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The undersigned certify that they have read, and recommended to the Institute of Engineering for acceptance, a thesis entitled " Optimal distribution of Propeller dynamic balancing correction weights to match pre-defined attaching points" submitted by Dipesh Thapa in partial fulfilment of the requirements for the degree of Master of Science in Mechanical Systems Design and Engineering

Supervisor, Dr. Laxman Poudel
Professor
Department of Mechanical and Aerospace
Engineering

Co-Supervisor, Dr. Sudip Bhattarai
Assistant Professor
Department of Mechanical and Aerospace
Engineering

External Examiner, Mr. Ashish Manandhar
Technical Department
Buddha Air Pvt. Ltd.

Committee Chairperson,
Dr. Surya Prasad Adhikari
Head of Department
Department of Mechanical and Aerospace
Engineering

Date

ABSTRACT

Dynamic balancing on an aircraft propeller is performed on frequent basis. An unbalanced propeller produces noisy and uncomfortable vibration to passenger. It also adds dynamic load to structure causing early failure of vital components compromising aircraft's safety and reliability. Therefore it is always desirable that any propellers during its service be balanced both statically and dynamically. A field dynamic balancing of propeller need frequent engine run up. An engine run up comes with additional cost, time and pollution. Moreover aircraft maintenance personnel get exposed to more air and noise pollution during propeller balancing than general aircraft departure due to longer exposure time and power run requirements. Hence any attempt to reduce the number of trail run will save cost, environment and health of these personals. Various standard procedure being used for dynamic balancing need at most three trail runs but additional to this extra run may require when there is a collective error due to approximation of attachment location from demanded location and approximation of balancing weight from actual balancing weights. Elimination of this error could be a key to reduce extra trail runs. This paper is an attempt to do so by splitting a demanded weight to best combinations of available weight in best available locations with the help of influence coefficient technique and resultant vector resolution method.

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LIST OF SYMBOLS

IC	Influence coefficient
\overrightarrow{TW}	Trial Load
\vec{T}	Trial Vibration
\overrightarrow{HS}	Heavy spot
\vec{O}	Initial Unbalance
$[k]_{n \times m}$	Influence Coefficient Matrix
$[p]_{m \times h}$	Trial Load Matrix
$[\Delta V]_{n \times h}$	Vibration matrix
\vec{e}	Unbalance eccentricity
m	Balancing mass
\vec{r}	Radius Vector
M	Unbalance mass
V_i	Mass at angle α_i
α_i	Angle of Hole i
n	total number of holes

CHAPTER ONE: INTRODUCTION

1.1 Background

Dynamic balancing on the aircraft propeller is performed on frequent basis. Propeller balancing is manufactures recommendation, regulatory requirement and operator's requirements. An unbalanced propeller produces noisy and uncomfortable vibration to passenger and this vibration could create various problems like loosening of screws, damage to various parts, early failure of life limited components etc.

So, it is always desirable that any propellers that are in service be balanced both statically and dynamically. Erosion and elongation of propeller blades, wear and tear of various rotating parts are common causes of propeller that has been subjected to service but in many cases the new propeller assembly also becomes imbalanced due to various manufacturing defect and defective process. Sometime having all individual blade balanced may also result with the assembly imbalanced because of the tolerance that individual blade when assembled could cause the resultant imbalance unacceptable. Hence propeller balancing is very important and is essential for optimizing performance of aircraft. For propeller balancing there are various equipment manufactured but all have their own limitation and this project is focused to a problem that is much unnoticed but reasonably important one.

During the propeller balancing at first all the previous loads will be removed and the first trial run is performed at no load. An accelerometer mounted on the stable platform with in phase vibration location is installed. A tachometer is used to measure the speed (RPM) of the propeller. Once the imbalance is calculated at no load is performed now we will add the trial load at appropriate location (there are various method for calculating a trial weight) and again measure the resultant vibration, this resultant vibration and trial load magnitude help us to calculate the total imbalance and the balancing weight to be added at appropriate location. Now the final run in performed to check if the system becomes balanced. The above method needs three different trial run but it is very unlikely that we can get the desired vibration level because the location where correction load can be inserted is finite (say 8, 12, 16 etc locations) but the angle which the correction load must be added would be any positive real number less than 360°). Just for an instance for the 12 point location the

load could be added to $(n \cdot 360/12)$ location i.e for $n=0$ its 0° and for $n=1$ it is 30° increment of 30° . Hence as it is very unlikely that the imbalance point coincides the given location creating resultant vibration level below acceptable level. In order to reduce this problem some propeller manufacturer gives provision to drill out the hole at the locations where ever desired. But since the propeller balancing is done very frequently a hole cannot be drilled in all the location because sometime the drilling location may become very near to the previous drilled hole which can become problem and sometime drilling the new hole is not an option because either manufacture does not allow it or drilling precisely becomes very difficult. So, as the distribution of correction load is very crucial for the reduction of unbalances. In this project we have focused on optimal distribution of correction weight at its appropriate location to match final unbalance point exactly at the predefined locations and calculate the resultant imbalance after the weight distribution approximation.

A propeller dynamic balancing need frequent engine run up. A single engine run up for small 17 passenger aircraft could cost as high as Nrs. 15000 moreover the efflux burnt in an engine run also adds pollution to the environment near aircraft location. Generally aircraft maintenance personal inhale more pollutant during propeller balancing than general aircraft departure due to longer exposure time and power run requirement. The sound produced by an engine also creates noise pollution. Hence any attempt to reduce the number of trial run could save huge financial losses, reduces pollution and also saves ground time on the aircraft. So, in this project we have planned to help small organisations to minimise their expense on the propeller dynamic balancing by providing our formula and developed matlab application for them. Although there are few equipment which can give the correction load insertion at predefined locations limited to two split but it does not take consideration of the available balancing weight masses also does not delivers the resulting imbalance after this approximation. The main objective of this project is to calculate the best possible combination of balancing mass for a given propeller for lowest resultant imbalance considering the number of holes available and mass resolution. Moreover we have also work out providing the resultant vibration level after the optimal load has been calculated. This calculation can be performed by user using the application that has been developed through this project. The user of this application has also the provision to choose any of best alternative mass combination to get the pre-defined

vibration level. Also we will plot the appropriate graph to show appropriate location. This is obviously going to help us to perform required trial run on calculator or computer reducing the number of trial run in real aircraft.

Propeller unbalances are major cause of aircraft vibration which may be either static or dynamic. Static imbalance of propeller occurs when the centre of gravity of a rotor does not coincide with the rotational axis of the propeller. Similarly Dynamic unbalance occurs when the CG of all the element of the propeller like blades, counter weights and cam doesn't fall on the same plane of rotation. Since the length of the propeller assembly along the engine crankshaft is short in comparison to its diameter, and since the blades are secured to the hub so they lie in the same plane perpendicular to the running axis, the dynamic unbalance resulting from improper mass distribution is negligible, provided the track tolerance requirements are met. Another case of propeller unbalance is aerodynamic unbalance which is caused due to unequal force distribution in propeller blades. This type of unbalance can be by examining the blade angle and blade profile.

1.1.1 Propeller Static Balancing

Propeller static balancing is accomplished by mounting the propeller on a balanced shaft that is positioned on a frictionless bearing. As the propeller is rotated on this shaft, the heavier side of the propeller prefers to stay at the lowest point while the lighter side tends to stay on the opposite side. Now, we begin adding weight to the lightest side and quickly rotate the propeller to see if it stops in the same place. If it does, we repeat the process, but if the propeller continues to move between different positions, the propeller is be balanced. Balancing a propeller statically can reduce a lot of vibration.

The figure 1 shows the difference between balance rotor and unbalanced rotor, notice that the c of g of imbalanced rotor has shifted above due to which the rotor blade on upper side will move downward once stopped after free rotation. Mostly static balancing is done in a workshop as huge equipment's are required for the static balancing. Balancing masses generally used for static balancing are of larger magnitude and tolerances level is higher in compare to dynamic balancing. Mostly conventional setups are used for static balancing.

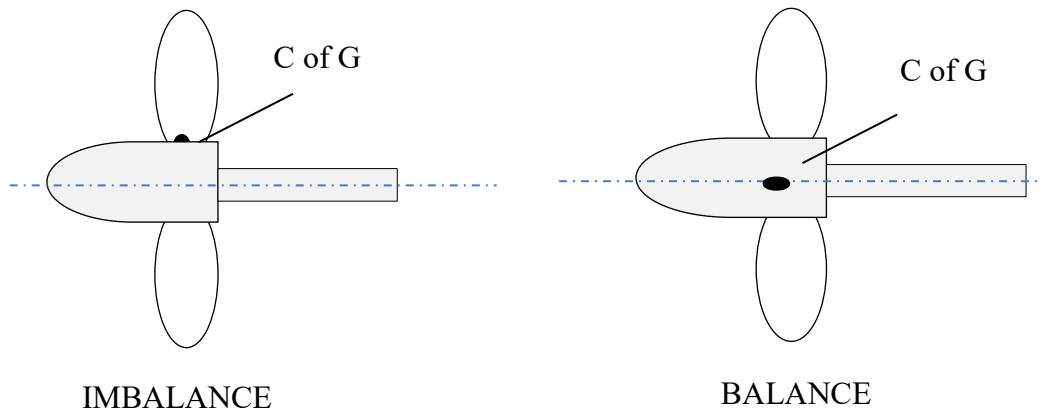


Figure 1.1 Static Balancing of propeller

The following steps are part of the standard technique for determining propeller imbalance:

Place a bush over the propeller's mounting hole.

- i. Place a mandrel or arbor through a bush.
- ii. Position the propeller assembly so that the knife edges of the balance stand support the ends of the arbor.
- iii. Verify that the propellers may freely rotate.

If the propeller is statically balanced appropriately, it stays in place no matter where it is positioned. Two-bladed propeller assemblies should be balanced with the blades in the horizontal and vertical positions, respectively. By placing the blade that was checked in the downward position in the upward position, repeat the vertical position check with the blade positions reversed.

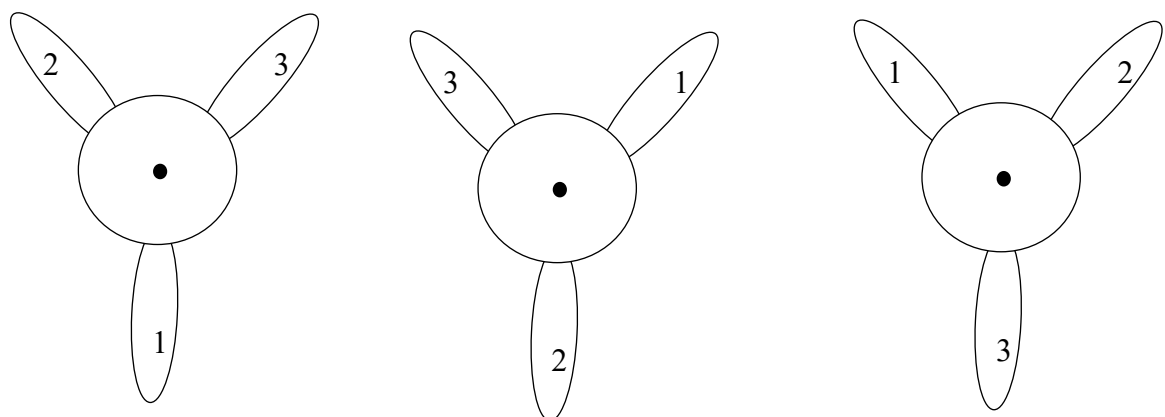


Figure 1.2 Static balancing of three bladed propeller

1.1.2 Dynamic balancing

To lower the vibration levels of the propeller and spinner assembly, propellers can additionally be dynamically balanced (spin balanced) with an analyser kit. Some aircraft already have the system hardwired, while other aircraft require installation of the sensors and wires prior to the balancing run. The propulsion system can be balanced to significantly reduce the amount of vibration and noise that is communicated to the cabin, as well as to prevent excessive wear and tear on other engine and aircraft parts. Any aerodynamic imbalance or a mass imbalance could be the root of the dynamic imbalance. Only the vibration brought on by the mass imbalance of the propulsion system's outwardly rotating components is reduced by dynamic balancing. If the engine or aircraft is in poor mechanical condition, balancing will not lower the vibration level. Balancing will be impossible if parts are damaged, worn out, or loose to large extent. Dynamic propeller balancing equipment is produced by many manufacturers, and their methods of operation may vary. A vibration sensor that is mounted to the engine near the propeller and an analyzer unit that determines the weight and placement of the balancing weights make up the conventional dynamic balancing system.

1.1.3 Standard procedure used for propeller dynamic balancing

Place chocks at the wheels and point the aircraft directly towards the wind (no more than 20 knots). Run the engine up at low cruise rpm after installing the analyzing equipment; the dynamic analyser will determine how much balancing weight is needed at each position of the blades. Run the engine up again after inserting the balance weights to see if the vibration levels have decreased. Prior to getting results that are satisfactory, this technique might need to be repeated multiple times.

Here is a sample dynamic balancing technique, but whenever executing any balancing procedures, always refer to the aircraft and propeller manuals. By precisely assessing the magnitude and location of the dynamic imbalance, dynamic balance is achieved. The maximum number of balance weights that can be fitted is limited by the propeller maker. In addition to the propeller's specs, follow the manufacturer's directions for dynamic balance equipment. Generally propellers are balanced using ISO 1940-1:2003 standards, according to which propeller shaft are balanced for less than 16mm/s.

The majority of equipment uses an optical pickup to detect reflective tape in order to measure rpm. Additionally, the engine is equipped with an accelerometer that measures vibration in inches per second (ips). But sometime the additional accelerometer may require to be used as some aircraft may not be equipped with dedicated accelerometer.

The propeller assembly should be visually inspected before dynamic balancing. On the blades and inside surface of a spinner dome, a fresh or reconditioned propeller assembly might leave a tiny amount of grease after its first run-up. To completely clean any oil from the spinning dome's inner surface or the blades, apply Stoddard solvent (or an equivalent). Check every propeller blade assembly visually for signs of grease leaks. Check for signs of oil leaks visually on the spinning dome's inner surface. Lubricate the propeller as per the maintenance handbook if there are no sign of grease leakage. Before performing dynamic balancing, locate the leak if grease leaking is apparent and make the necessary repairs. Make a note of the quantity and placement of each balancing weight before dynamic balance. When an overhaul or significant repair is carried out at a propeller overhaul facility, static balance is achieved. At most of cases number of places to attach weight is twelve, evenly spaced out. Using bolts or screws of the 10-3 2 or AN-3 type that are of aircraft quality, install the balancing weights. At least of one thread and a maximum of four threads must extend through nuts of balance weight screws mounted to the spinner bulkhead. Hartzell advises that the propellers be dynamic balanced to a result of 0.2 ips or less, unless the engine or aircraft manufacturer specifies otherwise. If reflective tape is employed for dynamic balancing, it must be removed as soon as the balancing is finished. Record the quantity, placement, and, if applicable, the reconfiguration of static balance weights in the propeller logbook.

Figure 3 shows the typical place where balancing weight can be used. In most of the propeller the balance weight in the form of washer and nuts will be attached on the bulk head of spinner whereas in many cases some cases the balance weight in the form of adhesive could be attached to the spinner inner wall. These adhesive are always recommended by propeller manufacture and curing process used for curing such adhesives are also mentioned in standard practices.

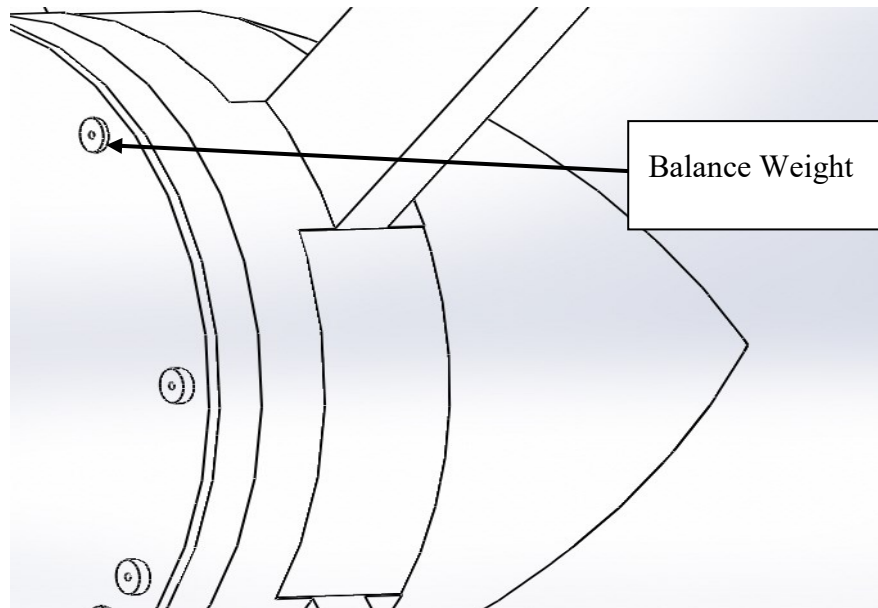


Figure 1.3 Propeller balancing weight

Hence, a standard procedure for propeller balancing consists of measuring the imbalance or vibration that existed within the propeller without any trial load added then the known trial weight is added to the known location to induce the measureable effect and this measureable effect such as vibrational amplitude is used for the calculation of actual location of unbalance. Now this load can be balanced using the available balance weight to an appropriate location. Final vibration level is measured and compared with an acceptable value. One must note that during propeller balancing we are measuring the unbalance at particular speed and specified torque and for a constant speed propeller as the angle of blade is changing with the torque being produced the propeller exactly being balanced at one torque value might not have been effectively balanced for another torque and speed setting.

1.1.4 Selection of Speed and Torque for dynamic balancing

Dynamic balancing is the manufacturer's requirement, authority requirement and operator's need to ensure passenger and cargo comfort. The manufacture of airframe determines the speed and torque at which the dynamic balancing is performed. This recommendation is based upon the condition at which aircraft flies. For constant speed propeller change in the torque value is due to the change in blade angle of propeller and as the change in blade angle also changes the actual CG of propellers, a balanced propeller at 30% torque may not be balance for 50% torque. So, the torque

requirement must also be specified by the manufacture. Moreover these propeller flies at more or less a constant speed. This speed for the majority of propeller is 96% RPM. The torque requirement for any propeller can be from 30% to 100% based upon the performance requirement. Hence for non-aerobatic/ commercial aircraft the manufacture generally recommends the torque of 30% as most of the aircraft with constant speed propeller flies almost all time with this torque value. So, this low cruise setting is the recommended torque for dynamic balancing of many commercial aircraft example ATR, but for some aircraft that needed to be operated on extreme situation have set their own requirement's. The frequency of dynamic balancing vary with the mode and frequency of operation additionally the non-routine dynamic balancing is also performed many time based on the passengers feedback and maintenance performed.

1.2 Statement Problem

During propeller balancing demanded balancing mass at particular location may not be insert able many time either due to an unavailability of exact balance weight or unavailability of holes at exact location, this could add number of trial run required to perform dynamic balancing. These additional trial runs could be reduced with an efficient algorithm.

1.3 Objective

Main Objective

Formulating a numerical technique for splitting the correction mass into two or more location by using an influence coefficient method and vector resolution technique

Specific Objectives

1. To develop an approximation technique for the distribution of correction mass to match pre-defined weight attachment location
2. To develop a matlab code for identification of an optimal locations for splitting the correction mass and calculating final unbalanced vibration
3. To develop a decision making numerical tool to identify the possibility of splitting correction mass for allowable unit location mass and given acceptable vibration level

4. To develop a computer aided model to verify the decision making numerical tool designed above

1.4 Structure

The thesis report has been divided into 7 different chapters

Chapter one provides the general introduction, Background, Problem Statements and structure of the project.

Chapter two is about the Literature review which discusses about past works related to our project

Chapter three is about the Research Methodology which presents about the research method and process that is implemented during this process

Chapter four Result and Discussion which demonstrates the result we obtained and present the information that we got in result deduction

Chapter five Conclusion and Recommendation presents the final conclusion and findings of our work and also recommends areas that can be improved.

CHAPTER TWO: LITERATURE REVIEW

2.1 Literature review

There are various journal published in order to demonstrate how the dynamic balancing is performed on the aircraft propellers, In Rotor Balancing Tutorial published by Gorge R. Brown convention centre, Kelm et.al.(2016) discussed on various method for field balancing method using graphical method which is very conventional method for dynamic balancing in addition to that they have also demonstrated the Influence coefficient method importance and how the influence coefficient method in combination of graphical method could give same result but in very faster pace. The paper has clearly demonstrate appropriate use of following equations

$$IC = \frac{\overline{TW}}{\overline{T}} \quad \overline{HS} = \vec{O} * \overline{IC} \quad \overline{HS} = \vec{O} * \overline{IC} \quad \text{Eq.2.1.1}$$

In the research paper General influence coefficient algorithm in balancing of rotating machinery, Xiaoping (2004) demonstrated the new method for influence coefficients with general formula, He also showed that how GICA can solve the IC's calculation task when the group of trial weights are installed of the rotor each time, trial weight are retained in the rotor system or there is redundant trial balancing data. In this paper the author has shown relation between vibration influence matrix, Trial matrix and Influence coefficient matrix

$$\text{i.e } [k]_{n \times m} \times [p]_{m \times h} = [\Delta V]_{n \times h} \quad \text{Eq.2.1.2}$$

Where, $[k]_{n \times m}$ = Influence coefficient matrix

$[p]_{m \times h}$ = Trial Load Matrix

$[\Delta V]_{n \times h}$ = Vibration Matrix

F Hynes (1917) in his journal "Dynamic Balancing of Rotating Part" shows his conventional mathematical technique to demonstrate the mathematical approach to solve dynamic balancing problem He in his paper calculated the dynamic balancing formula for various standard parts that is mostly useful in design stage of rotating parts.

ZACHWIEJA (2014) focused on the manual balancer but additionally he also described about automatic balancer and their uses.

Macdara MacCamhaoil in his paper Static and Dynamic balancing of Rigid rotors various type of imbalances and the principle of field balancing. He also showed the way to select the appropriate trial mass in order to achieve appropriate result immediately after first trial run. He also showed the procedure to perform balancing of overhanging rotor which is more or less similar to the balancing of aircraft propeller. The relationship between the correction mas and correction radius shown as

$$\vec{e} = \frac{m\vec{r}}{M} \quad \text{Eq.2.1.3}$$

Where, \vec{e} = *specific unbalance* , \vec{r} = *correction radius* , M = *Rotor mass* (MacCamhaoil, 2016)

William C. Foiles(1996) has demonstrated the mathematical relation between split weights and actual balancing weight as

$$\sum_{i=1}^n V_i \cos \alpha_i = d \cos \alpha \quad \text{Eq.2.1.4}$$

$$\sum_{i=1}^n V_i \sin \alpha_i = d \sin \alpha \quad \text{Eq. 2.1.5}$$

Although he has discussed much of the thing in his paper but the paper has not addressed the error that is caused by not considering the actual mass.

Austrow (1994) has made use of efficient way to use influence coefficient method for calculation of residual vibration and made its use to minimize the vibration with the help of following equation

$$V_{R \times M} = V_{0m} + [\alpha]_{m \times n} W_n \quad \text{Eq.2.1.6}$$

$$\text{And } V_{R1} = (W_1 - W_2) / S_1 \quad \text{Eq.2.1.7}$$

Where $[\alpha]_{m \times n}$ is the influence coefficient vector for point m with weight at plane n Furthermore he has mentioned the term S_m as the sensitivity and explains the point having small sensitivity will have larger influence on the balance than that of points with smaller sensitivity.

Nisbett(1996) has demonstrated an experimental method, its setup and table for appropriate calculation of the dynamic balancing process for double plane balancing. He has made use of vector resolution method to make identify the additional vibration induced to an attachment of trial mass into the system.

CHAPTER THREE: RESEARCH METHODOLOGY

An overview of general methodology consists of collection of literature from the internet, books, manuals and field experts. Those collected information helped us in deriving the mathematical relation between the actual balancing mass added and optimal balancing mass. These relations have been later used in matlab for solving the equation. We have tried to develop a user friendly application in matlab. This application can be used directly by the dynamic balancer. For the validation of the data produced we have made use of actual dynamic balancing sample reports. The report agrees with the data produced which helped us to validate our result. Also we have validated our data with the help of modal analysis creating the scenario that represent the actual experiment. As a future scope of this project one may extend this project to improve the technique to calculate final vibration more accurately.

3.1 Mathematical derivation

For the rotor to be balanced all the component of centrifugal component must be balanced and selection of the appropriate balance masses that gives less resultant error from that derivation listed on appendix A

We get,

$$\begin{pmatrix} m_{11} & m_{12} & \dots & m_{1N} \\ m_{21} & m_{22} & & m_{2N} \\ m_{31} & m_{32} & \ddots & m_{3N} \\ \vdots & \vdots & & \vdots \\ m_{j1} & m_{j2} & \dots & m_{j3} \end{pmatrix} \times \begin{bmatrix} \text{Cosa}_1 \\ \text{Cosa}_2 \\ \vdots \\ \text{Cosa}_N \end{bmatrix} - \begin{bmatrix} Z\text{Cosa} \\ Z\text{Cosa} \\ \vdots \\ Z\text{Cosa} \end{bmatrix} = \begin{bmatrix} \text{Error1}\Delta\text{cos} \\ \text{Error2}\Delta\text{cos} \\ \vdots \\ \text{Error3}\Delta\text{cos} \end{bmatrix}$$

But, We know $m_{jN} = \text{Subset } \{0 \ 1 \ 2 \ \dots \dots \ n\} \times M$ So, above can be written as

$$M \times \begin{pmatrix} 0 & 0 & \dots & 0 \\ 0 & 0 & & 1 \\ 0 & 0 & \ddots & 2 \\ \vdots & \vdots & & \vdots \\ n & n & \dots & n \end{pmatrix} \times \begin{bmatrix} \text{Cosa}_1 \\ \text{Cosa}_2 \\ \vdots \\ \text{Cosa}_N \end{bmatrix} - \begin{bmatrix} Z\text{Cosa} \\ Z\text{Cosa} \\ \vdots \\ Z\text{Cosa} \end{bmatrix} = \begin{bmatrix} \text{Error1}\Delta\text{cos} \\ \text{Error2}\Delta\text{cos} \\ \vdots \\ \text{Error3}\Delta\text{cos} \end{bmatrix}$$

.....(eqn 3.1.1)

$$\text{So, Resultant Error} = \sqrt{\text{Error cos}^2 + \text{Error Sin}^2} \quad \text{Eq.3.1.2}$$

Then, Giving square root on both side in eqn ...(3.1.1)

$$\frac{\sqrt{([\text{Combination Matrix}] \times [\text{Cos Matrix}] - [Z\cos\alpha])^2 + ([\text{Combination Matrix}] \times [\text{Sin Matrix}] - [Z\sin\alpha])^2}}{\sqrt{\text{Error cos}^2 + \text{Error Sin}^2}} = \text{Eq.3.1.3}$$

Now, as cos matrix, sine matrix, $Z\cos\alpha$, $Z\sin\alpha$ all are known value, also all the element of combination matrix are known, selecting the corresponding row of combination matrix that give less resultant or root mean error is our approximate solution.

Moreover, all the time we need to balance the propeller till we get resultant error less than some acceptable value of velocity of imbalance that is given by manufacturer, resultant error can be calculated with the help of Influence coefficient.

So,

$$\sqrt{\text{Error cos}^2 + \text{Error Sin}^2} (\text{Resultant error}) \leq \frac{\text{Influence coeffiecen calculated}}{\text{acepatabel error in velocity}} \text{Eq.3.1.4}$$

There could be one or more solution giving minimum error but the combination mass having lower sum will be our appropriate answer.

3.2 Matlab Application

The equation obtained from the mathematical derivation was solved using matlab. The code was designed such that the application was capable of taking all the required inputs from user and solves the problem. The result produced were both in the form of values and graph. These values directly indicate the angle at which the magnitude of load is to be inserted.

There is various information that are required in the form of initial values. These information's are utilize by the algorithm to calculate the required information. These inputs are discussed as follows:

3.2.1 Actual balancing mass

The actual balancing mass is the mass that is demanded by the analyser kit in order to balance the resulting vibration. The magnitude of these mass is exactly equal to the actual unbalance that existed. If the attached mass or trial mass is exactly equal to this mass and can be attached exactly as the demanded location the resultant vibration

must be zero but an inaccuracy that is caused due to either not having exact mass or attaching holes exactly at required location.

3.2.2 Actual angle of balancing mass

The actual angle of balancing mass is the angle at which the actual balancing mass needs to be attached in order to get zero resultant vibration. In most of the cases during the propeller balancing it is very less likely that the actual angle of balancing mass exactly coinciding with the available holes. This is the main problem that our project has addressed. The actual angle of balancing mass is exactly opposite to the angle of actual unbalance only when the shaft is rotating at very less speed that critical speed of shaft. When the speed of shaft is more than the critical speed of the shaft this angle either leads or lags the actual unbalance angle.

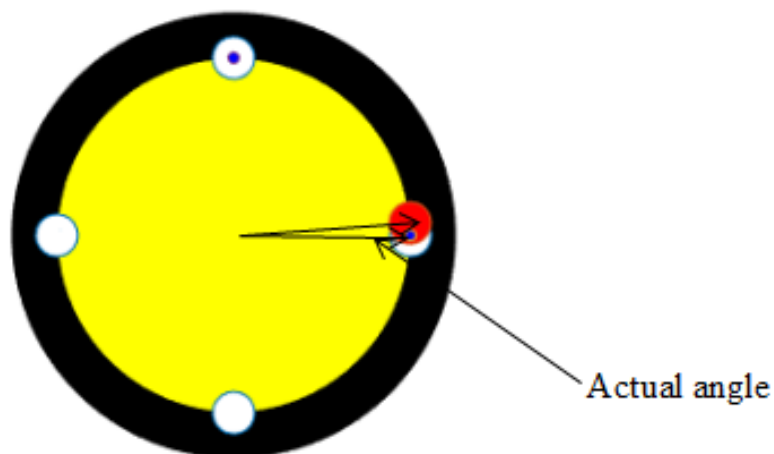


Figure 3.1 Actual balancing angle

3.2.3 Number of attaching holes

As we discussed many times that the propeller has some finite number of holes in its bulkhead intended for the attachment of balancing load, this information must be supplied for the calculation. The number of weigh attaching holes could be from 4 to as many as 24 but at most of the cases there are 10 numbers of holes. The Number of hole helps in the calculation of number of angles available for the attachment of balancing weights.

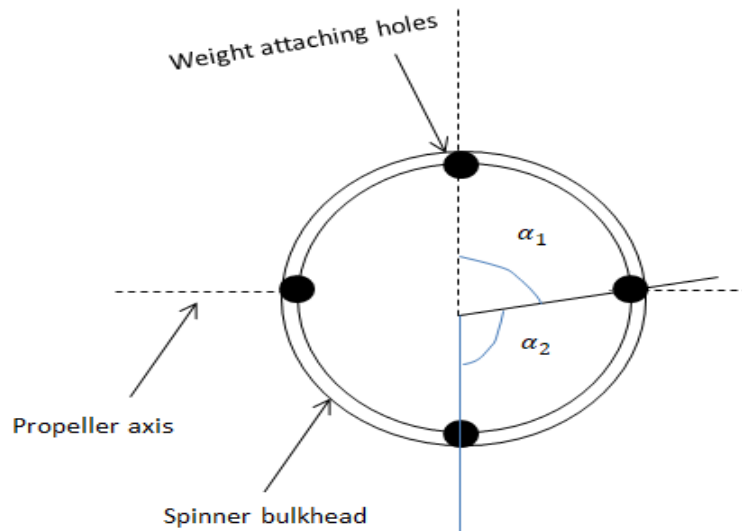


Figure 3.2 Weight attaching points

3.2.4 Radius of attachment holes

The radius at which the attachment holes are located is also an important deciding factor for the calculation of the magnitude of actual balancing mass. Larger the radius of attachment holes lesser the magnitude of actual balancing mass. Sometime for the ease of operator he/she may attach the calculated load in other location for trial run and finally attach the actual load in the attachment hole. The relationship between the correction mas and correction radius shown as

$$\vec{e} = \frac{m\vec{r}}{M} \quad \text{Eq.3.1.1}$$

Where, \vec{e} = *specific unbalance* , \vec{r} = *correction radius* , M = *Rotor mass*

3.2.5 Maximum mass allowable in a hole

The manufacturer of propeller usually specifies the maximum balancing mass that can be attached at a point. This is the design requirement of the propeller and one must not exceed this limit. In order to keep the mass within the limit the operator generally tries to split the masses.

3.2.6 Smallest mass available

The balancing mass comes into the particular shape and sizes usually these loads comes in the multiple of smallest mass. Say, if the smallest mass is of 5 g then the

available balance masses could be of sizes 5 g, 10 g, 15 g etc. Hence, the calculation uses the smallest mass to calculate all the possible masses and its combination. These masses may be in the form of washers, plates and patches of various sizes. In this project we have made an assumption that generally all the masses available are the multiple of the smallest masses available which has simplified our computation process.

3.2.7 Acceptable vibration level

During propeller balancing as there are many limitations, say, masses, angle of holes, this is more or less impossible to reduce the vibration level to zero. So, manufacturers of propellers generally provide the acceptable vibration level and also since the vibration level directly results in passenger discomfort, the operator may additionally restrict the acceptable vibration level to a lesser extent. Hence, providing acceptable vibration could help us to reduce the amount of balancing mass required without exceeding the vibration level. The acceptable vibration level is the target vibration level and meeting this level with a lesser number of trial runs is the actual art of balancing.

3.2.8 Initial vibration level

The first run of propeller balancing is done with no load attached. The vibration level that existed in this run is the actual vibration level of the propeller. This vibration level indicates the need for further balancing and in some cases gives much more idea on the missing or damaged parts, internal damage to parts, etc. Manufacturers of propellers in many cases also provide the maximum limit of initial vibration level and if this level of vibration is exceeded, it will recommend sending the propeller back to overhaul facilities for checking.

3.2.9 Angle of Initial vibration level

The angle of initial vibration level is an important factor for the calculation of the influence coefficient value of the propeller. If the influence coefficient of the propeller is known to the user already, this value may be directly used to calculate the actual angle of balancing mass needed to be attached.

3.2.10 Trial Weight

The magnitude of the trial load could be a very crucial factor for the reduction of the number of trial runs as the selection of a small trial load could generate very less

influence in the propeller that cannot be accurately captured by the analyser and the selection of very large trial load can significantly increase the vibration level that can damage the propeller. There are many techniques that can be used for the calculation of appropriate trial weight. The value of trial weight and its resultant influence helps to calculate the influence coefficient of the system.

3.2.11 Angle of Trial weight

The angle of trial load is the angle at which the trial load is inserted. As a general rule of thumb the angle of trial weight should be nearly opposition of actual angle of vibration. The angle at which trial load is inserted is also crucial as if the angle of trial load is near to the actual unbalance it will increase the vibration level of the system.

3.3 Expected output

3.3.1 Best mass combination for Lowest Error

The first and most important result that we can expect is the combination of available masses that can be attached on a particular angle specified to get least possible vibration.

```
Consider following angle in a sequence
```

```
ans = 1x5
```

```
324    0    36    72   108
```

```
Consider these masses combination in gram in above angular sequence for least
```

```
bestmasslowerror = 1x5
```

```
0    0    25    0    0
```

From the above result we got, we can say that if we attach 25 g at hole which is at 36° will give least vibration.

3.3.2 Best mass combination for lowest mass sum

Another output of the calculation is the best combination of mass that gives acceptable vibration. This result is also being an interest of an operator when the target is to minimise the total number of mass to be attached. Best mass combination for lowest mass is function of the acceptable value of residual vibration. Hence for different acceptable vibration level there may exist different combination of mass for low sum.

```

bestmassforlowsum = 1x5
    0    0   25    0    0

The vibration leve of expected after considering least sum is 0.000
Following are all possible combination sequence of masses for acceptatble vibrat

```

From the above result we can say if we attach 25 g at hole which is at 36° will be the less combination of mass that give the vibration at acceptable level.

3.3.3 Best alternatives Mass combination

Sometime attaching best combination for lower mass may not be possible due to lack of masses available or for any unfortunate reason the user will have choices to make. The application also provides other alternatives to the uses for the masses to attach.

```

The vibration leve of expected after considering least sum is 4.923
Following are all possible combination sequence of masses for acceptatble vibrat

```

```

bestalternatives = 5x6
    0    0   20   25   25    0
    0    0   25   25   20    0
    0    0   25   25   25    0
    0    0   25   25   25    5
    0    5   25   25   25    0

```

3.3.4 Graph representing the attachment point

The application also shows to which point the load is to be attached. The color of the weight to be attached is shown with blue color, the number of holes available is shown with white circle and the actual unbalance is shown with red color. The marker size of the weight to be attached resembles the magnitude of the mass attached. This graph represent the hole position in counter clockwise rotation and the stating position is 3 o clock position. The graph represents only the combination of masses that produces the lowest error. Figure 6 is an example of a graphical representation. This graph is presenting a real view of the propeller bulkhead where the load can be attached. The blue legend make over here indicate the location to which mass can be added.

OPTIMAL BALANCING GRAPH

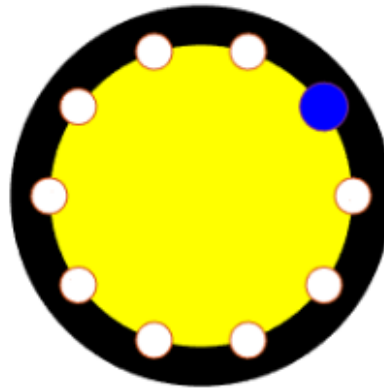


Figure 3.3 Graphical Representation of Balancing

3.4 Assumptions

There is few assumptions we have made to make the calculation more easier and smooth.

- i. The unbalanced vibration on the system is just due to an unbalance mass
- ii. The rotation speed of the shaft is within 1st critical speed
- iii. The rotation of the shaft is uniform while measurement
- iv. The available balancing masses are exactly multiple of the smallest masses
- v. The propeller balancing is a single plane balancing
- vi. Zero angle of master blade exactly coincide with the available holes

3.5 Limitations

- i. An unbalanced vibration must only be due to unbalance masses
- ii. There should some finite number of holes available for the attachment of holes
- iii. Balancing must be a single plane balancing and does not suggest anything for multi plane balancing

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Method of inertial property of rotor

As the dynamic imbalance is caused due to the shift of plane of centre of mass from centre of axis of rotation and static imbalance is caused by shifting of axis of centre from rotation axis, The overall shift in a centre of mass of balanced rotor using a known unbalance mass and again balancing with the help of our algorithm could help in the identification of actual remaining shift will help us to identify whether the rotor is balanced, unbalanced (static or dynamic) imbalance is left.

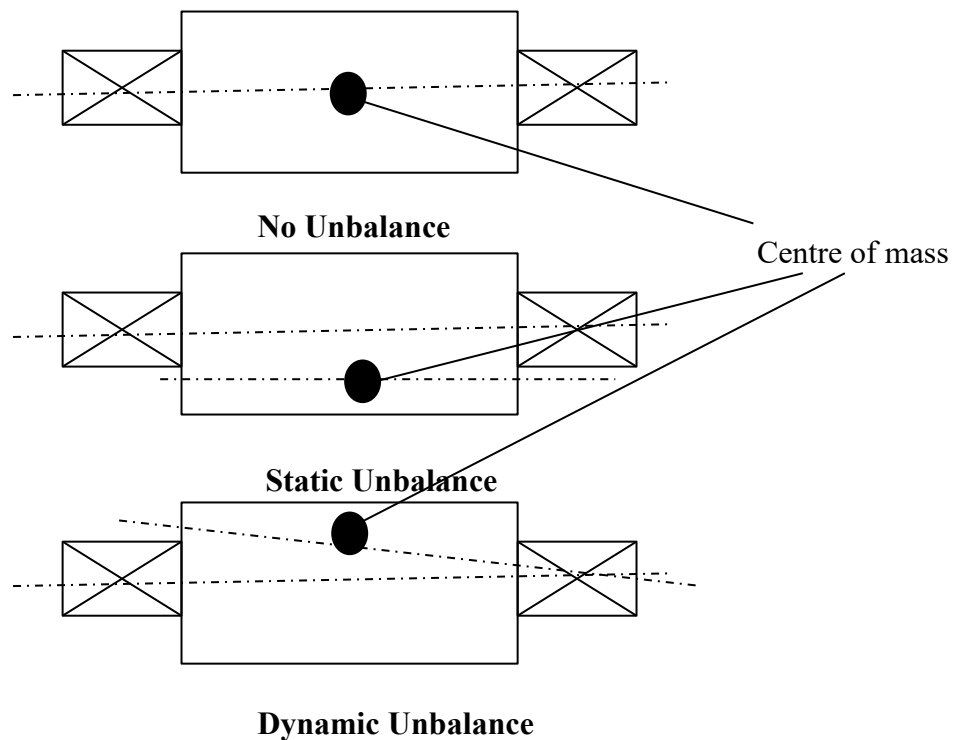


Figure 4.1 Static and Dynamic Balancing

Our algorithm is basically based upon the fact that the components of centrifugal force need to exactly balance at centrifugal component of unbalanced force. The selection of location and balancing weight is limited as our assumption hence without an efficient algorithm it is very difficult to balance at one. With the help of following study we have proven the accuracy of our calculation. The case has been deliberately set up to test the accuracy hence; the solution is compared with proven two split technique and various standard method of selecting weight.

The CAD modal here was developed with the help of solid works and the moment of inertia of modal was calculated using inbuilt mass properties function in solidworks as following figure.

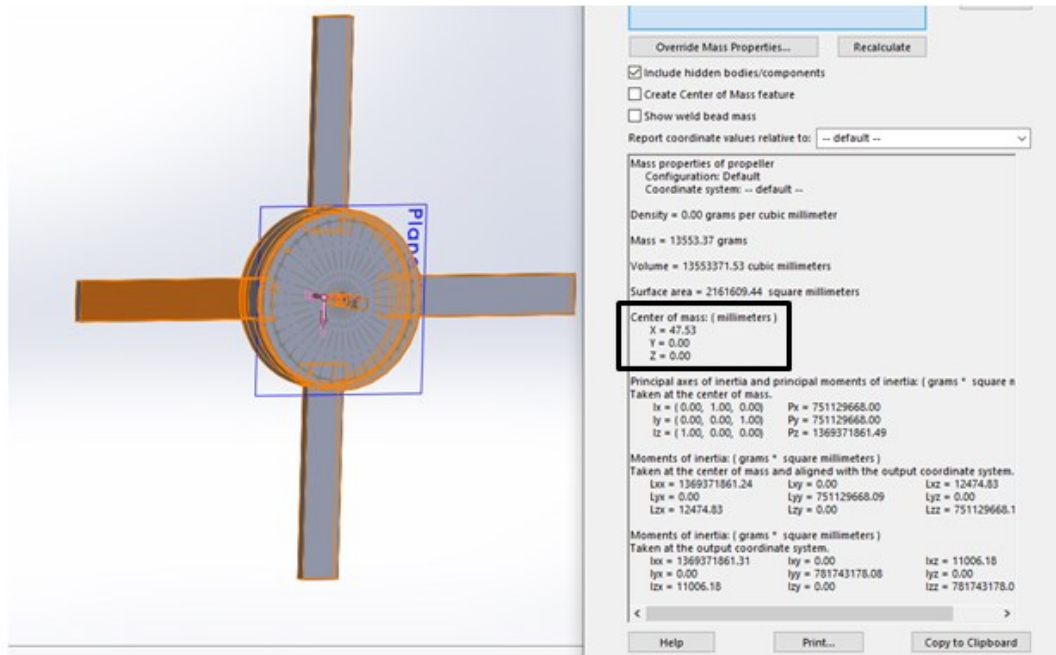


Figure 4.2 Calculation of Centre of Mass of rotor

Above balanced rotor was provided with imbalance of 20 g at 12^0 and the balancing weight was attached using various approximating technique and the result are plotted below.

4.1.1 Terms used:

No unbalance: No unbalance is the term used for geometrically balanced rotor, thus all result has been compared with this case

Unbalanced: An unbalanced version of balanced rotor with know unbalance

Logical Balanced: Superficial case that represent a most user would likely to select (Assumed)

Two split balanced : Unbalanced propeller balanced with combination of two balance weight

Algorithm Balanced : Balanced using our algorithm

Following coordinate of the center of mass for various combination of mass has been measured, as the shift in x coordinate doesnot impact in balancing since the axis of rotation of shaft doesnot get shifted but shift in y or z coordinates alone indicates the static imbalance and shift in the both y and z coordinate is likely to induce dynamic imbalance given that the imbalance mass lies far from shaft.

Table 4.1 Location and Shift of Centre of Mass of a rotor

Cases	Axis of Rotation	X-Coordinate	Y-Coordinate	Z-Coordinate	Remarks
		0	0	0	
		X	0	0	
1	Centre Of Mass (No Unbalanced)	X	Y	Z	Balanced
		0	0	0	
		47.53	0	0	
2	Centre Of Mass (Unbalanced)	X	Y	Z	Unbalanced
		0	0	0	
		47.51	-0.01	0.03	
3	Centre Of Mass (Algorithm Balanced)	X	Y	Z	No Imbalance
		0	0	0	
		47.74	0	0	
4	Centre Of Mass (Logical Balanced)	X	Y	Z	Unbalanced
		0	0	0	
		47.5	0.01	0	
5	Centre Of Mass (Two Split Balanced)	X	Y	Z	No Imbalance
		0	0	0	
		47.5	0	0	

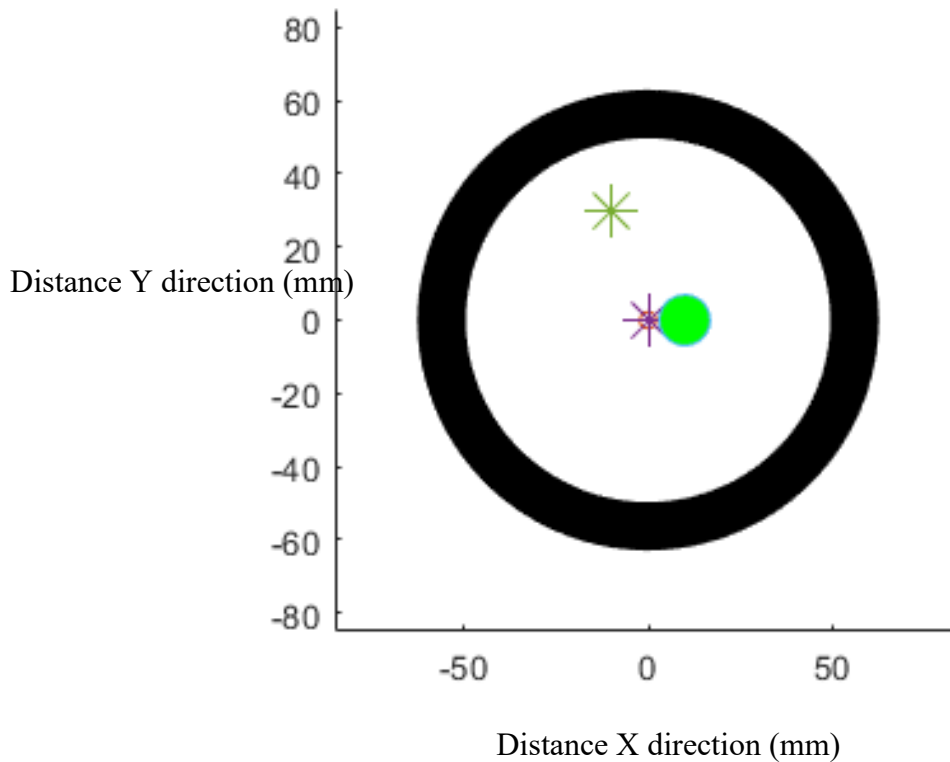


Figure 4.3 Representation of unbalance mass

From the above table it is very clear that combination of mass that has been obtained through the algorithm we developed fits the centre of mass near to its centre.

4.2 Method of known unbalance

In this method we have tried to establish the validation of algorithm using known weight unbalance and whose solution is very obvious. An example for this may be an unbalance of 5 g at 0° can be balanced using 5 g at 180° give, 5 g weight are available and weight attaching point is available at 180° .

4.2.1 Actual balancing mass and angle both zero

This example is first stage of validating our matlab codes is calculating as this is an obvious logical result since the mass we want to add is zero the best mass combination is also zero. Following case was solved using our algorithm and the result shown that 0 weights needed to be added, which validate the drift of our algorithm. More over one must note that after adding this resultant vibration is Zero.

Table 4.2 Inputs used for case mass and angle both zero

INPUTS	VALUE
Balancing Mass to be added	0 g
Angle of Mass from master blade ($^{\circ}$)	0
Number of attachment holes	10
Radius at which holes are located	10 cm
Maximum mass that can be inserted at a single hole	20
Small Available Mass	5
Acceptable value in IPS	0.05

Table 4.3 Output obtained for case mass and angle both zero

OUTPUT	VALUE				
Angles ($^{\circ}$)	288	324	0	36	72
Balancing Mass(in g)					
Best combination for lower error	0	0	0	0	0
Best combination for lower mass	0	0	0	0	0

OPTIMAL BALANCING GRAPH

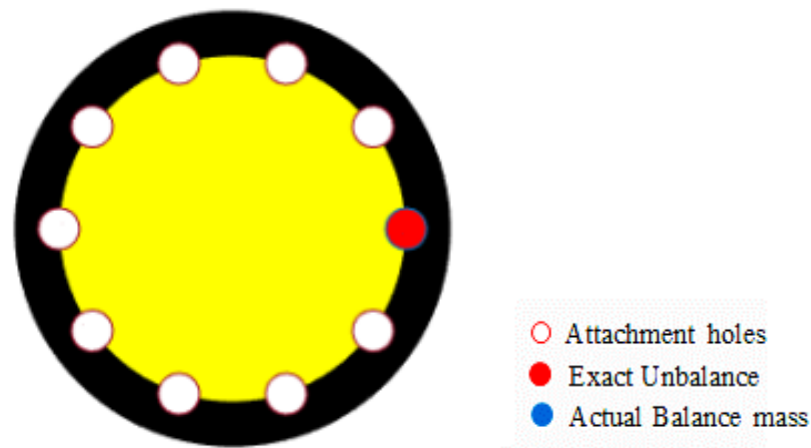


Figure 4.4 Recommended mass combination for 0 g at 0°

4.2.2 Actual balancing mass 25 g and angle 36° with 10 holes

This example is first stage of validating this calculation as this is an obvious logical result as the mass be want to add is 25 g at angle 36° , as there are 10 number of holes that means the weight of 25 g can be added to 36° which is hole number 2. This has also been shown clearly in graph.

Table 4.4 Inputs used for 25 g at 36°

INPUTS	VALUE
Balancing Mass to be added	25 g
Angle of Mass from master blade (°)	36
Number of attachment holes	10
Radius at which holes are located	10 cm
Maximum mass that can be inserted at a single hole	25
Small Available Mass	5
Acceptable value in IPS	0.02

Table 4.5 Output obtained for case 25 g at 36°

OUTPUT	VALUES				
Angles (°)	324	0	36	72	108
Balancing Mass(in g)					
Best combination for lower error	0	0	25	0	0
Best combination for lower mass	0	0	25	0	0

OPTIMAL BALANCING GRAPH

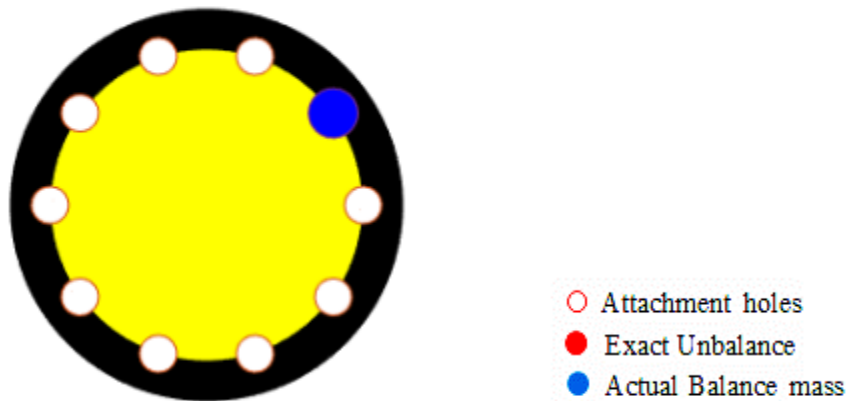


Figure 4.5 Recommended mass combination 25 g at 36°

4.2.3 Actaul balancing mass 85 g at 56° with 6 holes

This example is just a representative example showing the intent of this program. As the weight we want to add is of 85 g at 56°, it gives the result that 25 g, 25 g, and 25 g of load can be added at 0,60 and 120° to get lowest error of 4.492ips and the combination of mass 20,25,25 at 0,60 and 120° is the combination of lowest sum of

masses yet acceptable vibration i.e 4.923 ips. Finally best other combination of masses has also been shown for the user to make choice.

Table 4.6 Inputs used for 85 g at 56°

INPUTS	VALUE
Balancing Mass to be added	85 g
Angle of Mass from master blade(°)	56
Number of attachment holes	6
Radius at which holes are located	10 cm
Maximum mass that can be inserted at a single hole	25
Small Available Mass	5
Acceptable value in IPS	0.05

Table 4.7 Output obtained for 85 g at 56°

OUTPUT	VALUES					
Angles (°)	240	300	0	60	120	180
Balancing Mass(in g)						
Best combination for lower error	0	0	25	25	25	0
Best combination for lower mass	0	0	20	25	25	0

OPTIMAL BALANCING GRAPH

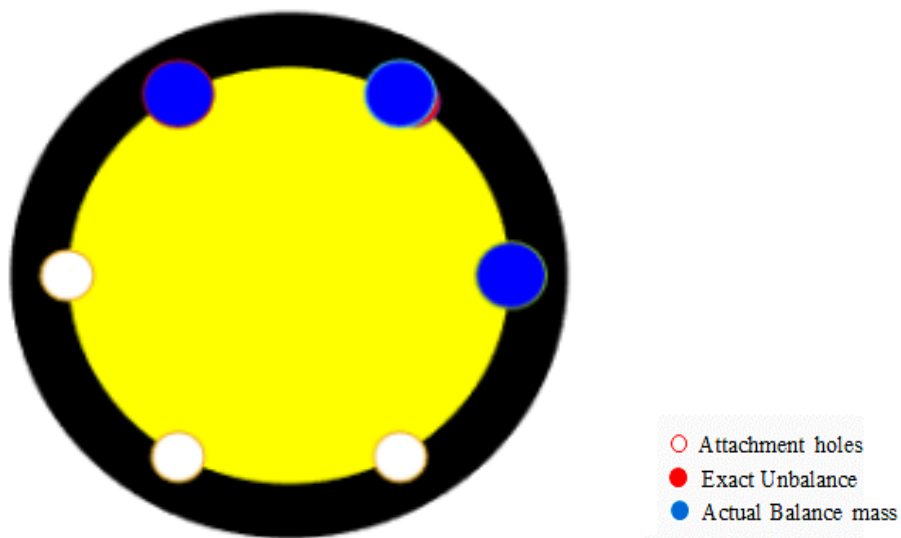


Figure 4.6 Recommended mass combination 85 g at 56°

4.3 Comparison with experiment results

As a case study we have selected a report that was generated by one of the best airline in Nepal. In this example at weight of 35.39 g has to be attached 226.2° finally they have managed to attached 23.5 g at 230° and 10.2 g at 200°, as per the result the final value of vibration they got is around 0.058 ips at 23.2°. Since angle of final vibration is not of our concern we will not consider it but 0.058 ips as a final resultant vibration as to minimize this is our major goal. Now, similar problem has been solved using matlab, the sense factor and tach offset for this case is 81 and 55 respectively. Solving the similar case say that inserting 23.2° at 240° and 10.2 g at 210° should give 0.062 ips (nearly similar to what actually we have got) but the solution extends furthermore that adding 5 g at 180°, 25 g at 210, 5 g at 240 and 10 g at 300 could have given error as less at 0.004 which is very low more than the result says that adding 10 g at 210 and 25 g at 240° could also give error as low as 0.043ips.

Initial Vibration Level: 0.286 IPS at 29.2 Deg						Difference:
Status	Weight in Gms	Degree	Vib. Level (IPS)			Remarks
1RN	22.85	29.2	0.286			
2RN						
	1TR	X		2TR	X	
Status	Weight in Gms	Degree	Vib. Level (IPS)			Remarks
RW1	27.78	226.2				
CRW	35.39	226.2				
AW1						
AW2						
AW3						
AW4						
AW5						
AW6						
SW1	23.5	240				FA
SW2	10.2	210				FA
SW3						
FW1						
FW2						
	FR1	X	FR2	X	FR3	X
	FR4	X				

Final Vibratio Level : 0.058 IPS at 23.2 Deg

Figure 4.7 Case study report

Table 4.8 Input used for Case study

INPUTS	VALUE
Balancing Mass to be added	39.35 g
Angle of Mass from master blade ($^{\circ}$)	226.2
Number of attachment holes	12
Radius at which holes are located	10 cm
Maximum mass that can be inserted at a single hole	25
Small Available Mass	5
Acceptable value in IPS	0.06
Sense Factor	81
Tach Factor	55

Table 4.9 Output obtained for case study

OUTPUT	VALUES						Vibration
Angles ($^{\circ}$)	150	180	210	240	270	300	
Balancing Mass(in g)							
Best combination for lower error	0	5	25	5	0	10	0.004
Best combination for lower mass	0	0	10	25	0	0	0.043

Table 4.10 Testing the selected combinations vibration

INPUT	VALUES						Vibration
Angles ($^{\circ}$)	150	180	210	240	270	300	
Balancing Mass(in g)							
Inserted Combination	0	0	23.5	10.2	0	0	0.062

OPTIMAL BALANCING GRAPH

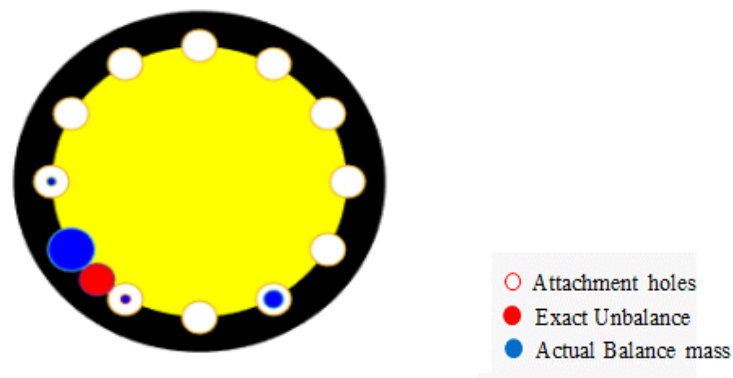


Figure 4.8 Recommended mass combination 39.35 g at 226.2 $^{\circ}$

4.4 Method of modal analysis (mode balancing)

It is known that large imbalance in the rotor changes or induced new mode shape of a rotor. Ensuring that the change in mode frequency that was caused by the unbalances and regaining back its balanced mode shape and frequency may indicate that the cause of unbalances has been cured. Hence the natural frequency of the balanced and unbalanced may be compared to identify the method correct balance mass combination. This method was performed using ANSYS software that uses the mathematical relation as follows:

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=\{F\}$$

Where, M is the mass matrix (That is affected by unbalances)

C is the damping

K is the stiffness matrix (May or may not be affected by unbalances)

F is an external force that causes the vibration

In this study the rotor of balanced geometry was unbalanced with the unbalance mass of 20 g and tried to balance using various techniques as below. The result of this analysis has been verified using mesh independence technique

4.4.1 Terms Used

No unbalance: No unbalance is the term used for geometrically balanced rotor, thus all result has been compared with this case

Unbalanced: An unbalanced version of balanced rotor with know unbalance

Logical Balanced: Superficial case that repersent a most user would likely to select (Assumed)

Two split balanced : Unbalanced propeller balanced with combination of two balance weight

Algorithm Balanced : Balanced using our algorithm

All the terms used above are not standard terms and has been uniquely selected to demonstrate an extreme examples where this algorithm can be useful.

4.4.2 Modes Shapes of Balanced Rotors:

Mode shapes is defined as the shape of physical body it assumes at different modes of vibration. The regain of mode shapes could indicate the absence of large uncorrected masses. The number of mode shape corresponds to the position of frequency as which it was induced. To analyse this case we have considered only first 6 modes of vibration and the figure shown below is an exaggerated version of total deformation of modes shape considering cylindrical support at the shaft ends.

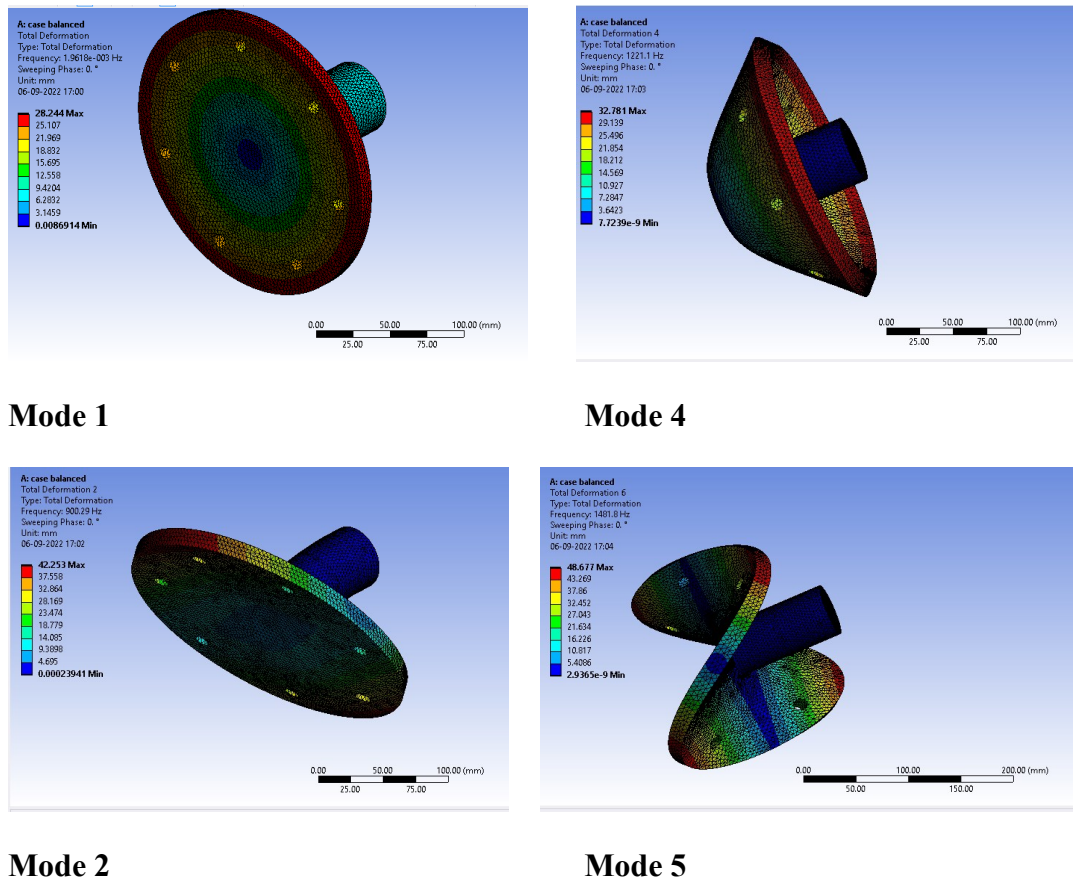


Figure 4.9 Various Mode shapes of balanced rotor (Example)

4.4.3 Mesh Independence:

Any approximate FEM may give an inaccurate result when there is poor quality meshing. The quality of meshing can be established with the help of mesh independence. The mesh independence test was conducted for various number of elements ranging from 6817- 160422 elements. The maximum error of around 1.5% existed when the number of element was just 6817 but as the number of element got increased from 6817 to 67189 the curve was flat enough hence we selected mesh

having 36245 element as best suited for our analysis. The most error existed here was in-between mode 2 and 3.

For performing of mesh independence test we considered the accuracy of 2 digits as later modes frequency was too large and more than 2 digit were not required but for lower mode especially at mode 1 the value bound to zero after considering two degree precision. In many cases the accuracy of less that 2.5% is considered as satisfactory but in our case the most inaccuracy in mesh is as less at 0.2% which easily defines the acceptably of the results

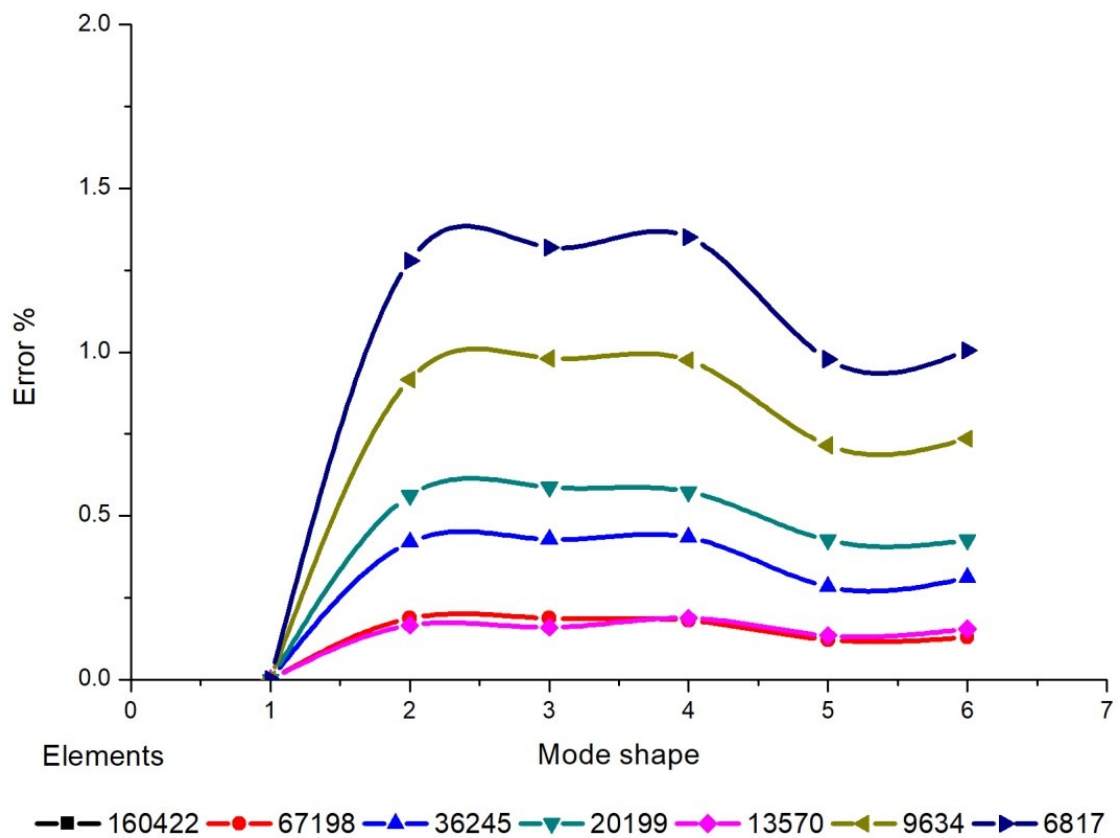


Figure 4.10 Mesh Independence chart

4.4.4 Method of study

A simple rotor of 20 cm diameter with 7 holes was first modelled using the solid works version 19; to perform the modal analysis. ANSYS workbench modal analysis is one of the most widely used software which uses Mechanical APDL solver to analysis the solution. The model was attached to ground with the help of cylindrical

support in a location as shown below. The mesh of around 39000 elements as proven by mesh independence was used to solve the problem.

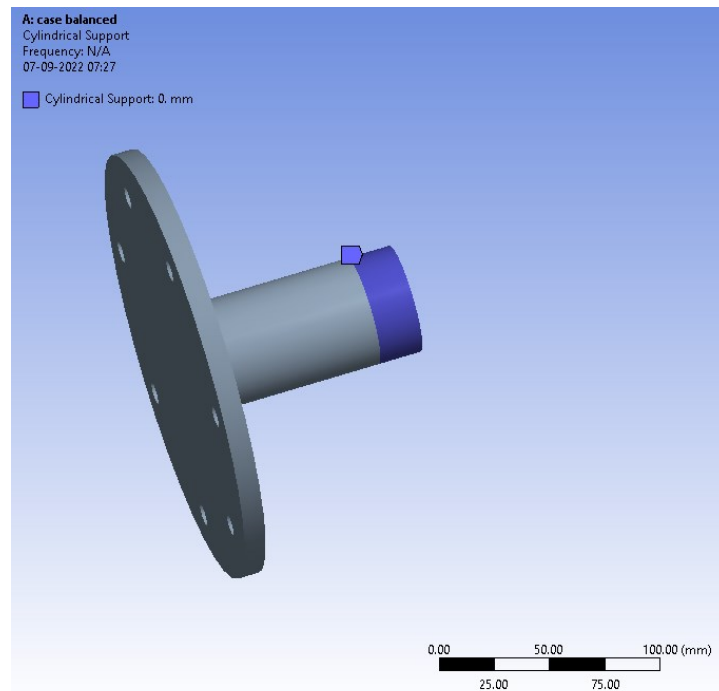


Figure 4.11 Cylindrical support

The samples of mode shape thus obtained were used for the analysed for appropriate balancing condition of rotor and the frequency at which these shape was induced was also taken into consideration while balancing the rotor.

4.4.5 Results

The mode frequency of the rotor was largely distorted due to unbalance. The second mode frequency was shifted to 0Hz from 901 Hz as previously noted for balanced condition. This shift was due to unbalance mass and we have used various techniques to ensure the shift in the solution gets back to its own original value. Following result were tabulated and graph was plotted between mode shapes and frequency. From the graph below it is very clear that there is very large shift in the frequency due to imbalance. The two split of 15,5 was clearly drawn to show that inappropriate selection of location good combination of mass could result in an error. Using all other technique the balancing was within a range as shown in graph below.

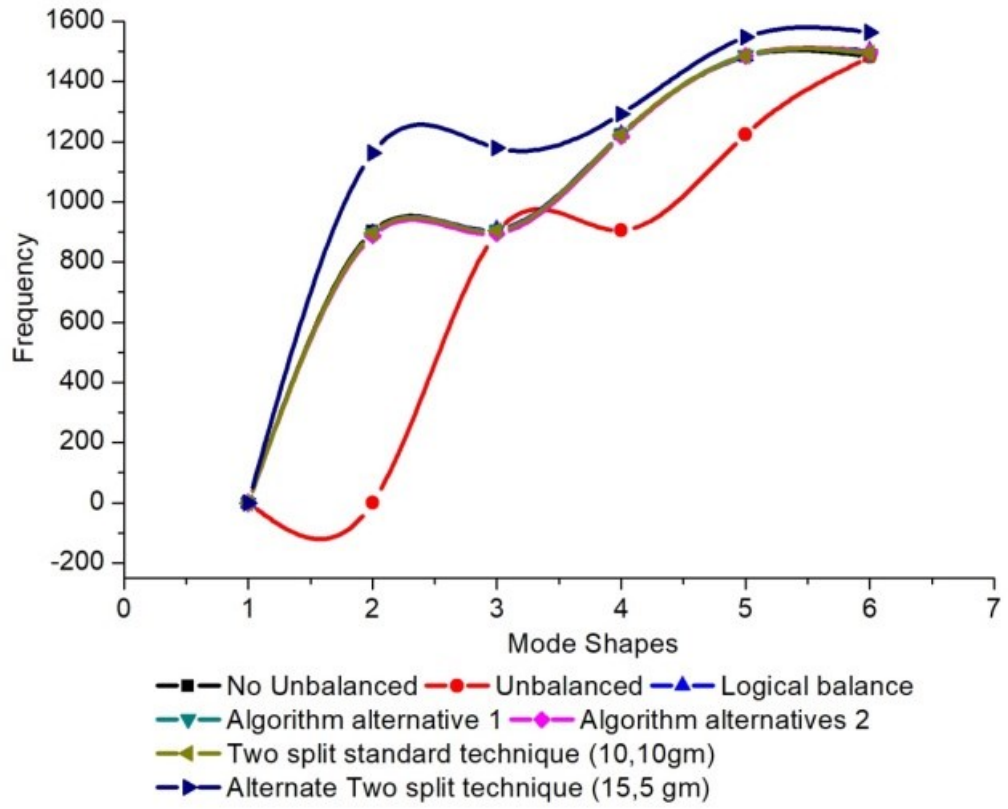


Figure 4.12 Mode Shape vs Frequency Graph

CHAPTER FIVE: CONCLUSION AND RECOMENDATION

This thesis was performed in a view to help small organisations to enable them to reduce the number of extra trial run that was needed during propeller dynamic balancing due to lack of an efficient technique to identify the exact locations and mass required to balance. Our thesis concludes that an iterative solving technique with the appropriate use of vector composition and influence coefficient method will be one of the most reliable techniques to split the balance weight. Thus developed algorithm can directly be used by dynamic balancing machine/users to identify the correction mass and location in at most three trial runs.

In much possible way this work can be extended in future, the following recommendation are made to open its enormous application in real life,

1. In this project we have considered that the balance weight being an integral multiple of small mass but this may not always be the case hence one can study for variable weights.
2. In this project we have considered the influence coefficient value to be too generic but can further be extended to improve its usability
3. In this project we have considered the single plane balancing but some propeller may be multi plane balancing propeller, so one can extend this work further for multi plane balancing

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APPENDICES A: MATHEMATICAL DERIVATION

Let, α_i be the angle of each holes from master blade stations, Let M be the smallest weight available for attachment and S be the maximum weight that can be attached on a single point. Now, since the weigh attaching holes will be at equal angle we get,

$$N\alpha = 360$$

$$\text{So, } \alpha_i = \frac{360}{n} \quad \text{Eq.A.1}$$

Then $\alpha_1 = 1 * \alpha$, $\alpha_2 = 2 * \alpha$ respectively

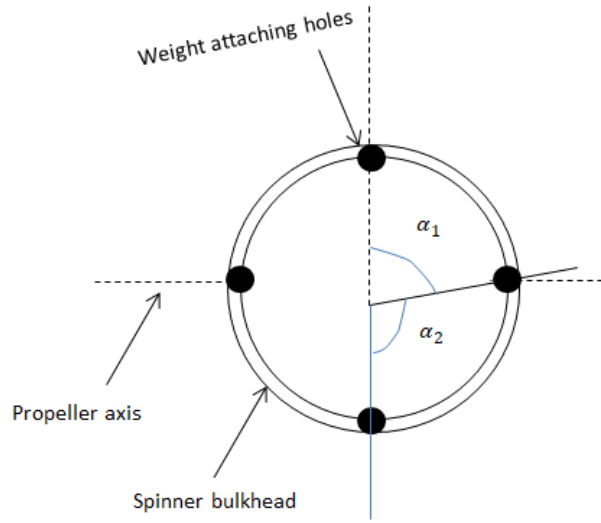


Figure A.1 Weight attaching points

Now, since in most of the case we get the balance weight generally multiple of small weight so we are assuming that the balance weight is always the multiple of small weights M . The maximum weight that can be attached in the single point be $n * S$

$$\text{Where, } n = \frac{S}{M} \quad \text{Eq.A.2}$$

Also, let m_{ji} be the mass attached at any point I at J^{th} trial run, As discussed earlier since only weight available is the multiple small weight we may also say, the attaching weigh can only be any from

$$m_{jN} = \{0 \ 1 \ 2 \ \dots \dots \ n\} * M$$

Z being the actual the actual balancing weight and α being the actual angle where weight can be added, but as there are only discrete points where the balancing weight can be added in so, error can be expected.

As per renowned papers,

$$\sum_{i=1}^N m_i * \text{Cos}(\alpha_i) = Z \text{Cos}\alpha \quad \text{Eq.A.3}$$

$$\sum_{i=1}^N m_i * \text{Sin}(\alpha_i) = Z \text{Sin}\alpha \quad \text{Eq.A.4}$$

Now, from equation (A.3) we can write,

$$m_1 \cos \alpha_1 + m_2 \cos \alpha_2 + \dots + m_n \cos \alpha_n = Z \cos \alpha \quad \text{Eq.A.5}$$

Writing equation in matrix form,

$$\begin{pmatrix} m_{j1} & m_{j2} & \dots & m_{jN} \\ 0 & 0 & & \\ 0 & 0 & \ddots & \vdots \\ \vdots & \vdots & & 0 \\ 0 & 0 & \dots & 0 \end{pmatrix} \times \begin{bmatrix} \cos \alpha_1 \\ \cos \alpha_2 \\ \vdots \\ \cos \alpha_N \end{bmatrix} = Z \cos \alpha + \text{Error}_j \Delta \cos \text{ (say)}$$

Error we got here is due to selection of some random masses,

Similarly,

$$\begin{pmatrix} m_{11} & m_{12} & \dots & m_{1N} \\ 0 & 0 & & \\ 0 & 0 & \ddots & \vdots \\ \vdots & \vdots & & 0 \\ 0 & 0 & \dots & 0 \end{pmatrix} \times \begin{bmatrix} \cos \alpha_1 \\ \cos \alpha_2 \\ \vdots \\ \cos \alpha_N \end{bmatrix} = Z \cos \alpha + \text{Error}_1 \Delta \cos$$

$$\begin{pmatrix} 0 & 0 & \dots & 0 \\ m_{21} & m_{22} & & m_{2N} \\ 0 & 0 & \ddots & 0 \\ \vdots & \vdots & & \vdots \\ 0 & 0 & \dots & 0 \end{pmatrix} \times \begin{bmatrix} \cos \alpha_1 \\ \cos \alpha_2 \\ \vdots \\ \cos \alpha_N \end{bmatrix} = Z \cos \alpha + \text{Error}_2 \Delta \cos$$

In this way we perform Numbers of Trial and writing in matrix form will give,

$$\begin{pmatrix} m_{11} & m_{12} & \dots & m_{1N} \\ m_{21} & m_{22} & & m_{2N} \\ m_{31} & m_{32} & \ddots & m_{3N} \\ \vdots & \vdots & & \vdots \\ m_{j1} & m_{j2} & \dots & m_{jN} \end{pmatrix} \times \begin{bmatrix} \cos \alpha_1 \\ \cos \alpha_2 \\ \vdots \\ \cos \alpha_N \end{bmatrix} - \begin{bmatrix} Z \cos \alpha \\ Z \cos \alpha \\ \vdots \\ Z \cos \alpha \end{bmatrix} = \begin{bmatrix} \text{Error}_1 \Delta \cos \\ \text{Error}_2 \Delta \cos \\ \vdots \\ \text{Error}_j \Delta \cos \end{bmatrix}$$

$$\text{Eq.A.6}$$

But, We know $m_{jN} = \text{Subset } \{0, 1, 2, \dots, n\} \times M$ So, eq (A.6) can be written as

$$M \times \begin{pmatrix} 0 & 0 & \dots & 0 \\ 0 & 0 & & 1 \\ 0 & 0 & \ddots & 2 \\ \vdots & \vdots & & \vdots \\ n & n & \dots & n \end{pmatrix} \times \begin{bmatrix} \cos \alpha_1 \\ \cos \alpha_2 \\ \vdots \\ \cos \alpha_N \end{bmatrix} - \begin{bmatrix} Z \cos \alpha \\ Z \cos \alpha \\ \vdots \\ Z \cos \alpha \end{bmatrix} = \begin{bmatrix} \text{Error}_1 \Delta \cos \\ \text{Error}_2 \Delta \cos \\ \vdots \\ \text{Error}_j \Delta \cos \end{bmatrix}$$

$$\text{Eq.A.7}$$

The matrix above represents every possible combination of masses that can be attached to all the point up the J^{th} trial run,

For our ease lets, represent

$$\begin{pmatrix} 0 & 0 & \dots & 0 \\ 0 & 0 & & 1 \\ 0 & 0 & \vdots & 2 \\ \vdots & \vdots & \dots & n \end{pmatrix} \text{ as [Combination Matrix]}$$

$$\begin{bmatrix} \text{Cos}\alpha_1 \\ \text{Cos}\alpha_2 \\ \vdots \\ \text{Cos}\alpha_N \end{bmatrix} \text{ as [Cos Matrix]}$$

$$\begin{bmatrix} Z\text{Cos}\alpha \\ Z\text{Cos}\alpha \\ \vdots \\ Z\text{Cos}\alpha \end{bmatrix} \text{ as [ZCos}\alpha]$$

$$\begin{bmatrix} \text{Error}1\Delta\text{cos} \\ \text{Error}2\Delta\text{cos} \\ \vdots \\ \text{Error}3\Delta\text{cos} \end{bmatrix} \text{ as [Error Cos]}$$

So, we can write

$$[\text{Combination Matrix}] \times [\text{Cos Matrix}] - [\text{Zcos}\alpha] = [\text{Error Cos}] \quad \text{Eq.A.8}$$

Similarly equation can be obtained from equation (ii) in form of Sine function so,

$$[\text{Combination Matrix}] \times [\text{Sin Matrix}] - [\text{Zsin}\alpha] = [\text{Error Sin}] \quad \text{Eq.A.9}$$

Now, squaring and adding eqn (vi) and (vii)

$$([\text{Combination Matrix}] \times [\text{Cos Matrix}] - [\text{Zcos}\alpha])^2 + ([\text{Combination Matrix}] \times [\text{Sin Matrix}] - [\text{Zsin}\alpha])^2 = [\text{Error Cos}]^2 + [\text{Error Sin}]^2 \quad \text{Eq.A.10}$$

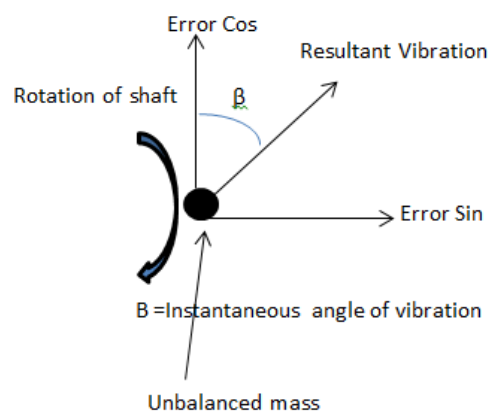


Figure A.2 Resultant error due unbalance mass

From, the above figure we can say, the resultant error that is best suited in mean square error or resultant error.

$$\text{So, Resultant Error} = \sqrt{\text{Error cos}^2 + \text{Error Sin}^2} \quad \text{Eq.A.11}$$

Then, Giving square root on both side in eqn ...(A.10)

$$\frac{\sqrt{([\text{Combination Matrix}] \times [\text{Cos Matrix}] - [\text{Zcos}\alpha])^2 + ([\text{Combination Matrix}] \times [\text{Sin Matrix}] - [\text{Zsin}\alpha])^2}}{\sqrt{\text{Error cos}^2 + \text{Error Sin}^2}} = \quad \text{Eq.A.12}$$

Now, as cos matrix, sine matrix, $Z\cos\alpha$, $Z\sin\alpha$ all are known value, also all the element of combination matrix are known, selecting the corresponding row of combination matrix that give less resultant or root mean error is our approximate solution.

Moreover, all the time we need to balance the propeller till we get resultant error less than some acceptable value of velocity of imbalance that is given by manufacturer, resultant error can be calculated with the help of Influence coefficient.

So,

$$\sqrt{\text{Error cos}^2 + \text{Error Sin}^2} \text{ (Resultan error)} \leq \frac{\text{Influence coeffiecen calculated}}{\text{acceptabel error in velocity}} \quad \text{Eq.A.13}$$

There could be one or more solution giving minimum error but the combination mass having lower sum will be our appropriate answer.

APPENDICES B: MATLAB CODES

```
clc; %%uses symmetry princple
clear all;
%% User Input area
disp('          Welcome you to this test application, ')

disp('this application helps you to distribute propeller
balancing mass')
while 1
prompt = "Please enter the mass that you want to add (in
g unit): ";
masstobeadded = input(prompt); %%ask in g to add;
if (masstobeadded >= 0)
    break;
end
disp('Error : Please Enter positive value only, Try
again')
end

while 1
prompt = "Please enter the angle of mass from master
blade in (0-359): ";
actualmassangledeg = input(prompt); %%ask from in deg
if (actualmassangledeg >= 0 && actualmassangledeg <=359 )
    break;
end
disp('Error : Enter in range 0 to 359, Try again')
end

while 1
prompt = "Please enter Number of holes to which mass can
be added: ";
numberofholes = input(prompt); %%ask from IPS
if (fix(numberofholes)-numberofholes == 0 &&
numberofholes >= 0 && numberofholes <=15)
    break;
end
disp('Please enter positve integer less than 16 , Try
again')
end
```

```

while 1
prompt = "Please enter the radius in inch at which holes
are located: ";
radius = input(prompt); %%ask from IPS
if (radius >=0 )
    break;
end
disp('Error : The radius only be positive, Try again')
end

```

```

while 1
prompt = "Please enter the Maximum mass that can be
inserted in one hole: ";
maxmassatonepoint = input(prompt); %%ask from IPS
if (maxmassatonepoint >=0 )
    break;
end
disp('Error : Max positive mass must only be positive,
Try again')
end

```

```

while 1
prompt = "Please enter small mass available: ";
smallmassavilabe = input(prompt); %%ask from IPS
if (smallmassavilabe >=0 )
    break;
end
disp('Error : Small mass avilabe can only be positive,
Try again')
end

```

```

while 1
prompt = "Please enter the acceptable value in IPS: ";
acceptablevalueinpis = input(prompt); %%ask from IPS
if (acceptablevalueinpis >=0 )
    break;
end
disp('Error : Enter in range positive value, Try again')
end
while 1

```

```

    prompt = "Do you have Sense Factor and Tach offset of
system under study? (y/n) ";
    option = input(prompt,"s");
    if (option == 'y')
        prompt = "Please enter the Sense factor in g/ips:
" %%generally 80
        influencecoeffuser = input(prompt);
        prompt = "Please enter the Tach offset in degree:
"
        influencecoeffangleuser = input(prompt)
        break;
    elseif(option == 'n')
while 1
prompt = "Please enter the Innitial Vibration with No
balancing mass in IPS: ";
initialvibration = input(prompt); %%ask from IPS
if (initialvibration >=0 )
    break;
end
disp('Error : Enter in range positive value, Try again')
end

while 1
prompt = "Please enter the angle of innitial vibration
(0-359): ";
initialvibrationangle = input(prompt); %%ask from in deg
if (initialvibrationangle >= 0 && initialvibrationangle
<=359 )
    break;
end
disp('Error : Enter in range 0 to 359, Try again')
end

while 1
prompt = "Please enter the trial load inserted in g: ";
trialloadvalue = input(prompt); %%ask from IPS
if (trialloadvalue >=0 )
    break;
end
disp('Error : Value of trial load can only be multiple of
small mass available, Try again')

```

```

end

while 1
prompt = "Please enter the angle of trialmass from master
blade in (0-359) (Nearly opposite to innitia vibration) :
";
trialloadangle = input(prompt); %%ask from in deg
if (trialloadangle >= 0 && trialloadangle <=359 )
    break;
end
disp('Error : Enter in range 0 to 359, Try again')
end

while 1
prompt = "Please enter the Vibration level with trial
mass in IPS: ";
vibrationlevelafttrial = input(prompt); %%ask from IPS
if (vibrationlevelafttrial >=0 )
    break;
end
disp('Error : Enter in range positive value, Try again')
end

while 1
prompt = "Please enter the angle vibration after adding
trial mass from master blade in (0-359): ";
vibrationaangleaftertria = input(prompt); %%ask from in
deg
if (vibrationaangleaftertria >= 0 &&
vibrationaangleaftertria <=359 )
    break;
end
disp('Error : Enter in range 0 to 359, Try again')
end
break;
    disp('Choose correction option')
end
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%Calculation Starts from here
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

```

if(option == 'y')
    influencecoeff = influencecoeffuser;
    influencecoeffangle = influencecoeffangleuser;
else
    coscompantinnitial = initialvibration *
    cos(initialvibrationangle*(pi/180))
    sincompantinnitial = initialvibration *
    sin(initialvibrationangle*(pi/180))
    coscompantaftertiral = vibrationlevelafttrial *
    cos(vibrationaangleaftertria*(pi/180))
    sincompantaftertiral = vibrationlevelafttrial *
    sin(vibrationaangleaftertria*(pi/180))
    coscompantoftrial = coscompantaftertiral -
    coscompantinnitial
    sincompantoftrial = sincompantaftertiral -
    sincompantinnitial
    Trialvibrationmag = sqrt(coscompantoftrial^2 +
    sincompantoftrial^2)
    plaseoftrialmass =
    atand(sincompantoftrial/coscompantoftrial)
    influencecoeff= trialoadvalue/Trialvibrationmag %%find
    the formula (ips/g)
    influencecoeffangle = trialoadangle-plaseoftrialmass;
end
acceptablevalueinmass =
acceptablevalueinpis*influencecoeff;
actualmassanglered = (actualmassangledeg*pi/180);
CPUCONSTRAINTS = 7;
%%influencemassval = 0.8;
%%numberofholes=10;%%ask
actualnumberofholes = numberofholes;
if (numberofholes > CPUCONSTRAINTS)
    if rem(numberofholes,2) == 0
        numberofholes = numberofholes/2
    else
        numberofholes = (numberofholes/2)+0.5
    end
end
end
%%maxmassatonepoint= 25; %%ask
%%smallmassavilabe=5; %%ask
if (actualnumberofholes > CPUCONSTRAINTS)
    angleofeachhole= (2*pi)/actualnumberofholes;

```

```

    anglematrixto2pifull = [-4*pi:angleofeachhole:4*pi];
    anglematrixto2pi = anglematrixto2pifull(:, 1:end)
    minangle= (actualmassanglered-0.5*pi)
    maxangle = (actualmassanglered+0.5*pi)
    maxangledeg
wrapTo360((actualmassanglered+0.5*pi)*(180/pi)) =
    minangledeg = wrapTo360((actualmassanglered-
0.5*pi)*(180/pi))
    anglematrix =
anglematrixto2pi(anglematrixto2pi>=minangle &
anglematrixto2pi<=maxangle)
    anglematrixdeg = wrapTo360(anglematrix*180/pi)
else
angleofeachhole= (2*pi)/actualnumberofholes;
    anglematrixto2pifull = [-4*pi:angleofeachhole:4*pi];
    anglematrixto2pi = anglematrixto2pifull(:, 1:end-1)
    minangle= (actualmassanglered-pi)
    maxangle = (actualmassanglered+pi)
    maxangledeg =
wrapTo360((actualmassanglered+pi)*(180/pi))
    minangledeg = wrapTo360((actualmassanglered-
pi)*(180/pi))
    anglematrix =
anglematrixto2pi(anglematrixto2pi>=minangle &
anglematrixto2pi<maxangle)
    anglematrixdeg = wrapTo360(anglematrix*180/pi)
end
anglecosidered = anglematrixdeg;
cosval = cos(anglematrix);
sinval = sin(anglematrix);
cosmatrix = cosval';
sinmatrix = sinval';
%%k = maxmassatonepoint/smallmassavilabe;
remmoddivisonb = mod(maxmassatonepoint,smallmassavilabe);
k = (maxmassatonepoint-remmoddivisonb)/smallmassavilabe;
massmatrix = [0:1:k];
allmassmatrix = massmatrix;
    for i= 1:size(anglematrix,2)
allmassmatrix = [allmassmatrix massmatrix ];
    end
allcombs = nchoosek(allmassmatrix, size(anglematrix,2) );
combs = unique(allcombs, 'rows');

```

```

masseffectactcos = masstobeadded*cos(actualmassanglered);
masseffectactsin = masstobeadded*sin(actualmassanglered);
massapproxcos = smallmassavilabe*combs * cosmatrix ;
massapproxsin = smallmassavilabe*combs * sinmatrix;
masserrorcosmatrix = abs(massapproxcos-masseffectactcos);
masserrorsinmatrix = abs(massapproxsin-masseffectactsin);
resultanterror      =      sqrt(masserrorcosmatrix.^2      +
masserrorsinmatrix.^2);
[minerror index] = min(resultanterror);
bestmasscombi = combs(index,:);
bestmass = smallmassavilabe * bestmasscombi;
erroronbestmasscos      =      (bestmass*cosmatrix-
masseffectactcos);
erroronbestmasssin      =      (bestmass*sinmatrix-
masseffectactsin);
resultanterrorbestmass = sqrt(erroronbestmasscos.^2 +
erroronbestmasssin.^2)
angleerrorbestindeg      =
wrapTo360(atan2(erroronbestmasssin/erroronbestmasscos))
%%in degree
otheralternative      =
find(resultanterror<acceptablevalueinmass); %% 1.5 is
accepablemassinfluence
bestalternatives      =      smallmassavilabe      *
combs(otheralternative,:);
sumofmassbestalternative = sum(bestalternatives,2);
[minsum indexsum] = min(sumofmassbestalternative);
anglematrixdeg = wrapTo360(anglematrix*180/pi)
bestmassforlowsum = bestalternatives(indexsum,:)
erroronbestmasslowsumcos = (bestmassforlowsum*cosmatrix-
masseffectactcos);
erroronbestmasslowsumsin = (bestmassforlowsum*sinmatrix-
masseffectactsin);
resultanterrorbestlowsummass      =
sqrt(erroronbestmasslowsumcos.^2      +
erroronbestmasslowsumsin.^2)
angleerrorbestindeglosum      =
wrapTo360(atan2(erroronbestmasslowsumsin/erroronbestmassl
owsumcos)); %%in degree
bestmasslowererror = bestmass
vibrationafteraddindbestmass      =
resultanterrorbestmass/influencecoeff
vibrationafteraddinbestlowsum      =
resultanterrorbestlowsummass/influencecoeff
%%bestmasssmallmass = smallmassavilabe * bestmasscombi

```



```

disp('Consider following angle in a sequence')
fix(anglematrixdeg)
disp('Consider these masses combination in gram in above
angular squence for least error')
bestmasslowererror
fprintf('The vibration leve of expected after
considering least error is
%.3f',vibrationafteraddindbestmass);
disp('Consider these masses combination in gram in above
angular sequence above for least mass')
bestmassforlowsum
fprintf('The vibration leve of expected after
considering least sum is
%.3f',vibrationafteraddinbestlowsum);
disp('Following are all possible combination sequence of
masses for acceptatble vibration')
bestalternatives
ang1=0:0.01:2*pi;
outerradius = radius + radius/4;
xp=outerradius*cos(ang1);
yp=outerradius*sin(ang1);
p(1) = patch(xp,yp, 'black');
title('OPTIMAL BALANCING GRAPH')
hold on
axis square
angradius=0:0.01:2*pi;
xp1=radius*cos(angradius);
yp1=radius*sin(angradius);
p(2) = patch(xp1,yp1, 'yellow');
angcorrect = 0:((2*pi)/actualnumberofholes):2*pi;
x=radius*cos(angcorrect);
y=radius*sin(angcorrect);
p(3) = plot(x,y, 'o', 'MarkerFaceColor', 'white', 'MarkerSize', 15);
angcorrect = actualmassangledeg*pi/180;
x=radius*cos(angcorrect);
y=radius*sin(angcorrect);
p(4) = plot(x,y, 'o', 'MarkerFaceColor', 'red', 'MarkerSize', 15);
xcorrectlowererror = radius*cos(anglematrix);
ycorrectlowererror = radius*sin(anglematrix);

```

```

%%lgd = legend(p(3:4), 'Attachment holes', 'Actual
unbalance', 'Optimal load', 'Location', 'Southoutside');
for i=1:numberofholes
    if (bestmasscombi(i)==0)
        else
p(4+i)
plot(xcorrectlowererror(i), ycorrectlowererror(i), 'o', 'MarkerFaceColor', 'blue', 'MarkerSize', 4*bestmasscombi(i));
end
end
lgd = legend(p(3:4), 'Attachment holes', 'Actual
unbalance', 'Location', 'Southoutside');
xlim([-radius-radius*0.7 radius+radius*0.7])
ylim([-radius-radius*0.7 radius+radius*0.7])
hold off

while 1
prompt = "Do you want to check you own mass combinations?
Enter y/n ";
txt = input(prompt, "s");

    if (txt == 'y')
        for i = 1:numberofholes
            str = ['Enter the value of mass hole number '
num2str(i) ' :'];
            selectedoptions(i) = input(str);
        end
        selectedoptions %%selected option
        optionerrorcos = abs(selectedoptions * cosmatrix-
masseffectactcos);
        optionerrorsin = abs(selectedoptions * sinmatrix-
masseffectactsin);
        resultantoptionerror = sqrt(optionerrorcos.^2 +
optionerrorsin.^2);
        vibrationaftersselectedmass =
resultantoptionerror/influencecoeff;
        fprintf('The vibration level of selected mass is
%.3f', vibrationaftersselectedmass);
        disp('')
        disp('Thank you for testing this application,')
        disp(' Have a great day')
        disp('Any Error or Queris call 9851273300 Dipesh
Thapa')
    end
end

```

