Modal Analysis of Flowers

Mechanical and Mechatronic department

Dr. Sebastian Oberst

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Submitted by
Adesh Grewal

25040003

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Executive summary:

Flowers have evolved intricate mechanisms such as buzz pollination, where bees use vibrations to release pollen from anthers. This study focuses on understanding how flowers respond to these vibrations, mainly through modal analysis of their petals. By investigating the mechanical properties and vibrational responses of petals, the research aims to bridge gaps in floral biomechanics.

The experimental approach utilised two flower species, Plumbago auriculata and Phalaenopsis amabilis, chosen for their structural diversity. A custom setup was employed featuring a modal shaker to simulate bee vibrations, an impedance head for mechanical response measurement, and a laser vibrometer for precise vibrational data collection. This rigorous methodology ensured accurate analysis of frequency responses and modal characteristics.

Key findings revealed distinct resonant frequencies: Plumbago auriculata at 392 Hz and Phalaenopsis amabilis at 126 Hz. Additionally, the study provided insights into petal bending and torsional behaviours under vibrational excitation, which is essential for understanding their structural integrity. The research enhances knowledge of floral vibrations and proposes a robust experimental framework applicable across diverse flower species.

In conclusion, this study contributes significantly to understanding how flowers interact with vibrational stimuli, shedding light on their mechanical responses and laying the groundwork for future advancements in floral biomechanics.

Introduction:

Flowers play a crucial role in the reproduction of plant species, with many evolving specific adaptations to attract pollinators like bees. One such adaptation is buzzing pollination, where bees use vibrations to extract pollen from flowers. Despite extensive studies on buzz pollination, there remains a significant gap in understanding the mechanical properties and responses of flowers, particularly their petals, to these vibrations.

The study addresses this gap by conducting a detailed modal analysis of flower petals subjected to vibrational forces. The research focuses on determining the material properties of petals and understanding their bending and torsional behaviours under vibrational excitation. This research aims to explore how flowers react to the vibrational frequencies generated by pollinators and to develop a method for accurately measuring these responses.

Two flower species, Plumbago auriculata and Phalaenopsis amabilis, were selected for their contrasting structural characteristics. The experimental setup involved a modal shaker to simulate bee vibrations, an impedance head to measure the mechanical response, and a laser vibrometer to capture the vibrational data. By analysing the frequency responses and modal characteristics of these flowers, the study aims to provide a comprehensive understanding of the effects of vibrational pollination and contribute to the broader field of floral biomechanics.

Literature Review:

Flowers are crucial for the survival and reproduction of plant species. Over time, plants have evolved to attract bees and optimise their propagation methods to benefit both the plants and pollinators. One significant adaptation is using floral scents, which attract beneficial pollinators while repelling harmful insects.

A paper by Mario Vallejo investigates the rapid physiological response of flowers to the sounds of pollinators, specifically focusing on the increase in nectar sugar concentration. The study reveals that within minutes of exposure to pollinator sounds, flowers can alter their nectar composition, making them more attractive to pollinators and enhancing pollination success. Vallejo suggests that flowers may detect pollinator sounds through specific vibrations rather than auditory mechanisms. This research delves into the mechanisms and evolutionary reasons behind buzz pollination, where bees use vibrations to extract pollen, finding it to be an efficient method for pollen release.

Another paper examines the variations in the natural frequencies of stamens in six different Solanum species and their relationship to bee vibrations. This study aims to understand how morphological diversity affects the resonance frequencies and pollination efficiency, concluding that there is significant variation in the natural frequencies of stamens across different Solanum species. Matching these vibrations is crucial for effective pollen release.

Brito's 2020 paper also explores the biomechanical properties of buzz-pollinated flowers, focusing on their structural integrity and resilience to vibrational forces. The study provides a detailed analysis of how these flowers withstand and utilise vibrational energy during pollination. It finds that they possess specialised biomechanical properties optimised for durability and efficient pollen release.

Furthermore, Vallejo's research on bee behaviour examines the buzzing behaviour of bees and its implications for buzz pollination. It offers a comprehensive overview of the biological, ecological, and mechanical aspects of buzz pollination, highlighting that the mechanical vibrations produced by bees are finely tuned to maximise pollen extraction.

While there are numerous studies on buzz pollination, there still needs to be a gap in understanding the mechanical properties and analysis of flowers and petals under various conditions and species. To address this gap, I have developed an experimental procedure designed to be flexible for use under different conditions and with multiple species while maintaining accuracy and repeatability in identifying mechanical properties.

Flower Selection:

Multiple flowers were used in the experiment.

a. **Artificial flower:**
   An off-the-shelf artificial flower was used to create a template to determine vibrational analysis for actual flowers. The artificial flower is assumed to be made of hard plastic for the body and polyester fabric for the petals, as seen in Figure 1.

Figure 1a: Top view of the artificial flower

Figure 1b: Front view of the artificial flower

Figure 1: Artificial Flower

b. **Plumbago auriculata**

Figure 2: Plumbago Auriculata

Plumbago auriculata, an evergreen shrub often known as a climber, belongs to the Plumbaginaceous family and has a perennial life cycle. This plant is native to South Africa. The flower petals are approximately 2 cm wide and have five petals, with a salverform corolla and a superior ovary position. The stems are long and thin, making them delicate and highly susceptible to damage from cutting and handling. The specimens used in this study exhibited purple. The flowering period for Plumbago auriculata peaks from August to October. “Plumbago" typically refers to Plumbago auriculata. Plumbago comprises approximately 15 species of annuals, perennials, and shrubs native to Central America, Southern Africa, Southern Asia, and Australia. Plumbago auriculata thrives in well-drained soil and prefers full sunlight, although it benefits from filtered sunlight in regions with extreme temperatures. This species is an evergreen shrub, though it may lose some leaves in winter climates. It features simple, 5 cm long, light to mid-green oblong leaves. The flower was chosen due to its fragility to determine how the testing methods would affect flowers whose structures are soft and prone to breakage. This is done to make the testing method more robust and to choose a practical and less tensing approach for the flowers, as seen in Figure 2.

c. **Phalaenopsis amabilis**

Figure 3: Phalaenopsis amabilis.

Phalaenopsis, commonly known as the moth orchid, belongs to the Orchidaceae family. Phalaenopsis orchids are characterised by their compressed stems and alternate, broadly elliptic to obovate leaves with entire margins. The flowers, or florets, consist of five tepals and a distinct modified lower petal known as the lip. They are arranged in a raceme on a long, sturdy green peduncle and are known for their exceptional longevity, with some species maintaining their blooms for several months. Phalaenopsis orchids exhibit an arching, epiphytic habit, typically growing in a vase-like form. They have a coarse texture and mature to a height of 0.2 to 0.4 meters with a spread of 0.6 to 1.0 meters. The growth rate of these orchids is slow. These orchids are native to Australia, New Zealand, Southeast Asia, Japan, and China and are cultivated in gardens. They thrive in hardiness zone 11, withstanding temperatures above four °C. Phalaenopsis orchids prefer filtered shade and require a well-drained growing medium. The inflorescence of Phalaenopsis is typically a raceme, although it can occasionally form a panicle-like structure with side branches. The flowers are perfect, containing both male and female reproductive organs. They have three petals and a bilabiate corolla shape with an inferior ovary position. The flower has a bigger form factor, with flowers ranging from 7 to 12 cm, as seen in Figure 3. The flower was chosen to test the designed concept and rectify any flaws or drawbacks in the experiment.

Material preparation:

A significant challenge in this experiment was handling and preparing the flower samples to ensure accurate vibrometer measurements. Flowers are delicate, and low reflectivity posed significant logistical issues requiring meticulous preparation and handling procedures. I have documented the problems encountered, the steps to prepare the samples, and potential solutions identified that have yet to be implemented due to time or resource constraints.

Issues and Solutions

1. **Handling and Storage of Flowers:**
   - **Issue:** The freshness of the flowers is crucial for accurate measurements. Flowers tend to wilt quickly, affecting their physical properties and the experiment's results.
   - **Solution:** Flowers were plucked as close to the testing time. The average time to set up and conduct each experiment was 30 to 45 minutes to minimise any degradation in the flowers' condition. Flowers were stored in a cool, humid environment to maintain freshness before testing.
2. **Low Reflectivity:**
   - **Issue:** The naturally low reflectivity of the flowers generated noise in the readings, making it challenging to obtain clean and accurate measurements. The results are shown in the picture of the laser vibrometer, and the results in the figure show the comparison of reflective and non-reflective readings of the same point on the petal.
   - **Solution:** Reflective tape was used on the petals to enhance reflectivity. Despite the added weight and potential minor damage to the petal structure, the tape provided much cleaner and sharper peaks in the readings, significantly reducing the need for post-processing.
3. **Reflective Spray:**
   - **Issue:** Reflective spray did not adhere to the petal material and would fall off as it dried, rendering it ineffective.
   - **Solution:** Reflective tape was chosen over reflective spray due to its better adhesion and effectiveness in improving measurement accuracy.

Material Preparation Steps

1. **Flower Plucking and Storage:**
   - Pluck flowers as close to the testing time as possible.
   - Store flowers in a cool, humid environment to maintain freshness until testing.
2. **Reflective Tape Application:**
   - Cut small patches of reflective tape, each weighing 0.0025g.
   - Carefully apply the tape to 18 designated measurement points on the petals, minimising damage.
3. **Measurement Setup:**
   - Ensure the flower is securely placed and aligned with the vibrometer.
   - Experiment within 30 to 45 minutes of flower preparation to ensure data accuracy.

Potential Solutions Not Implemented

1. **Spray Airbrush:**
   - Identify an airbrush in which spray particle size and air pressure can be controlled so that the application is accurate with minimum damage to the petal

Experimental Setup:

The setup contains a vibrometer used for measurement and an impulse head, considered the reference, as shown in Figure 5. The impulse head is mounted between the shaker and the clamp used to clamp the stem, figure 4. The impulse head screws into the shaker, and the flower clamp has threaded that screw into the impulse head. The length of the impulse head and the clamp used to hold the flower are considered part of the flower during the experimentation. They are added as the flower's stem length in the geometry. The flower is mounted on a modal shaker and is aligned in a horizontal direction. The measurements are done by defining the flower axis and followed throughout. The flower is mounted in the xy plane and extends out in the +ve z direction.

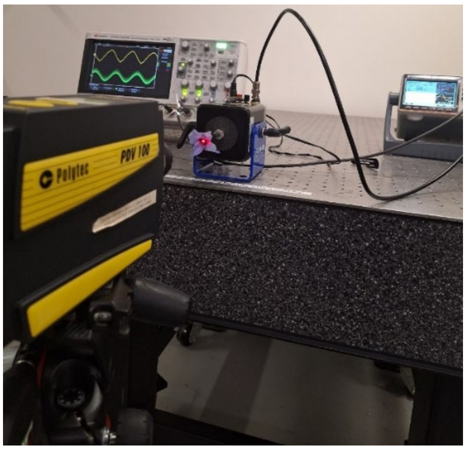

Figure 5: Set up

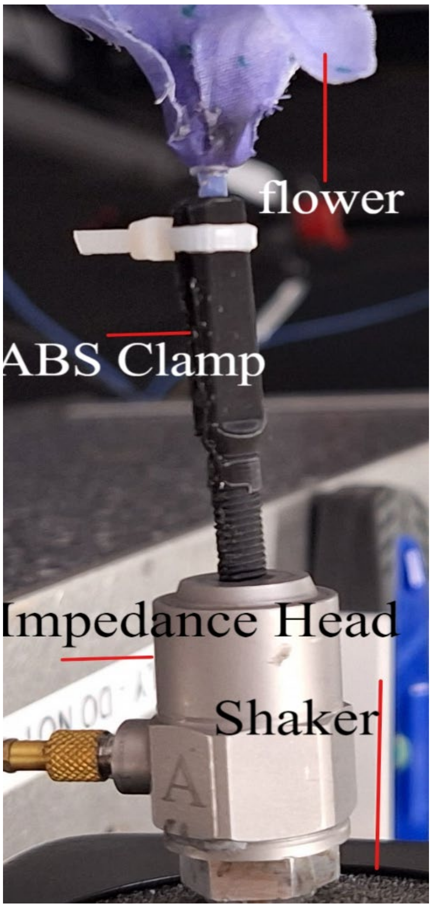

Figure 4: Shaker and clamp setup

The flower orientation is fixed, and the petals are labelled see Figure 6. The vibrometer laser is moved to target other parts of the flower. The flower petals are divided into a predetermined number of points to get values from multiple locations. The flower is attached to a modal shaker and is exited from the base/stem of the flower. Once the setup is fixed, there is no change till the end of the experiment.

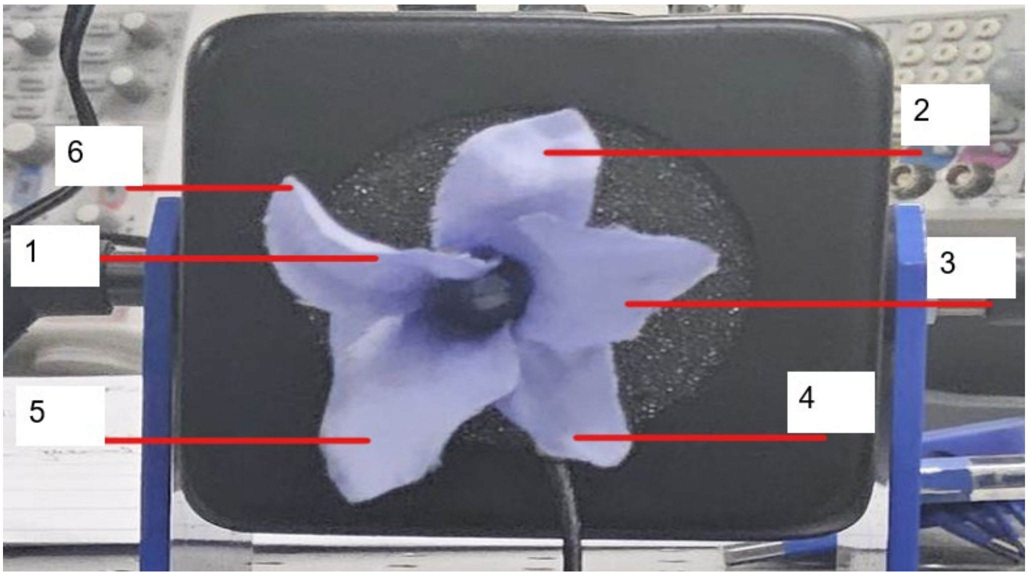

Figure 6: petal labelling

Experimental Procedure:

The equipment used in the experiment is a modal shop shaker K2004E01, an AF/100/10 AF IEPE Impedance Head and a PDV 100 laser vibrometer. Manufacturer tables for all the equipment are listed in the appendices under tables 4,5,6. The modal shop shaker K2004E01 was chosen due to the ability its ability to excite in very low frequencies, as mentioned in the datasheet; it has a Frequency Range of DC-11 kHz, where DC stands for direct current, and the DC input, or the shaker is 12v, also, due to its compact form and ease of mounting impedance head. The DJB instrument AF IEPE Impedance Head AF/100/10 was chosen because it is susceptible to acceleration changes and can measure the low-frequency range ranging from 0.5 Hz to 5khz. Which suited the testing range. The Polytech PDV -100 was chosen for its accuracy and sensing capability for small vibrations. Given the actuation frequency, the PDV sat between the range (0.5 – 22k HZ), making it an easy choice.

The petal is attached to a custom 3d printed clamp (figure 8), which further screws in the modal shaker. The clamp is screwed into the impedance head, which measures the mechanical response of the flower when actuated and assists in determining the operational mode shapes. For the Plumbago, a unique sleeve (figure 7) was used to give the stem rigidity to prevent it from breaking while being tested. The sleeve is tightly wound-up paper sourced from a q tip by removing the cotton ends. The stem of the plumbago fixed in the sleeve was very close, and no adaptations were required to secure the stem. It also gave the stem rigidity to be clamped by the abs clamp; otherwise, it would break when being clamped. The shaker is mounted on an optical table. Reflective tape is used on the petals' surface to increase the laser's reflection. The reflective tape is cut into 2mm*2mm pieces and weighed 2.5 mg on average for each piece of reflective tape. The data acquisition system used is Siemens SCADAS.

Figure 8: 3D - printed clamp

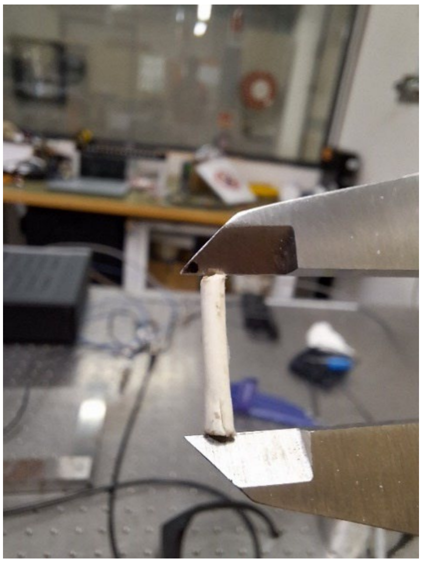

Figure 7:Q tip sleeve

Set Up conditions:
The setup conditions for the devices are listed in the tables below.

Table 1: EXCITATION CONDITIONS for Siemens SCADAS Test lab

TYPE	PERIODIC CHIRP
TIME	4 SECONDS
LEVEL	0.1 V
MODE	BURST
RANGE	100 – 4096 HZ
RESOLUTION	0.25
BANDWIDTH	4096
NUMBER OF AVERAGES	30
CONDITIONING	NONE

The PDV-100 is set up using the conditions shown in Table 2.

Table 2: LASER VIBROMETER SETUP CONDITIONS

SENSITIVITY (VELO)	500/4V (mm/s/V)
LOW PASS FILTER	5
HIGH PASS FILTER	NONE

Geometry definition for analysis:

Fake flower

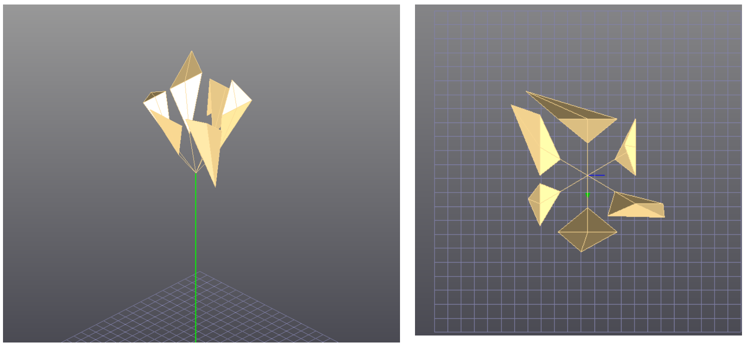

Figure 9: Fake flower CAD geometry

The geometry is defined in the Siemens test, as shown in Figure 9. Each petal was divided into four sections, as seen in Figure 10. Three significant points were taken on for each petal: where the petal begins, the second is mid-way, the total length of the petal, and finally, the petal tips. Each petal is measured at these three points with the laser vibrometer.

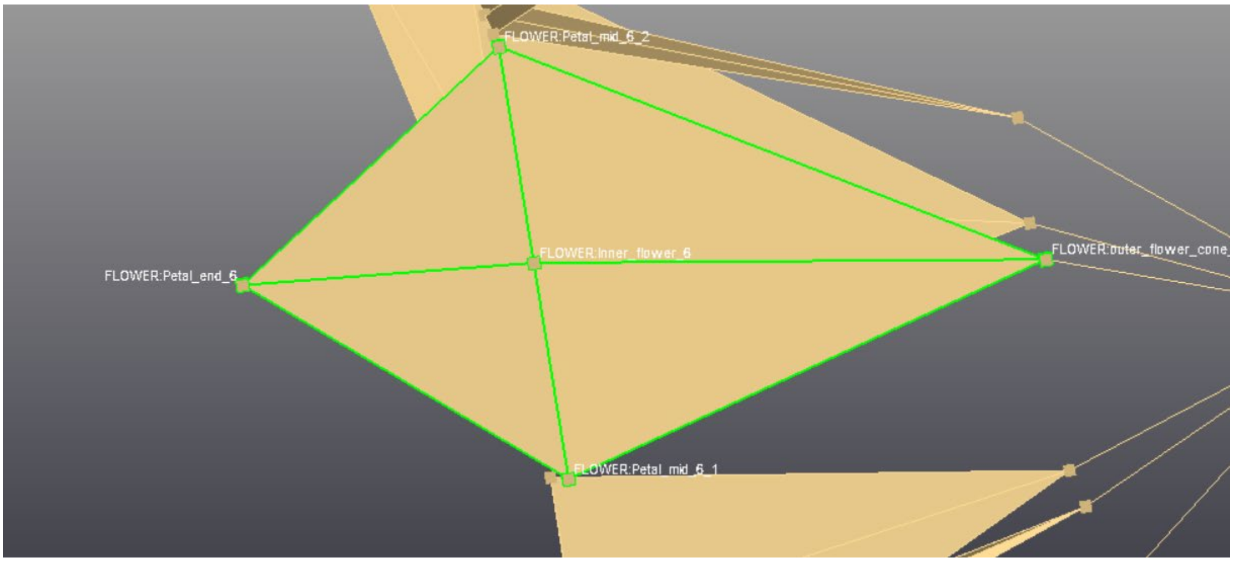

Figure 10: Petal Division

Plumbago auriculata

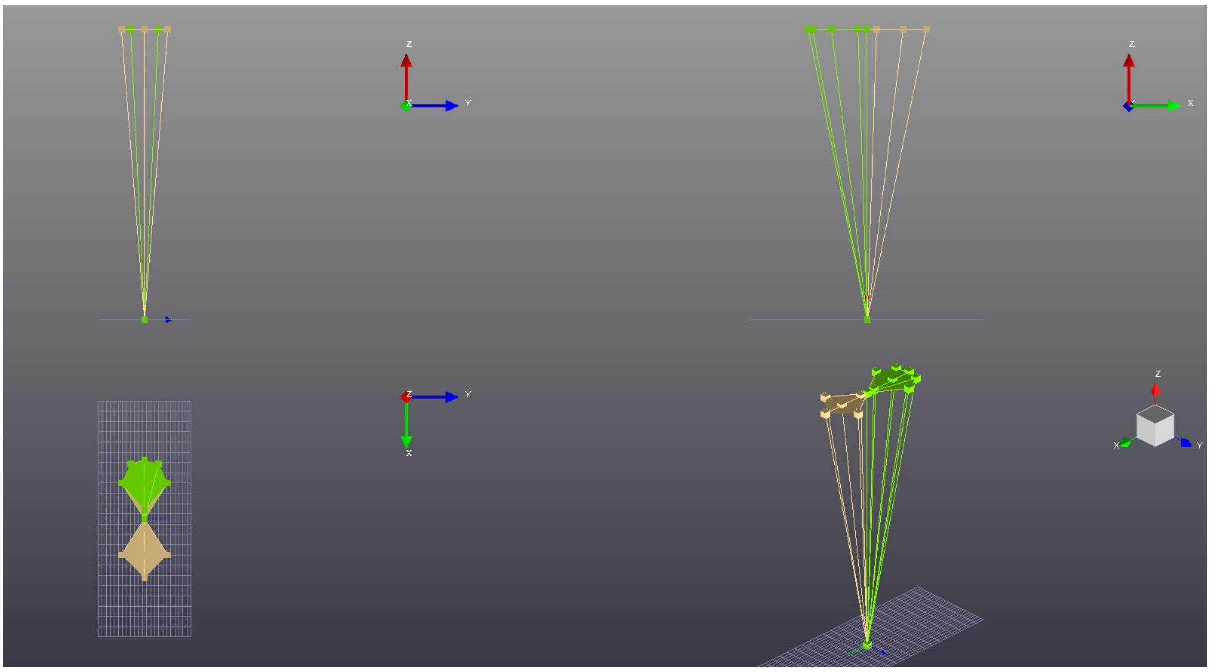

Figure 11:Plumbago auriculata CAD geometry

A similar approach is taken with Plumbago auriculata, and a cad geometry (figure 11) is generated in the Siemens test lab to determine the flower's natural vibrations and bending moments.

Phalaenopsis amabilis

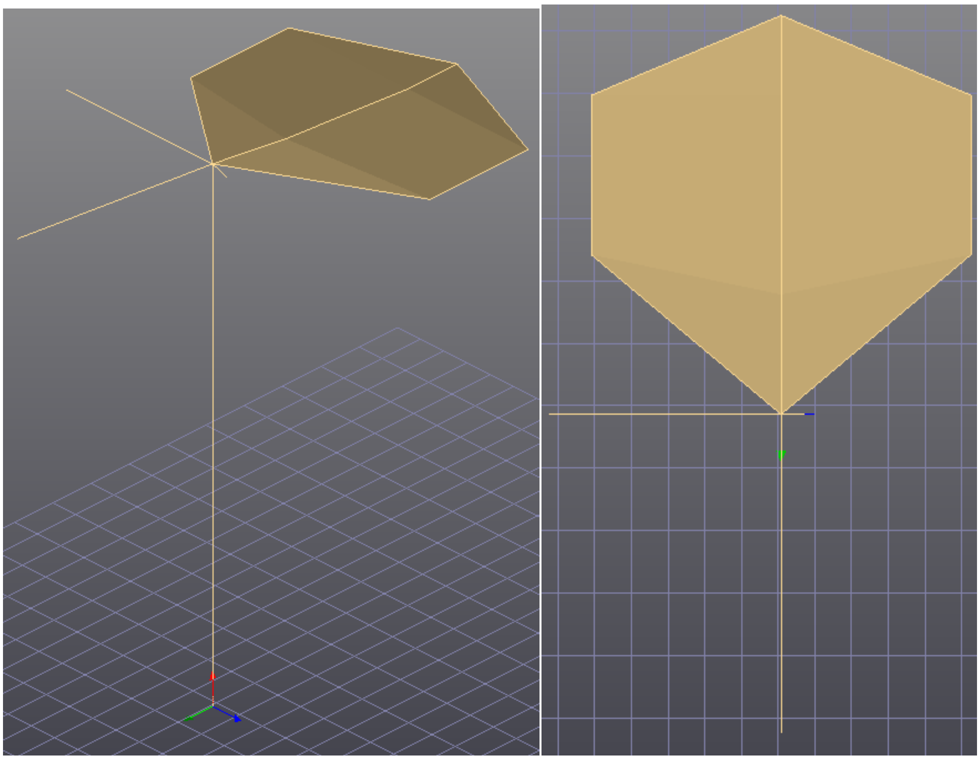

Figure 12: Phalaenopsis Amabilis CAD

The Phalaenopsis Amabilis Figure 12. is defined with more resolution on the petal as it is used to determine the material properties and bending moments of the petals, which gives the petal higher importance. This can be seen in Figure 13, where multiple points on the petal are labelled.

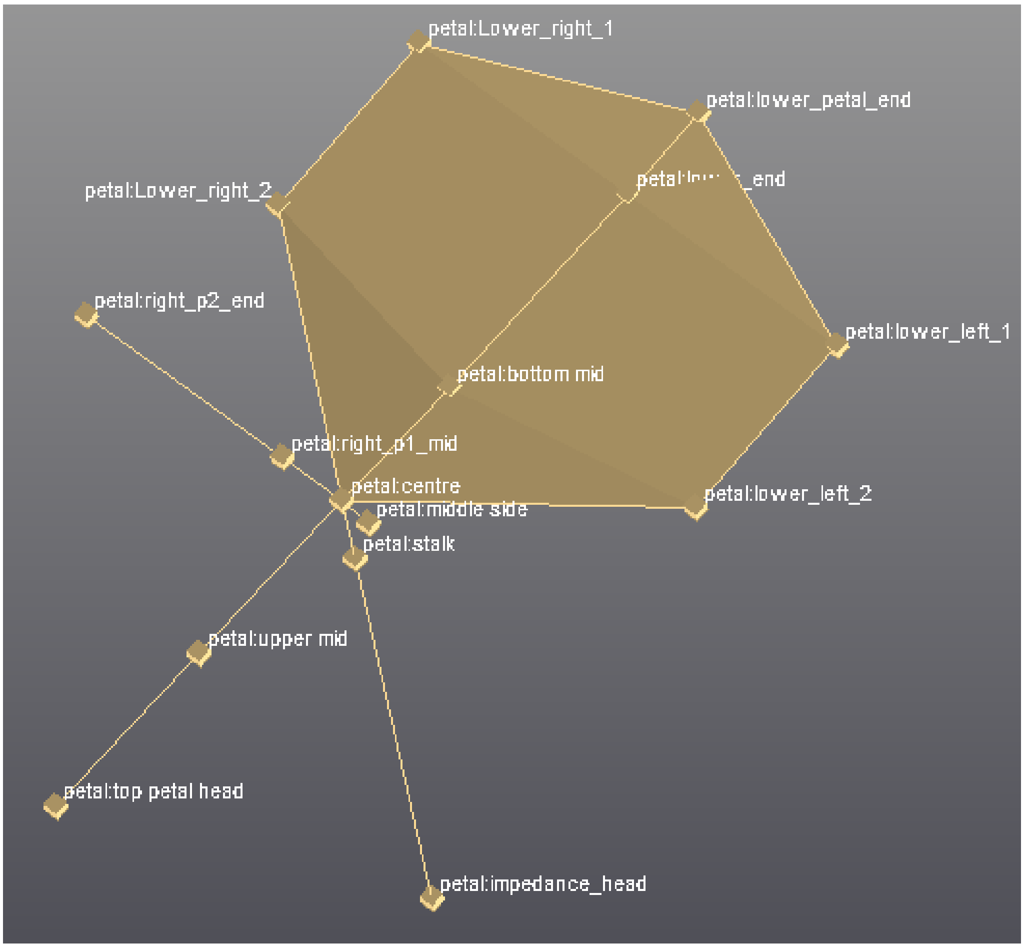

Figure 13: Nodes on Phalaenopsis Amabilis

Dimensions determination:

The dimensions and weight of the flower are determined using the pictures in Figures 14 and 15.

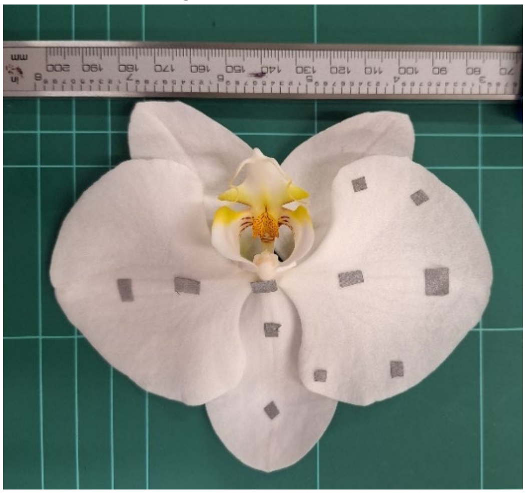

Figure 15: Phalaenopsis amabilis Dimensions

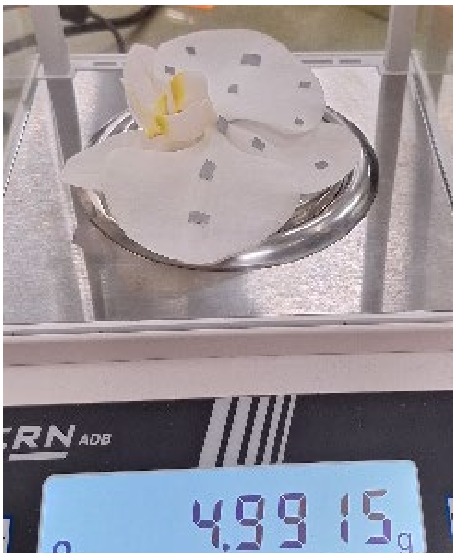

Figure 14: Phalaenopsis amabilis weight

- **Width of the Flower:** 75 mm
- **Length of the Flower:** 80 mm
- **Height of the flower**: 137 mm
- **Weight of the Flower**: 4.99 g
- **Radius of the Flower**: 65 mm

Results:

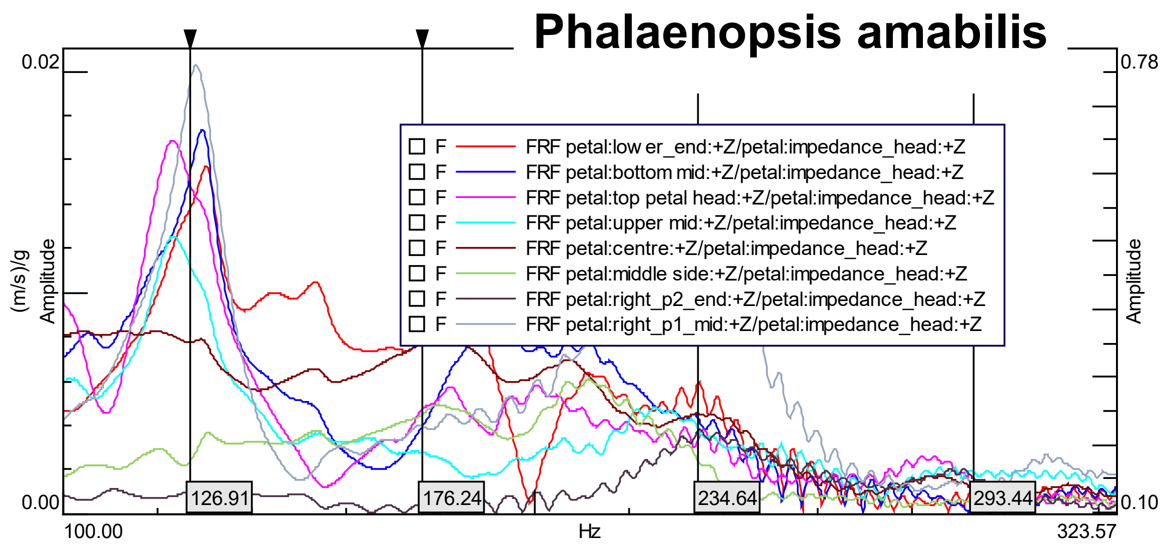

Figure 16: Response of Phalaenopsis amabilis

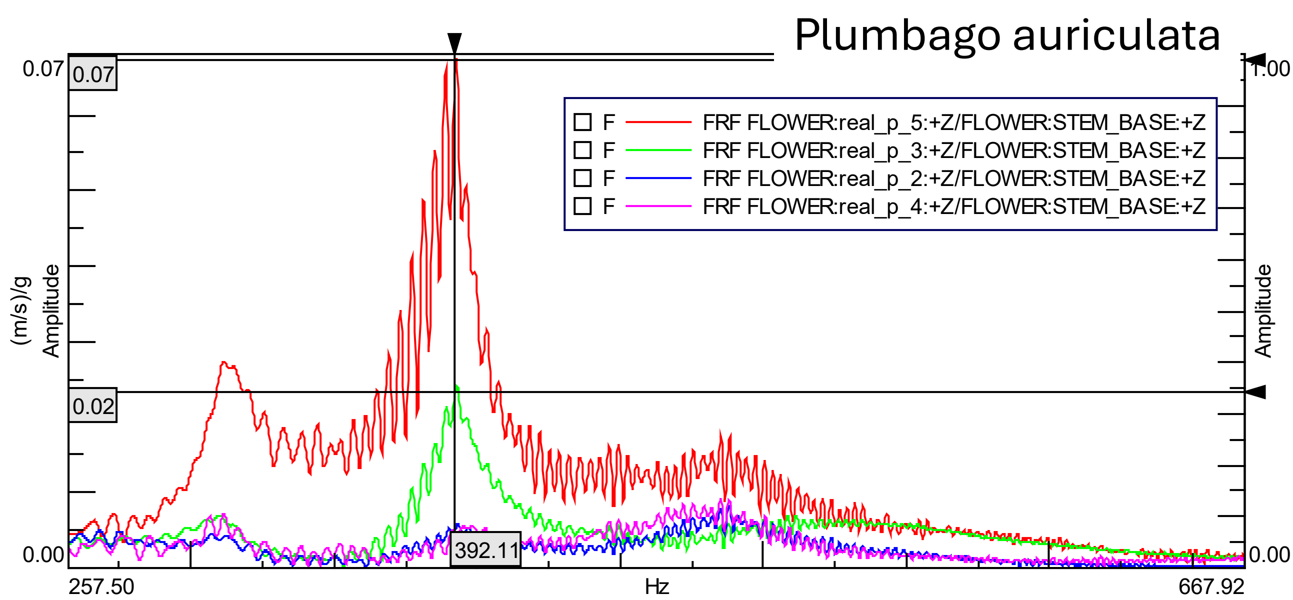

Figure 17:Response of Plumbago auriculata

As seen from the figures, the flowers have a range for resonance, and each point resonates with a different amplitude while in the frequency range. The Plumbago auriculata has a resonating frequency of 392 Hz Figure 17, while The Phalaenopsis amabilis has a resonating frequency of 126 Hz Figure 16. The petal of the Phalaenopsis amabilis is further analysed to determine its bending characteristics. When excited, the petal behaves similarly to a beam fixed at one end, displaying prominent first and second-order bending and torsional moments. These are shown in table 3.

Table 3: Phalaenopsis amabilis frequency response table

Frequency	Mode
121	1st order
128	2nd order
138	Torsion
150	2nd order
184	Twisting
205	2nd order + torsion (MIXED)
305	MIXED

The analysis reveals the bending behaviour of the petals at various frequencies. These frequencies and the similarities between the bending modes are illustrated in Figure 18. The Model Assurance Criterion (MAC) graph presents a mix of similar and unique bending modes exhibited by the petals.

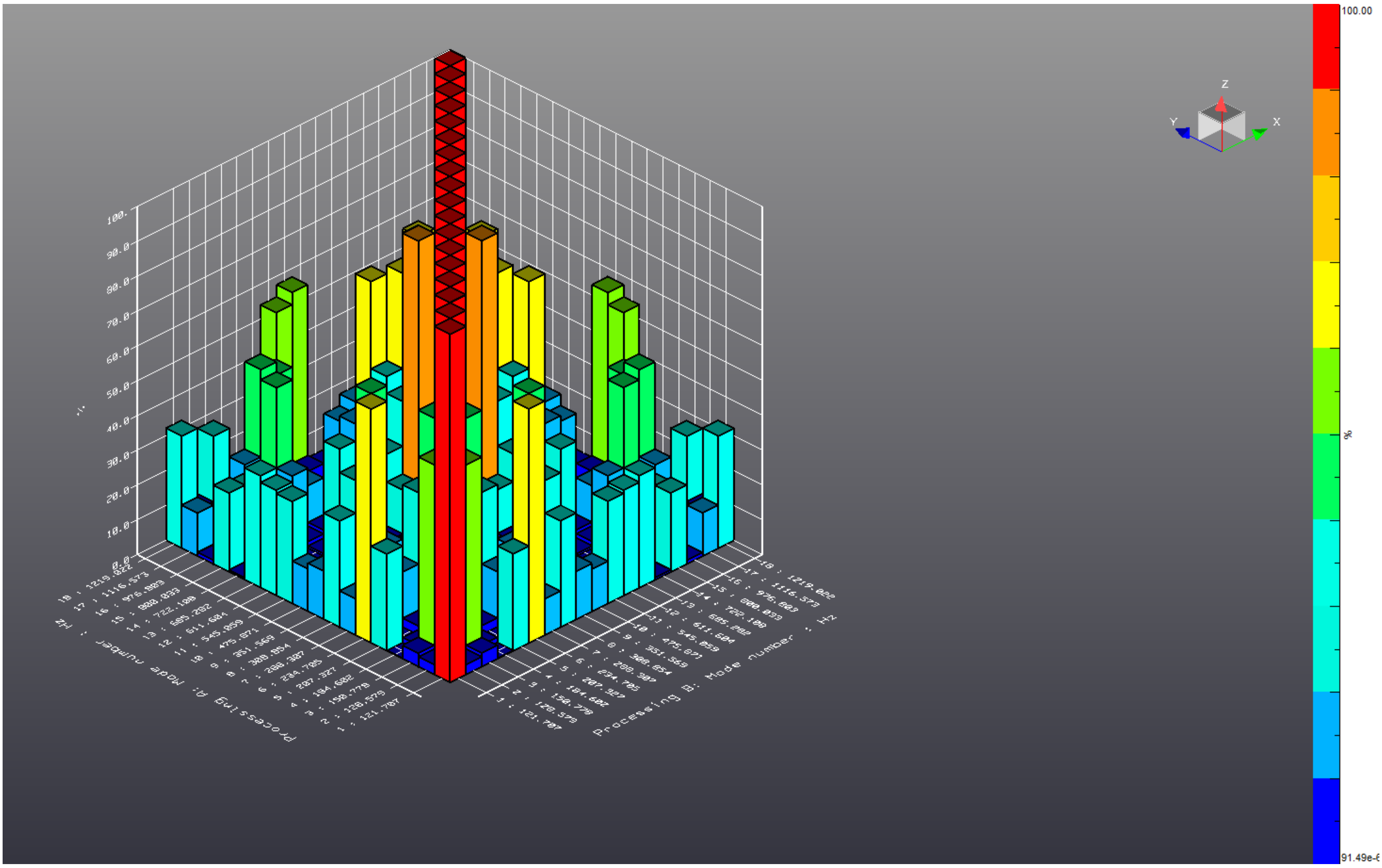

Figure 18: MAC graph

Material properties determination

The material properties of the orchid flower are being determined; I have used the moment of inertia formula for a circle as the flower most accurately fits in a circle.

$$I = \frac{1}{2} M.R^2$$

Where,

I = moment of inertia of a circle

M = Weight of flower,

R = Radius of the flower

$$I = \frac{1}{2} \times 0.00499\, kg \times 0.065^2\, m$$

$$I = 0.00001054125 \mathrm{kg} \cdot \mathrm{m2}$$

Calculate the volume of the flower by considering it to be a cylinder.

$$\mathrm{V} = \pi \mathrm{r}^2 H$$

$$\mathrm{V} = \pi \times (0.065)^2 \times (0.137)$$

$$\mathrm{V} \approx 0.00182298\mathrm{m3}$$

Calculating the density of the flower.

$$\rho = \frac{\mathrm{m}}{\mathrm{v}}$$

$$\rho = \frac{0.00499\mathrm{kg}}{0.00182298\mathrm{m}^3}$$

$$\rho \approx 2.737\mathrm{kg/m3}$$

Determine Young's Modulus (EEE) and Shear Modulus (GGG) using natural frequency determination for the petal.

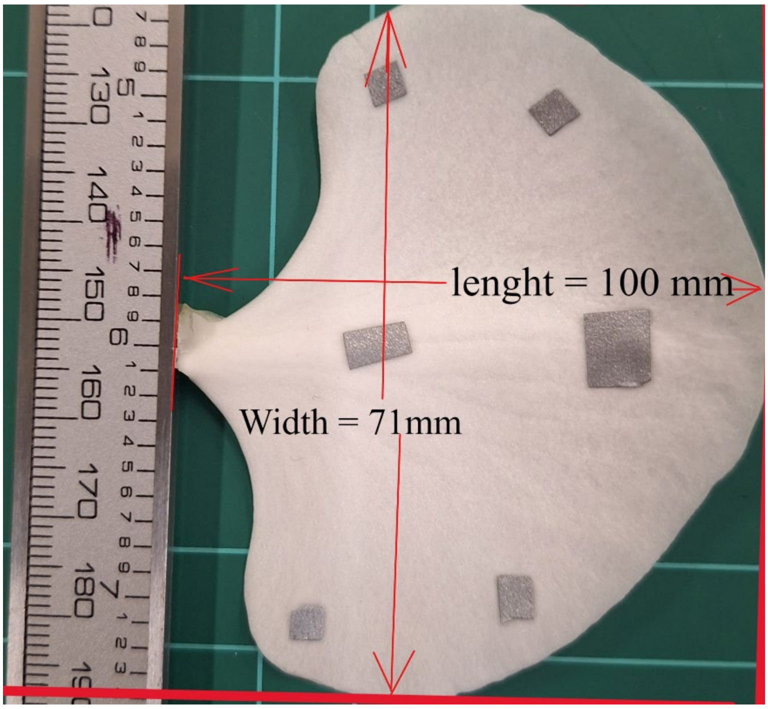

Figure 19: Dimension of the petal

The average thickness of the petal is 0.75 mm. The petal's width is 71 mm, and length is 100 mm, as seen in Figure 19.

Using cantilever beam formula rectangular

Using the moment of inertia of a bar

$$\mathrm{I} = \frac{\mathrm{wt}^3}{12}$$

$$\mathrm{I} = 120.075 \times (0.071)^3 \approx 120.075 \times 0.000357911 \approx 2.24 \times 10^{-6}\mathrm{m}^4$$

The cross-sectional area A is given by:

$$A = w\,x\,t$$

$$W = 0.075$$

$$T = 0.071$$

$$\mathrm{A} = 0.075 \times 0.071 \approx 5.325 \times 10^{-3}\ \mathrm{m}^2$$

The Natural Frequency identified by the petal of the flower is 126 Hz

To determine the natural frequency of an object, the formula is used shown in the equation

$$\mathrm{f} = \frac{1.875^2}{2pi}\left(\frac{E * L}{rho * A * L}\right)^{\frac{1}{2}}$$

rearranging the equation and solving for E (Young's Modulus)

$$E = 50634.46 \times 0.065 \approx 3291.24\ N/m^2$$

Young's Modulus is extremely low compared to typical engineering materials. This value suggests that the material is very soft and flexible.

Discussion and Conclusion:

The key findings from the experiment are that both the flowers showed an increase in their response when in the region of their pollinating insects, further solidifying the significance of buzz pollination evolution for flowers. The setting up test procedure for flowers is shown to be repeatable and reliable. It also aligns with the buzz pollination concept, making the flower release pollen efficiently in a specific frequency range. An attempt to determine the material properties of the flower has been made, which will provide an idea of the material properties of a petal, assisting others to make better predictions and predict more accurately how a flower reacts to excitation.

The areas that require further study are how the addition of tape or environmental factors such as manual handling and picking the flowers affect the structure of the flower. Also, the time it takes to show the damage and how it affects the structure of the flower. Effect of withering and how it affects the structure of the flower as it would make it more brittle. A more in-depth analysis of the bending modes due to the petal having low-resolution points as a measurement with higher-resolution petals will give better results—a more accurate way to determine the material properties of a flower.

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Appendices:

Table 4: Shaker specification

Specification	
Performance	K2004E01
Shaker performance	
Output force, sine pk	
Natural Air Cooling	4.5lbf(20N)
Output force, random RMS	
Natural Air Cooling	3 lbf (13.3N)
Output Force, shock pk	9 lbf (40N)
Stroke length	
Continuous pk-pk	0.2 in (5mm)
Between Stops	0.35 in (9mm)
Frequency range	DC – 11KHz
Acceleration	
No load	64 g pk
0.1 lb (0.045 kg) load	26 g pk
1 lb (0.454 kg) load	4.2 g pk
2 lb (0.907 kg) load [max payload]	2.2 g pk
Maximum Current	5 A
DC resistance	1.5 ohm

Table 5: Impedance Head table

Impedance Head	AF/100/10
Sensitivity (20°C) Force ±10	10mV/N
Sensitivity (20°C) Acceleration ±10	100mV/g
Measuring Range Force	500N
Measuring Range Acceleration	±50g
Typical Frequency Range Force	~0.5Hz~5kHz
Typical Frequency Response ±5% ±10%	1Hz – 4kHz 0.7Hz – 5kHz
Typical Frequency Range Acceleration	~0.5Hz~5kHz
Temperature Range	-40 to +121°C
Weight	30gms
Case material	Stainless steel
Mounting Type	x2 M5
Dimensions	20 x 27mm
Output impedance	<100Ω
Base Strain Sensitivity	≤ 5%

Table 6: PDV 100 specification table

Metrological Specifications	
Decoder type	Digital velocity decoder, 3 measurement ranges
Frequency range	0.5 Hz - 22 kHz

Measurement range (mm/s/V)	5	25	125
Full scale output (peak, mm/s)	20	100	500
Velocity resolution[1] (μm s^{-1}/$\sqrt{}$Hz)	<0.02 <0.02 <0.1		
Analog output Velocity,	±4 V, 24-bit DAC		
Connector	BNC		
Dynamic range[2]	>90 dB		
Calibration accuracy	±1 % (20 Hz ... 22 kHz)		
Output impedance	50 Ω		
Filters	Digital low pass filter (FIR type):	1 kHz, 5 kHz, 22 kHz (±0.1dB),	
	roll-off	120 dB/dec	
	Analog high pass filter:	100 Hz (-3dB), roll-off 60 dB/dec	