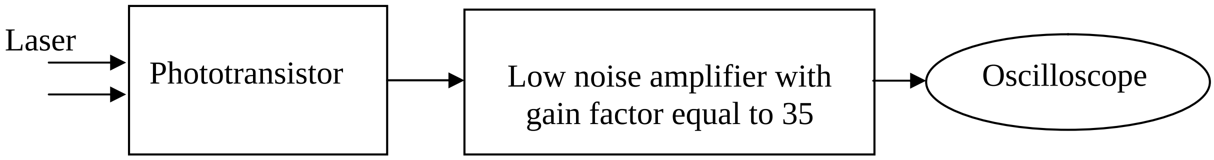
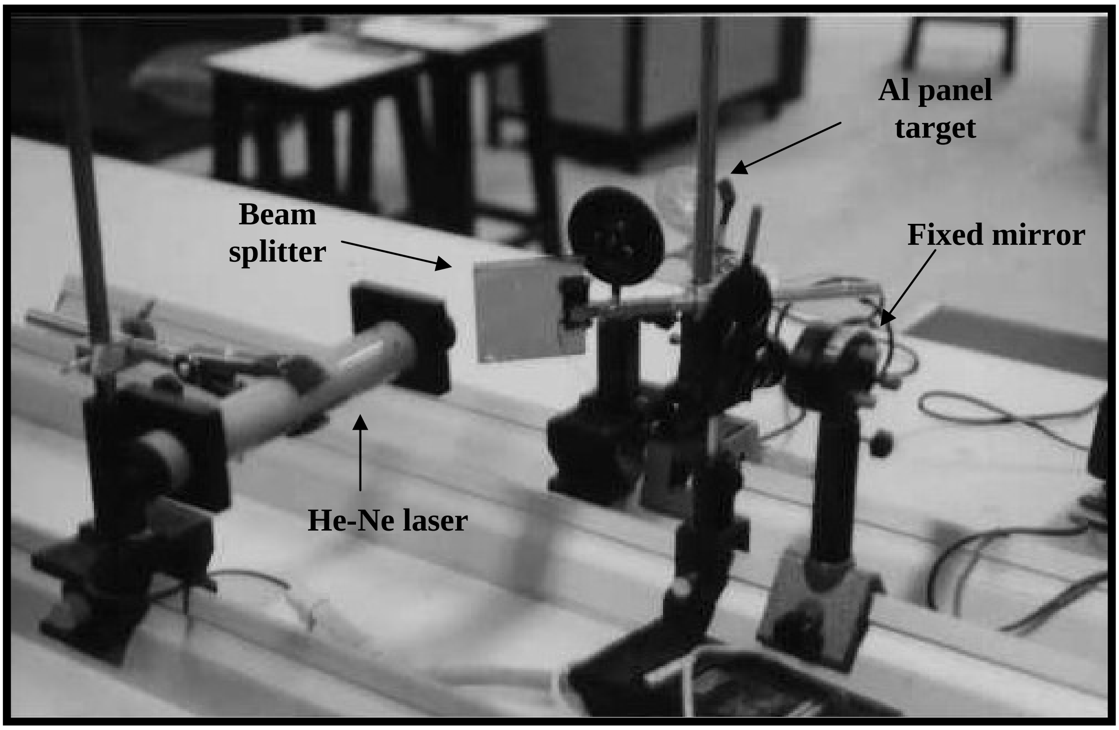


Figure (3) Configuration of the detection circuit



The detection unit has not appeared as it lies at 5.0 m from this position

Figure (4) Photograph of the experimental arrangement**.**

Natural frequency of the X-ray film is calculated assuming properties of polyethylene, because polyethylene is the essential material for manufacturing X-ray films.

To facilitate better evaluation, two different types of materials of different sizes have been selected for experiments. Each material has been experimented with a different spectrum of vibration frequencies, aluminum with a spectrum up to five times its natural frequency, and the X-ray film with a spectrum down to one fifth of its natural frequency.

Table (1): Properties and calculated natural frequency of the vibrating panels uesd

	Modulus of elasticity E (GPa)	Density γ (Mg/m^3)	Poisson's ratio ν	Natural frequency f_n (Hz)
Aluminum foil	69	2.7	0.3	50
X-ray film	0.7	0.96	0.3	20

5. Results and Discussion

The experimental results of vibration measurement of the two panels are illustrated in table 2 for the aluminum panel and table 3 for the X-ray film.

Table (2): Experimental results of the aluminum panel vibration

Applied frequencies (Hz)	Measured frequencies (Hz)
10	11.2
20	22.8
50	70.0

Table 2 shows that aluminum panel behave as a linear system when the applied frequency is away from its natural frequency. But the system becomes nonlinear and suffers from increased divergence of the measured frequency as the applied vibration approaches the natural frequency of 50 Hz.
Photographs of the above measurements of vibration frequencies are shown in figures 5, 6 and 7 respectively. The envelope of the output signals represents the vibration frequency of the target.

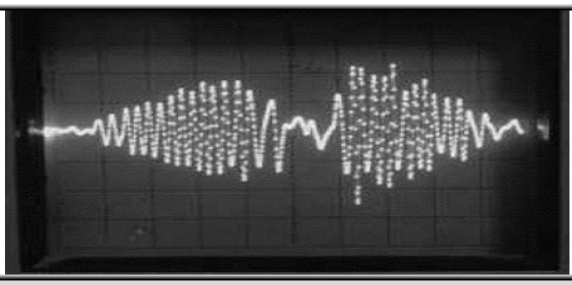


Figure (5) Measured vibration 11.2 Hz of aluminum panel for applied frequency of 10 Hz.

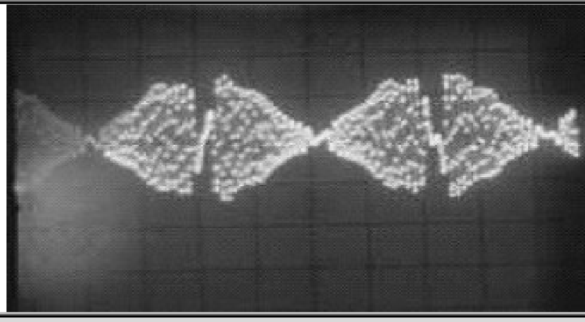


Figure (6) Measured vibration 22.8 Hz of aluminum panel for applied frequency of 20Hz

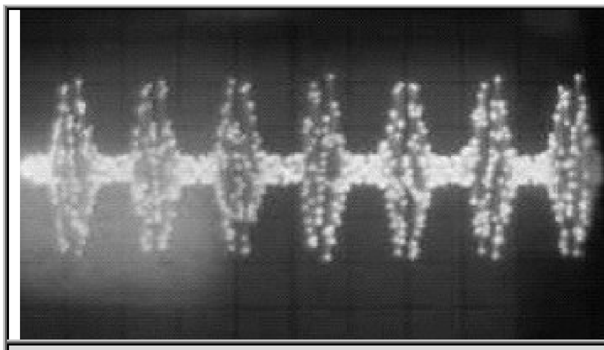


Figure (7) Measured vibration 70 Hz of aluminum panel for applied frequency of 50 Hz.

As well, Table 3 shows that X-ray film behave as a linear system when the applied frequency departs from natural frequency region, while the system becomes nonlinear when the applied vibration approaches the natural frequency.

Table 3: Experimental results of the X-ray film vibration

Table (2): Experimental results of the aluminum panel vibration

Applied frequency (Hz)	Measured Frequency (Hz)
100	100
70	70
40	49
20	35

This can be noticed from the increased difference between measured and applied signals for frequencies below 70 Hz, as shown in figures 8, 9, 10 and 11.

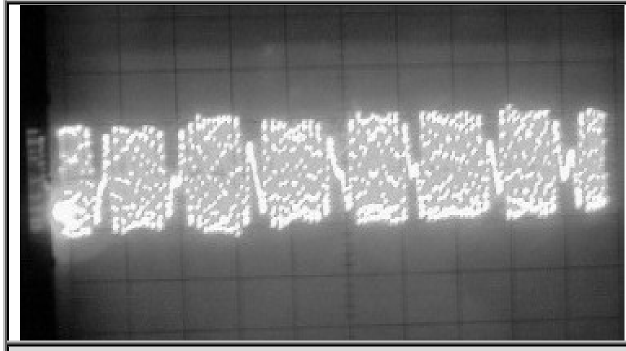


Figure (8) Measured vibration 100 Hz of aluminum panel for applied frequency of 100 Hz.

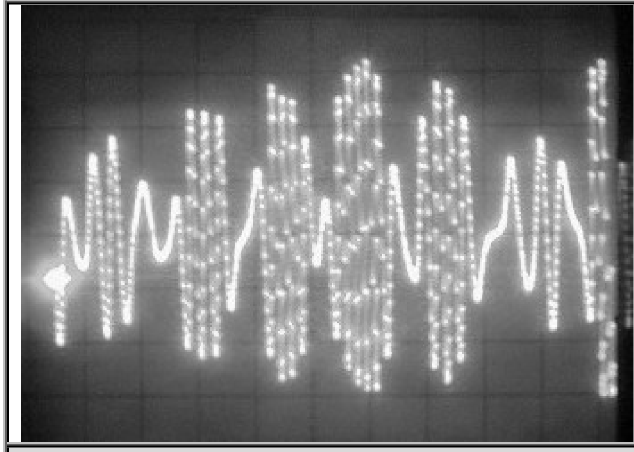


Figure (10) Measured vibration 49 Hz of aluminum panel for applied frequency of 40 Hz.

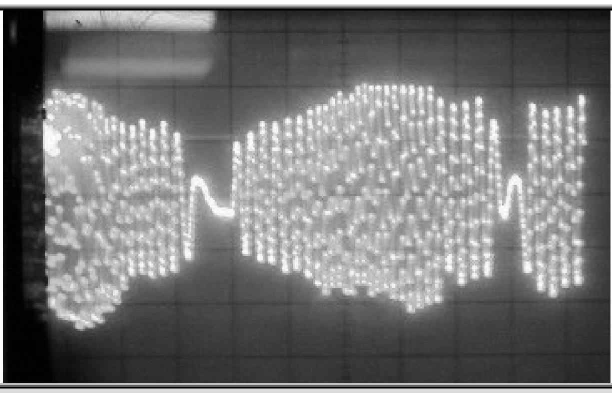


Figure (9) Measured vibration 70 Hz of X-ray film for applied frequency of 70 Hz.

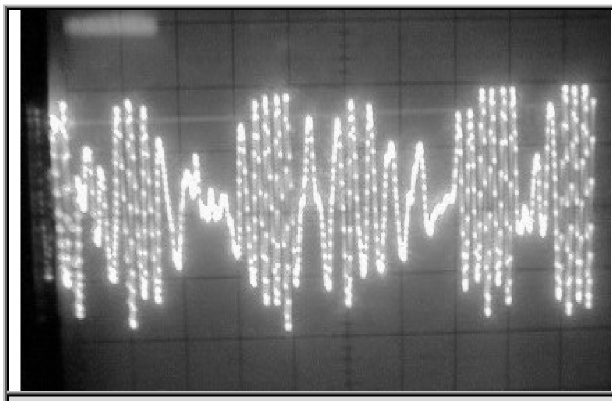


Figure (11) Measured vibration 35 Hz of aluminum panel for applied frequency of 20 Hz.

These results show that the two panels behave as linear systems when the ratio between the applied frequency of acoustic wave and the natural frequency is greater than two (or less than one half), so that, the panels may vibrate with same frequency of applied signal. On the other hand, the two panels behave as nonlinear system when the ratio between the applied frequency of acoustic wave and the natural frequency is less than two (or greater than one half). This conclusion is in good agreement with the phenomenon of partially damped resonance vibration presented by Thomson [4], and is depicted in figure 12 with arbitrary scale.

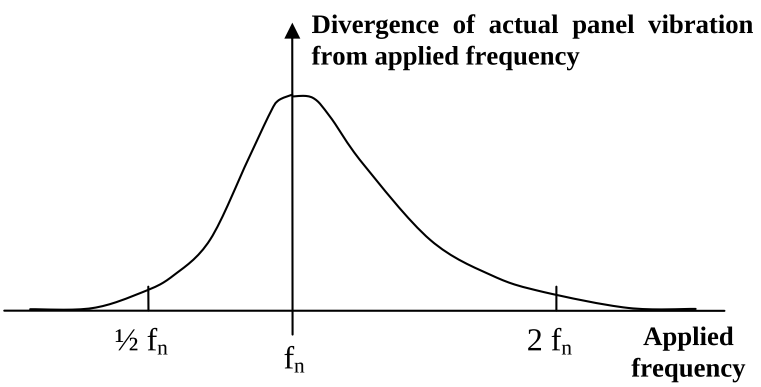


Figure (12) Behavior of panel vibration for the spectrum close to the natural frequency.

5. Conclusions

1. Vibrating frequencies which are produced by the two panels are associated with the panel's natural frequency.
2. Experimental results show that vibration frequency of object is the same frequency of the applied force when the applied vibrations are well outlying from natural frequency of the object.
3. Experimental results show that when the applied vibration approaches the region of the object natural frequency, the object behaves as a nonlinear system and suffers from increased divergence of the measured frequency.
4. The two vibrating targets suffer from increased divergence of the measured frequency when the ratio of applied frequency to the natural frequency is greater than 0.5 or less than two.

6. References

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قياس وتحليل الاهتزاز باستخدام طريقة الكشف الهترودايني لليزر

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الخلاصة

تم في هذاالبحث تنفـيـذ منـظومة مـدخال مايـكلسون مختبرية وبأستخـدام مبـدأ دوبلر لقياس الأهتزاز. وقد أستخدم ليزر الهيليوم–نيون كمصدرضوئي متشاكة في هذه التجارب. تم بناء دائرة الكترونية للكشف الهيترودايني وذلك لكشف وتسجيل اشارات دوبلر. استخدم نوعان من المواد لتعـمل كالواح اهتزاز حيث جعل هذان اللوحان يهتزان بتأثير الموجات الصوتية المنبعثة من مكبر صوت موصول بمولد للدوال الموجية. كانت مدى الترددات المستخدمة هي ١٠–١٠٠ذبذبة/ثانية. وقد بينت نتائج الأختبارات التي تم تسجيلها بأن اهتزاز الالواح يتوافق مع الاهتزازات المسلطة عندما يكون مقدار التردد المسلط اكبر من ضعف تردد الأهتزاز الطبيعي للوح (او أقل من نصفه).