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Helicopter rotor hub vibration reduction using passive methods

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1. INTRODUCTION

Helicopter vibration is defined as the oscillatory response of the helicopter airframe to the rotor hub forces and moments [1]. Although there are other vibration sources like engine and transmission, and aerodynamic loads on the fuselage and tail rotor, their effects are mostly local. The vibratory hub loads from the main rotor are the major source of vibration [3]. These loads are transmitted to the fuselage through the rotor hub, and a reduction in these loads is expected to reduce the vibrational level of the whole helicopter. Therefore, vibrations that are induced by main rotor forces and moments were considered. The Rotor is the main source of lift, propulsion, and control in helicopters. The rotor blades rotate at high speeds in a complex unsteady aerodynamic environment and the interaction of blades with this aerodynamic environment is the main source of vibration [2]. The maximum flight speed and fatigue are some of the performance parameters that get degraded because of the vibration effect. Last but not least, the vibration effect on the flight crew and passengers should not be underestimated. A High level of vibration causes whole-body vibration which occurs when the human body is supported by a surface that is shaking. The vibration from the shaking surface is transmitted through the body of the human in contact with the surface including the skeleton, nervous system, and spine [4].

Optimization methods are very popular in multi-disciplinary engineering applications. Helicopter operation has strong aerodynamic and structural dynamics interactions therefore optimization algorithms are also used in the rotorcraft industry so that lighter, safer, cheaper, and high-performance helicopters can be designed. However, while algorithms solve the mathematical relations the physical world should also be represented. Rotorcraft comprehensive analysis is the best choice for this purpose which has been very popular in the rotorcraft industry due to its fast and reliable solutions for the whole helicopter. Therefore, if the coordination between optimization algorithms and rotorcraft comprehensive analysis is ensured, rotorcraft design can benefit from multidisciplinary optimization. For this purpose, an optimization procedure that can reduce the main rotor-induced vibrational level was proposed. Additionally, that procedure was illustrated on the existing isolated blades and full helicopter configuration including the main rotor, tail rotor, and fuselage.

2. VIBRATION REDUCTION TECHNIQUES

The techniques can be passive or controlled actively. The passive techniques do not require any actuation and try to reduce vibrations after the vibratory loads are generated. On the other hand, active techniques work according to the measured vibration on the helicopter and try to reduce vibratory loads by generating opposing air loads [5].

The active vibration reduction systems are also called excitation reducers which generate opposing aerodynamic loads so that the vibratory loads are cancelled [7]. The most popular active control systems are the higher harmonic control, active flaps, and smart structure application on rotor blades. The swash plate control excites the surrounding air once in every rotor revolution in normal operation as it was discussed in Section 1.2. The idea behind the higher harmonic control (HHC) is to excite the swash plate at a higher frequency in addition to the 1/rev cyclic input so that the cancellation of vibratory air loads occurs due to additional excitation that cancels the vibratory air-loads [9]. HHC application to a helicopter having 4 blades to reduce vibrations at the blade passing frequency. The system measures the vibrations by using the accelerometers located in the pilot seat. The measured vibrations which are supposed to be reduced are converted into signals and then fed into the flight computer. The flight computer calculates the necessary motion of the swash plate. The suitable combination of the vertical and tilting motions of the stationary swash plate generates the required cancelling loads [9]. Since the cancelling loads reduce vibratory loads, which are the sources of the transmitted vibrations to the fuselage, the vibrations on the pilot seat can also be reduced.

Individual blade control (IBC) is an improved method of HHC. In this concept, the pitch of each blade is excited so that better results can be obtained with the addition of more control degrees of freedom [10]. There are also other ways of exciting the blade individually which are the active flap control [11] and smart blade [12]. The flaps located on the rotor blades are actuated such that the resulting air loads cancel the vibratory loads as in the case of HHC. There is an increase in the number of flaps per blade. This method consumes less power than IBC with a mechanically simpler system [11]. Smart blade concepts make use of piezoelectric actuators. Depending on the level of vibrations, the elastic twist of the blade is altered by using the actuators and therefore the vibratory loads can be reduced [12].

Passive vibration reduction can be achieved by self-actuated systems which include vibration isolation, absorption, and attenuation. The isolators reduce the undesirable effects of vibration by designing the connection between the body which is required to be isolated and the foundation which is the source of vibration itself [6]. On helicopters, they are located between the critical equipment on the fuselage and the supporting structure which transmits the vibration. the isolators either reduce the magnitude of the vibratory motion transmitted from the vibrating foundation or reduce the magnitude of force transmitted from the foundation.

Vibration absorption refers to extra degrees of freedom addition so that the unwanted effects of vibration are transferred to a new degree of freedom rather than to the structure [6]. The most popular absorbers in helicopters are pendulum absorbers and bifilar absorbers which can be mounted on the blade in flap-wise and in-plane directions. Significant reductions in blade root loads can be achieved by the pendulums which are mounted in flap-wise and chordwise directions [7]. The application of the pendulum modifies the motion of the blades so that a favourable blade response reduces vibratory loads.

The bifilar absorber is another passive method that is composed of a support arm, a tuning mass, circular holes, and tuning pins. The support arm connects the tuning mass to the hub whereas the tracking holes and tuning pins provide relative motion of the tuning mass. The motion of the tuning mass is governed by the loads acting on it and the natural frequency of the system which is determined by the dimensions of the holes and pins and angular rotor speed. The natural frequency of the system is tuned to the in-plane frequency in the rotating frame at which the vibratory in-plane shear force is supposed to be reduced [8]. The bifilar absorbers are relatively heavier as compared to pendulums and can only reduce in-plane loads. The attenuators are the non-structural masses that are added to the rotor blade which helps in moving blade natural frequencies away from excitation frequencies. They are usually applied at the blade tip or mid-span [7]. All three types of passive vibration reduction techniques are effective at a specific tuning frequency at which the vibratory loads are supposed to be reduced. If vibratory loads exist at any other frequency, the techniques are ineffective, and additional vibration reduction systems should be implemented.

Through [15] the results of Optimizing Tuning masses for Helicopter Rotor blade vibration reduction by including Computed Air loads and Comparison were discussed. Using CAMRAD/JA the optimization procedure was performed to reduce the harmonics of the hub-shear for the four-bladed rotor, where the design variables are the tuning masses and mass locations on the rotor blade, the tests were performed by placing 3 tuning masses and 6 tuning masses on the rotor blade in the forward flight condition as presented in Figure 1 which provided the good results and also by placing the single mass of fixed value on the blade to reduce the hub shear in all the flight conditions which obtained good results in mass locations and entirely not successful in providing the absolute fixed system loads' magnitude.

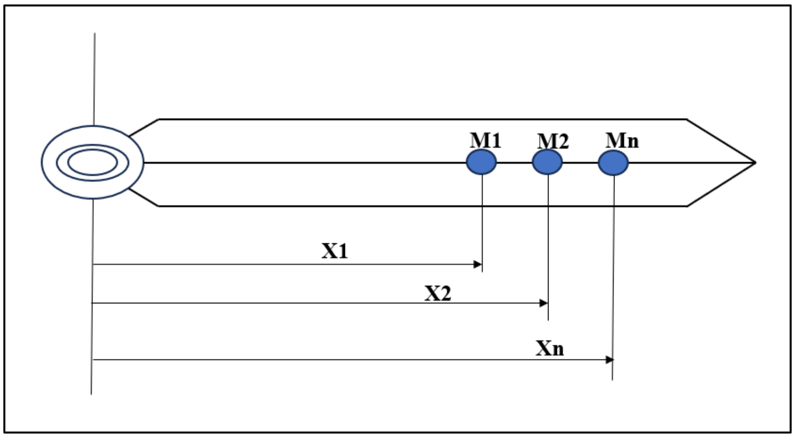

Figure 1. Design Variables of masses and placed at different locations on the helicopter rotor blade

Lee implemented a genetic algorithm for rotorcraft multidisciplinary optimization in 1995 [13]. The purpose of using genetic algorithms is their applicability to parallel computing which is a big advantage in multidisciplinary optimization so that the multidisciplinary problems can be handled by dividing the whole system into subsystems. A finite element-based multibody formulation was used to model the blade. A weighted sum of vertical vibratory hub loads was formulated as the objective function which was subjected to the design constraints including power required, autorotational inertia, natural frequencies, rotor thrust, blade weight, and buckling stress. The design variables were the tuning masses, blade cross-section dimensions, blade twist, blade taper ratio and its initiation point, rotor RPM, and the ply angles of the cross-sections.

3. THE APPROACHES OF ROTOR-INDUCED VIBRATORY LOAD REDUCTION

The rotor-induced vibrations can be handled in two ways which can be identified as direct and indirect approaches. In the direct approach, the blades were designed or modified for the minimized rotor hub vibratory loads. The vibratory loads include inertial and aerodynamic loads which are caused by the complex aerodynamic environment and blade response to oscillatory loads.

On the other hand, the indirect approach benefits from the relationship between the blade's natural frequencies and aerodynamic excitation frequencies instead of direct load calculation. These direct and indirect approaches were referred to as "Hub Loads Minimization" and "Natural Frequency Separation" respectively.

The calculation of blade natural frequencies is critical in the determination of blade dynamic characteristics. The problem of finding the natural frequencies is a free vibration problem for rotating beams and the knowledge of the blade equations of motion is essential. The helicopter's main rotor blades are characterized by slender, elastic beams which are usually subjected to high-speed angular rotation. Generally, the blades are twisted; the mass and stiffness values are variable over the blade.

The elastic axis and centre of mass are usually separated with an offset and the application of non-structural masses is quite common. In addition to the problems arising from the blade geometry, even at usual operating conditions, the blades are under a significant centrifugal force field that varies over the blade. This centrifugal force has a stiffening effect on the blade and dominates the dynamics of the blade. The dynamic analyses of blades show considerable difficulties because of all these geometric, elastic, and inertial effects. To achieve a successful blade model this elastic, inertial, and coupling effects should be treated carefully.

The natural frequency separation method is very advantageous if the rotor aerodynamic model is unreliable for high-frequency load computations or computationally too expensive. The excitation frequencies are irrespective of the magnitudes of the aerodynamic loads and are always the integer multiples of the rotor angular speed (Ω). Since the natural frequencies of the blade should not come close to those excitation frequencies, the blades can be designed for reduced vibrational levels by a natural frequency separation approach [1]-[2]. Since blade natural frequencies are evaluated for the in-vacuo condition, the solution of the rotor aeroelastic motion is not required.

The second method of vibration reduction is the direct calculation of hub loads which can be performed with an overall rotor evaluation including aerodynamic and structural dynamic models. The blades respond to oscillatory aerodynamic loads which in turn cause oscillatory blade motion. This interaction between excitation and response generates the dynamic loads at the blade root. The dynamic blade loads from each rotor blade root are integrated at the rotor hub and the overall dynamic loads at the rotor hub excite the body and cause helicopter vibration. Figure 2 presents the representative rotating and non-rotating coordinate systems and related forces and moments.

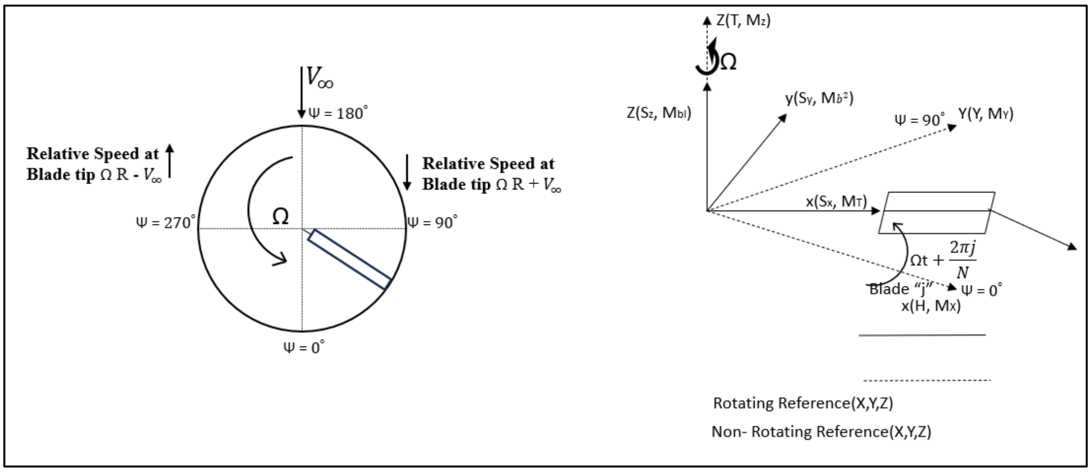

Figure 2. Hub and Blade Reference Frames and Vertical Shear Forces

When the blades are uniform and equally spaced, some frequencies of the blade root loads are cancelled at the hub. The rotor acts as a filter and only harmonic loads at integer multiples of the rotor (kN/rev) speed are transferred to the hub as vibratory loads. For the vertical hub loads, only kN/rev harmonics of blade loads contribute to kN/rev vertical hub loads whereas for in-plane loads (kN-1)/rev and (kN+1)/rev harmonics of blade loads contribute to kN/rev hub loads. It is also important to observe that the blade root tension force and twisting moment are cancelled and have no contribution to the hub loads.

Due to the filtering characteristics of the rotor, engineers consider vibratory loads at kN/rev frequency to approach a jet-smooth flight. The lower the vibratory loads, the smaller the level of fuselage vibrations. That effectively means the dynamic loads at the frequency of integer multiples of blades per cycle (kN/rev) should be decreased. Generally higher frequencies have very small amplitudes therefore it is usually enough to consider N/rev loads [14]. Due to the periodic nature of the rotor, it is common practice to represent hub loads by sine and cosine components and functions of rotor angular coordinate (Ψ).

The three force and three-moment components of vibratory hub loads excite the fuselage at every kN/rev frequency. The fuselage response to these vibratory loads causes the vibration 34 of the airframe. In addition to the airframe- structure other components in the non-rotating frame such as avionics, flight crew, passengers, and payload are also affected.

As opposed to "The Natural Frequency Separation method, "Hub load Minimization" has the advantage of contributing vibratory loads that are of aerodynamic origin. The exact values of the loads to be minimized provide better physical insight into the problem.

4. METHODOLOGY

The objective of the project is to reduce the vibratory load on the helicopter rotor blade, by placing three tuning masses on the rotor blade at three different locations and experimenting by placing the masses on the elastic axis and offset to the elastic axis to analyse the results by varying twist. The whole optimization is carried out through RCE, VAST is integrated into RCE and connected to Optimizer. The description of the functioning and process of tools involved in optimization to minimize the vibratory loads on the helicopter rotor blade is as follows:

VAST is a multi-physics, multi-model simulation program with a very modular and generic approach. The architecture is strictly divided between the simulation framework and the actual implementation of physics. It is being developed for helicopter aeromechanic calculations but the Simulation Core, the User Interface, the Configuration, and the IO - in short, the entire simulation framework is developed in such a way that it could be used for any numerical simulation field requiring multi-model-simulation. Apart from physical models, there are tasks implemented in the framework both completely generic like the transient solution through time, and specific to the use-case like the free-flight trim of a helicopter.

The main design idea is to divide a simulation problem into different disciplines and to model their respective sub-problems in separate models which are then connected and simulated in conjunction with each other. All sub-models are formulated in a generic state-space form with input, output, and states as well as dynamic and output equations.

The main components of VAST are depicted in Figure 3. A Graphical User Interface (GUI) is employed to set up the system to be simulated and to specify simulation parameters and cases. This information is stored in input files which are then used by the actual simulation, here called Simulation Framework, to perform the simulation and produce output files. These output files are used by a post-processor or visualization engine to produce visual results of the simulation. The GUI controls and monitors the calculation which can either be run as a predefined batch process or in an interactive mode.

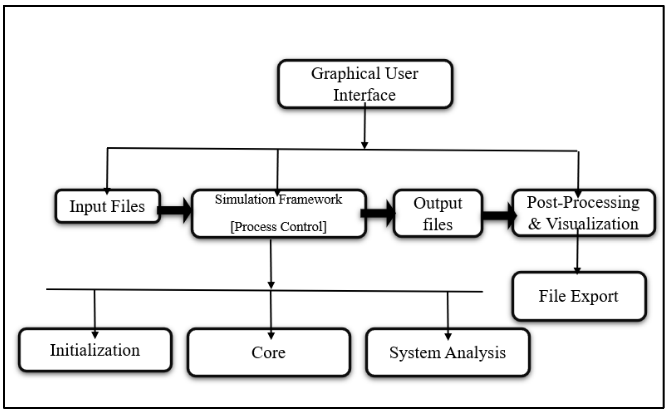

Figure 3. Main components of VAST

A simple configuration for a generic trim case (wind-tunnel or free-flight) in VAST consists of a simple configuration for a generic trim case (wind-tunnel or free-flight). This tries to find valid values for a set of unknowns to fit the trim objectives to their target values.

In general, during the trim task, an iterative optimization method is used to find trim values that lead to fulfilled trim objectives. That is, starting with initial trim values, the algorithm performs a time simulation with exactly these parameters and checks if the trim objectives are already fulfilled. If this is not the case, the trim values are adapted and another simulation is performed. This procedure is pursued until the trim objectives are fulfilled (or a different stopping criterion is reached). Each of the simulations consists of several steps, which are described as 1) Initiation,2) The Time Simulation,3) Measurement of the Trim Objective, and 4) Stopping criteria.

When the rotor rotates, the air mass above the rotor is sucked through the rotor disc. This induces a flow perpendicular to the rotor disc, reducing the effective angle of attack of the blade section as shown in Figure 4. The induced velocity depends on the blade loading at each section. Since the blade loading varies along the radial and azimuthal directions and also concerning, the induced velocity is a function of radial distance, azimuth angle, and time. Hence, the angle of attack of the airfoil section also varies for radial and azimuthal locations. So, the proper estimation of the induced velocities through the rotor disc is very critical in rotorcraft aeromechanical studies.

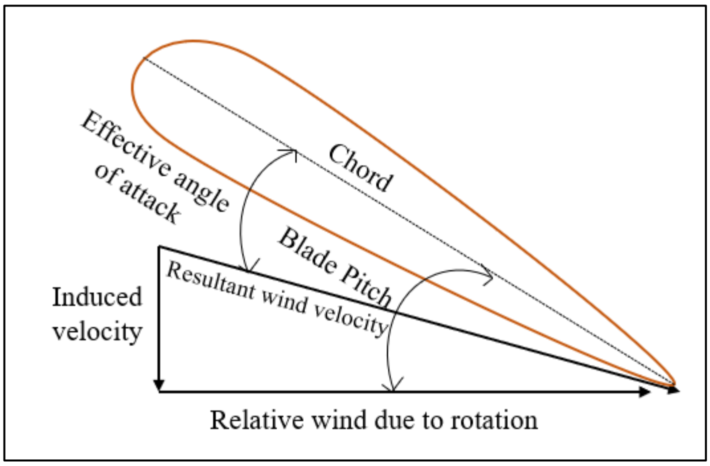

Figure 4. Velocity components and angle of attack at the blade element

Currently, there is a range of inflow models starting from very simple uniform inflow models to very complex computational fluid dynamics models. Most of the inflow models are extensions of propeller theories like momentum theory and vortex theory. The following inflow models are commonly used in helicopter flight mechanics simulation tools. They are uniform inflow, Glauert inflow, Drees inflow, Pitt-Peters three-state dynamic inflow, generalized dynamic wake model, Wake distortion model, Free wake, and Prescribed wake model. Each inflow model has its advantages and disadvantages. In general, these inflow models can be categorized into static or time-averaged inflow models and dynamic inflow models.

With the model analysis and trim analysis, to execute the optimization in VAST the scripting is pre-written in the form of an XML document which is termed vast_config.xml, it contains all the data regarding the blade geometry, shaft tilt, wind velocity, and other parameters responsible in operating the task in VAST. The process can be clearly explained in Figure 5 presenting the flowchart.

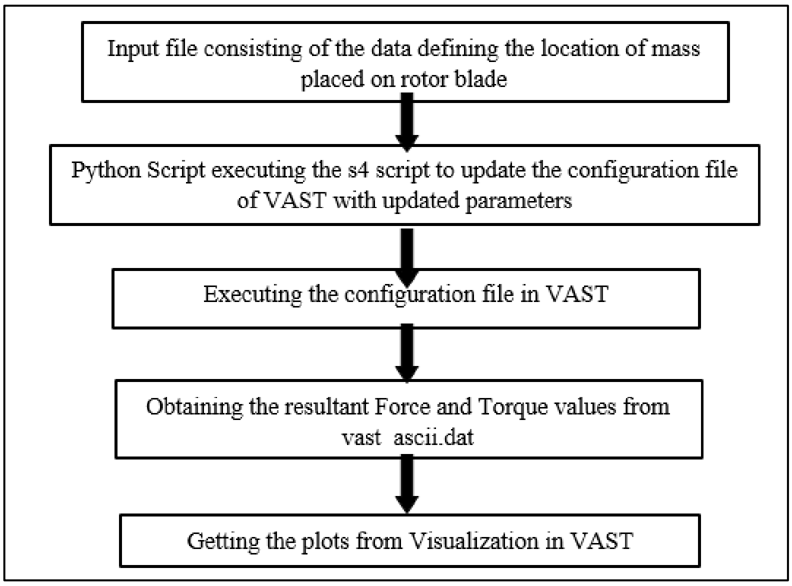

Figure 5. Flowchart describing workflow process in VAST

After executing the vast_config.xml file inside VAST, it performs the task and exports the results in the vast_ascii.dat file where all the forces, and torques acted were involved on the rotor blade. Here, the major concern is the main constraint forces[N] acting on 3 Dimensions which can be termed F_X, F_Y, and F_Z, and the main constraint torques [Nm] acting on 3 Dimensions which are termed M_X, M_Y, M_Z. Each force and torque provide the 25 sets of values each are to be extracted concerned to the time provided in the vast_ascii.dat file. Using the set of values harmonic analysis is performed and the 4th harmonic's amplitude of each 3 Forces is termed as F'_X, F'_Y, F'_Z, and 3 Torques M'_X, M'_Y,M'_Z which is the root cause of the vibration on the rotor blade, then the calculated objective function is termed as follows;

$$f = \sqrt{({F'_X}^2 + {F'_Y}^2 + {F'_Z}^2)}\,[N] + \frac{1}{R[m]}\sqrt{{M'_X}^2 + {M'_Y}^2 + {M'_Z}^2}\ [\text{Nm}]$$

Here R is the radius of the rotor blade, in this case, the Radius is 2.0 m.

These results are analysed and optimized results by integrating the VAST into RCE(Remote Control Environment), the features, and the tools involved in RCE. RCE (Remote Component Environment) is an open-source software. RCE creates, manages, and executes complex calculation and simulation workflows for engineers, scientists, and others. RCE workflow consists of predefined inputs and outputs connected. A component can be a tool for data access, a simulation tool, or a user-defined script. Connections define which data flows from one component to another also predefined components with common functionalities, like an optimizer or a cluster component. Additionally, users can integrate their tools. RCE instances can be connected externally through a networking component where the tools can be executed locally or on remote instances of RCE (if the component is configured to allow this). Using these building blocks, use cases for complex distributed applications can be solved with RCE.

Before the calculation of the objective function, there is an input file that plays a key role in evaluating the objective function when mass is placed on the rotor blade, this input file contains the data with locations of the rotor blade[m], angle of tilt[θ], amount of mass placed[kg], the moment of inertia[kg.m2] when the mass is placed and the scalar value of which mass is placed on the elastic axis[m](if the mass is on the elastic axis of the rotor blade it is zero when the mass is placed offset to the elastic axis the scalar value is to be noted at the space).

Later after updating the input file with the required data, then the script from the S4 tool is used to combine these values into the vast_config.xml as this feature is not yet updated in VAST due to time constraints. By executing the script of the S4 tool the data with the modified values gets updated into the VAST tool's XML file. Now, when the updated XML file gets executed in VAST extracts the data of force and torques which were mentioned above to perform the harmonic analysis and calculate the objective function. All the scripts and tools are integrated into RCE for better optimization and multiple experiments are implemented to obtain better results to reduce the objective function.

5. DESIGN OF EXPERIMENTS & EXPERIMENTS PERFORMED ON THE OPTIMIZATION PROBLEMS

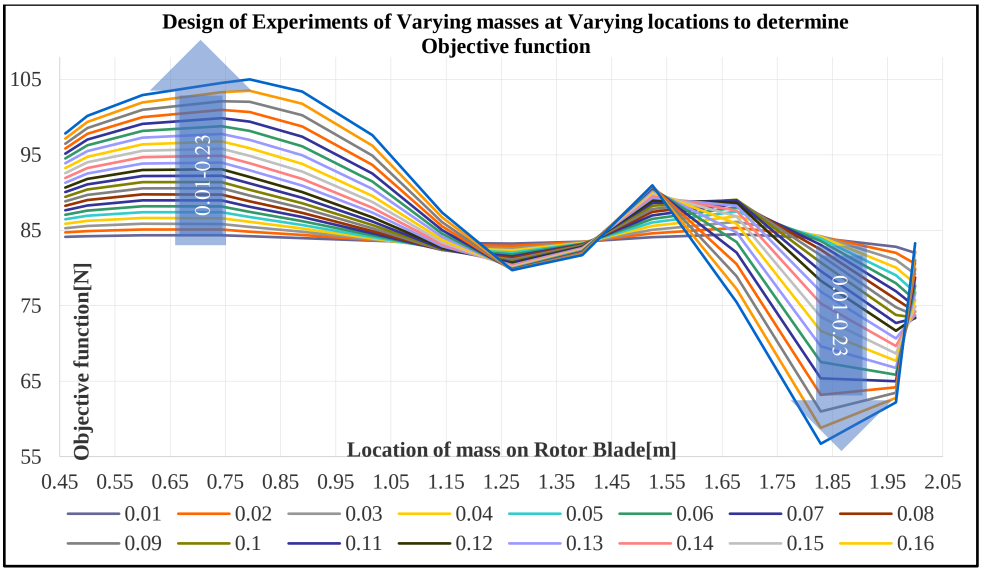

Figure 6. Design of Experiments when varying mass with 0.01 kg increment at varying locations

The plot in Figure 6 describes the design of experiments when mass from 0.01 to 0.23 is applied on the helicopter rotor blade at the location of 0.4640m to 2.000m from the rotor hub of the helicopter at forward decent flight condition, from the plot it is observed that minimum objective function is achieved at the locations of 0.794m, 1.270m, 1.524m, 1.829m and at 2.000 m when the mass of 0.02kg, 0.1kg and 0.23kg is applied at the respective single mass at the single locations.

For better observation of the effect of the objective function at varying locations with varying mass, a new set of design experiments was carried out by placing the single mass of 0.02kg,0.1kg, and 0.23kg individually at 0.794m, 1.270m, 1.524m, 1.8229m and at 2.000m with an offset from a range of -0.0060 to +0.0060. By performing this design of experiments.

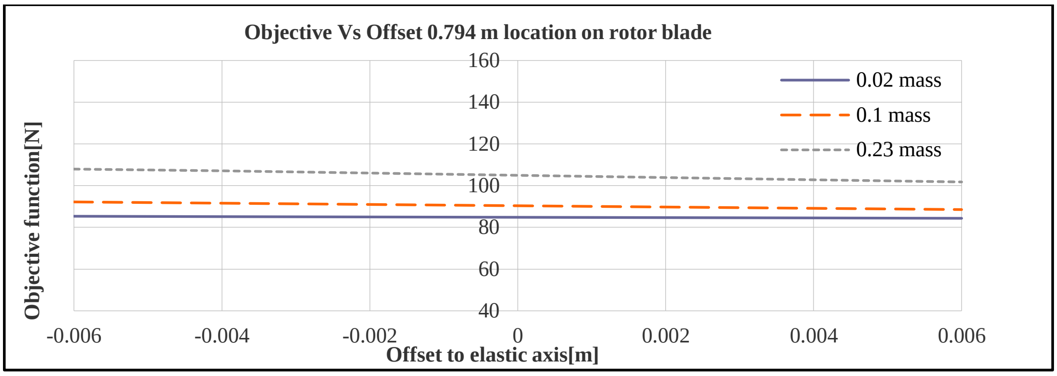

Figure 7. Objective Function Vs mass placed at 0.794m location Offset from the elastic axis

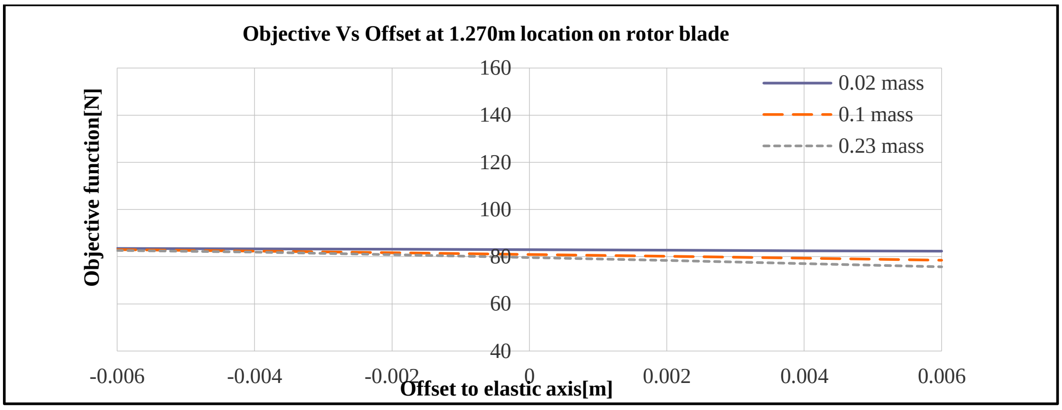

Figure 8. Objective Function Vs mass placed at 1.270m location Offset from the elastic axis

Figure 7 and Figure 8 are the plots that describe the behaviour of the objective function when the single masses of 0.02kg,0.1kg, and 0.23kg are placed offset to the elastic axis ranging -0.0060 to +0.0060 on the helicopter rotor blade at 0.794m and 1.270m away from the rotor hub. From the design of experiments, it was observed that at the specific locations, minimization of the objective function is observed with the increase of mass from 0.02kg to 0.23kg when the mass is placed above the elastic axis.

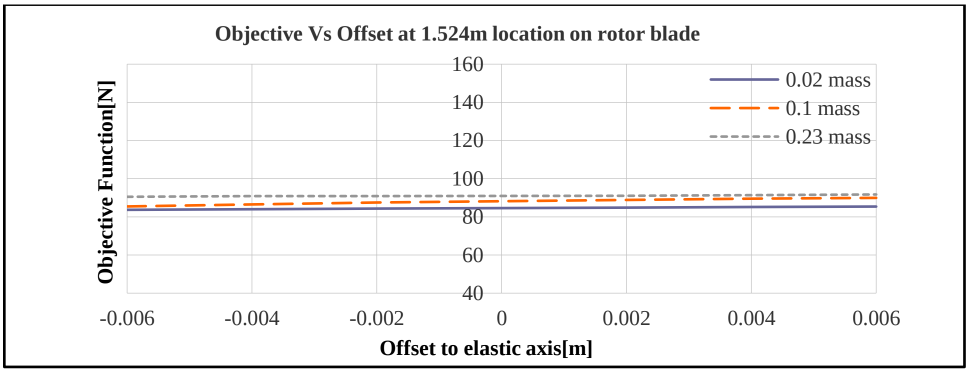

Figure 9. Objective Function Vs mass placed at 1.524m location Offset from the elastic axis

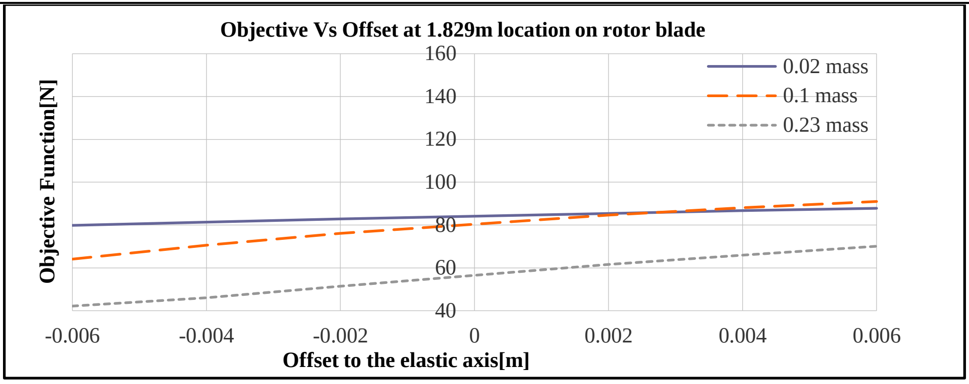

Figure 10. Objective Function Vs mass placed at 1.829m location Offset from the elastic axis

Figure 9 and Figure 10 are the plots that describe the behaviour of the objective function when the single masses of 0.02kg,0.1kg, and 0.23kg are placed offset to the elastic axis ranging -0.0060 to +0.0060 on the helicopter rotor blade at 1.524m and 1.829m away from the rotor hub. From the design of experiments, it was observed that at the specific locations, minimization of the objective function is observed with the increase of mass from 0.02kg to 0.23kg when the mass is placed below the elastic axis and by comparing with the earlier cases from Figure 7 & 8, the minimization of the objective function is more in the later cases as the minimum objective function is 42.106N.

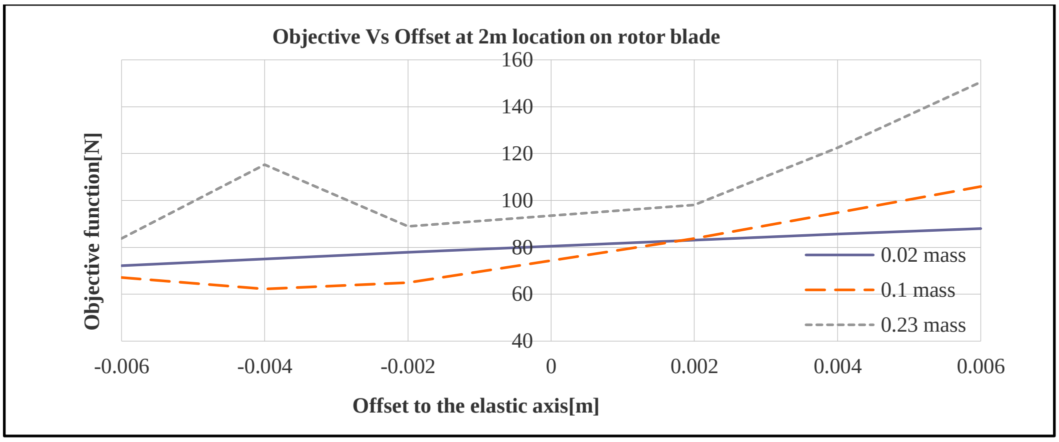

Figure 11. Objective Function Vs mass placed at 2.000 m location Offset from the elastic axis

Figure 11 is the plots describe the behaviour of the objective function when the single masses of 0.02kg,0.1kg, and 0.23kg are placed offset to the elastic axis ranging -0.0060 to +0.0060 on the helicopter rotor blade at 2.0m away from the rotor hub which is at the tip of the rotor blade. The achieved objective function is more than the initial cases when 0.23kg mass is placed at the tip of the rotor blade. By observing all the plots where the mass is placed at varying locations offset to the elastic axis, the minimized objective function is more effective when it is placed below the elastic axis and near the tip of the helicopter rotor blade.

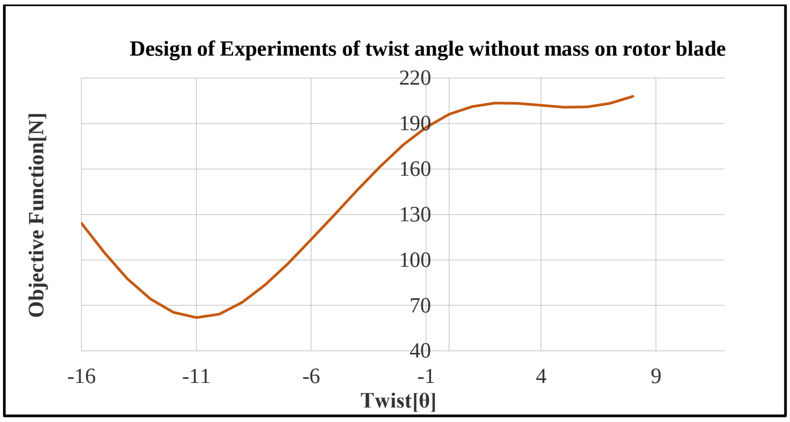

Figure 12. The plot of Objective function Vs twist angle

Figure 12 represents the plot obtained when the design of experiments is performed to observe the objective function without mass on the rotor blade, the only design variable is the twist angle whose lower and upper bounds are -16 and 8. Based on the plot the minimized objective function can be observed at a twist angle of -11 and then there is a steady incline of the objective function till a twist angle of 8.

Before starting the optimization process to reduce the vibration by placing tuning masses on the helicopter rotor blade by minimizing the objective function, the baseline run was performed to know the objective function value without masses placed, it ended up obtaining the baseline value of the objective function as 83.584N.

Later, the optimization experiments are carried out to observe the behaviour of the objective function when three tuning masses are placed at three locations on the rotor blade, three tuning masses are placed offset to the elastic axis at varying locations and finally three tuning masses are placed offset to the elastic axis at varying locations and twist angle. All the experiments are carried out under Forward descent flight conditions. Table 1 represents the lower and upper bounds for the design variables to undergo the optimization process.

Parameters	Lower Bound	Upper Bound
Location 1[m]	0.46	2
Location 2[m]	0.46	2
Location 3[m]	0.46	2
Mass 1[kg]	0	0.05
Mass 2[kg]	0.025	0.075
Mass 3[kg]	0.05	0.1
Offset 1[m]	-0.0060	+0.0060
Offset 2[m]	-0.0060	+0.0060
Offset 3[m]	-0.0060	+0.0060
Twist[θ]	-16	8

Table 1. Bound conditions of all the design variables for the optimization process

The first experiment for the optimization process is carried out by placing three tuning masses at varying locations at forward descent flight conditions, consisting total of six design variables provided as inputs to the tool in RCE through optimizer under Single Objective Genetic Algorithm calculates the objective function and provided the optimized result which can be observed through Table 2 and Figure 13 represents the convergence plot for optimizing vibrations on rotor blade.

Parameters	Results
Objective function[N]	6.586e+001
Mass 1[kg]	3.426e-002
Mass 2[kg]	6.761e-002
Mass 3[kg]	8.454e-002
Location 1[m]	1.9650
Location 2[m]	2.000
Location 3[m]	1.6764

Table 2. Best parameters obtained through optimizer in RCE

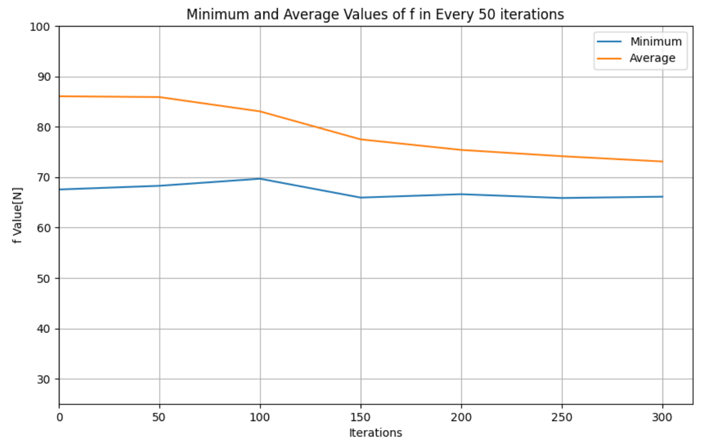

Figure 13. Convergence plot of Optimization to minimize the vibration when three masses are placed at varying locations

The second experiment for the optimization process is carried out by placing three tuning masses offset to the elastic axis at varying locations at forward descent flight conditions, consisting of nine design variables provided as inputs to the tool in RCE through optimizer under Single Objective Genetic Algorithm calculates the objective function and provided the optimized result which can be observed through Table 3 and Figure 14 represents the convergence plot for optimizing vibrations on the rotor blade.

Parameters	Results
Objective Function[N]	4.44E+01
Location 1[m]	1.6764
Location 2[m]	1.8290
Location 3[m]	1.9650
Mass 1[kg]	4.91E-002
Mass 2[kg]	7.42E-002
Mass 3[kg]	9.43E-002
Offset 1[m]	-5.63E-003
Offset 2[m]	-4.76E-003
Offset 3[m]	-5.11E-003

Table 3. Best parameters obtained through optimizer in RCE

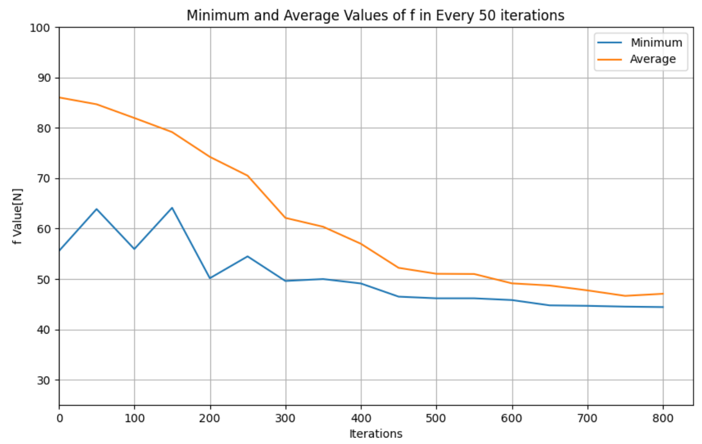

Figure 14. Convergence plot of Optimization to minimize the vibration when 3 masses are placed at varying locations offset to the elastic axis

The third experiment for the optimization process is carried out by placing three tuning masses offset to the elastic axis at varying locations and twist angle at forward descent flight condition, consisting total of ten design variables provided as inputs to the tool in RCE through optimizer under Single Objective Genetic Algorithm calculates the objective function and provided the optimized result which can be observed through Table 4 and Figure 15 represents the convergence plot for optimizing vibrations on rotor blade.

Parameters	**Results**
Objective Function[N]	2.89E+001
Location 1[m]	1.6764
Location 2[m]	1.890
Location 3[m]	1.9650
Mass1[kg]	3.70e-002
Mass2[kg]	6.71e-002
Mass3[kg]	8.93e-002
Offset 1[m]	2.51e-003
Offset2[m]	5.81e-003
Offset3[m]	-3.81e-003
Twist[θ]	-11

Table 4. Best parameters obtained through optimizer in RCE

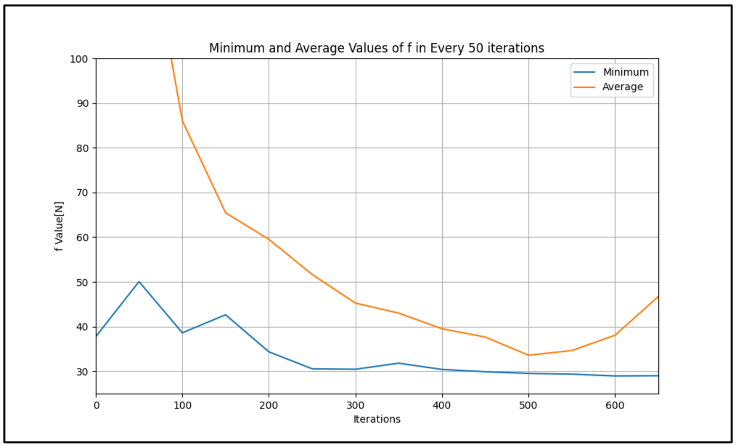

Figure 15. Convergence plot of the optimizer in RCE with varying mass at varying locations, offset to the elastic axis with varying twist angle

6. RESULTS & DISCUSSION

After performing the experiments to minimize the vibratory loads when tuning masses are placed on the helicopter rotor blade using an optimizer in RCE based on the Single Objective Genetic Algorithm the minimization of the objective function has been achieved, in comparison with the baseline objective function to all the three optimization processes there is a steady decline in objective. From Figure 16 it can be observed that the objective function has been decreased to 65.37%.

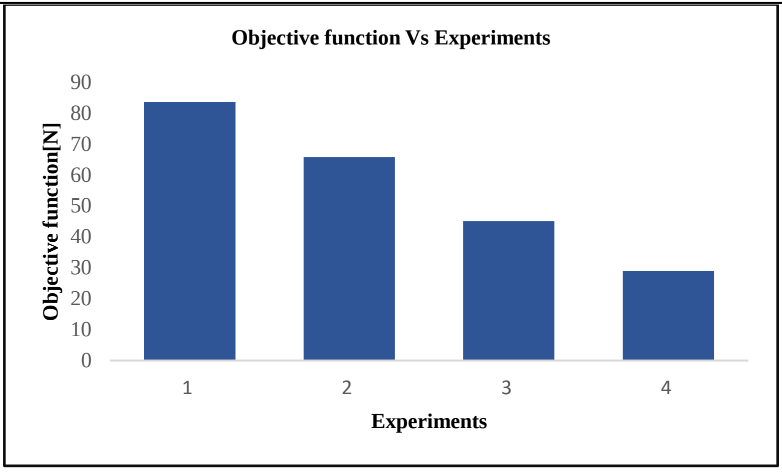

Figure 16. Plot comparing the objective function from baseline to optimization experiments

Along with the objective function, the forces and moments at Three dimensions of baseline values are compared with the best parameters achieved through optimization. The plots can be observed through Figure 17 and Figure 18.

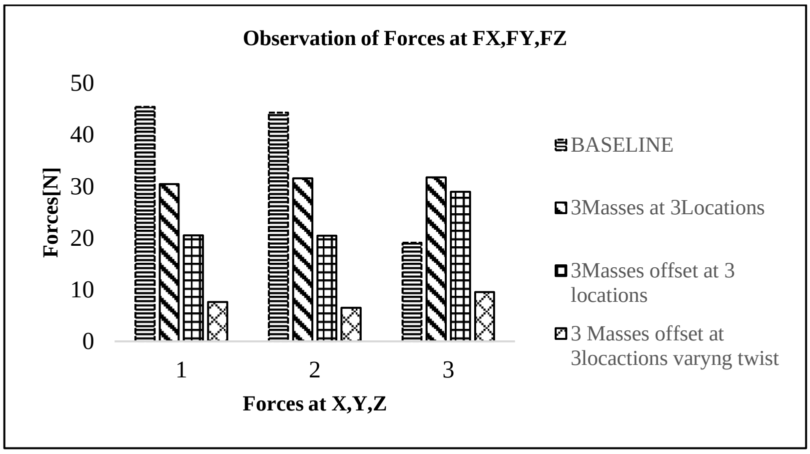

Figure 17. Comparing the Forces [FX, FY, FZ] of baseline with the forces obtained through Optimization

As these results are encouraging, the same can be subjected to other flight conditions and can be compared with the baseline objective function, which can explore a wide range of possibilities in reducing the vibration acting on the rotor blade. Also, during the process of optimization, there are a few challenges faced while working with RCE and VAST.

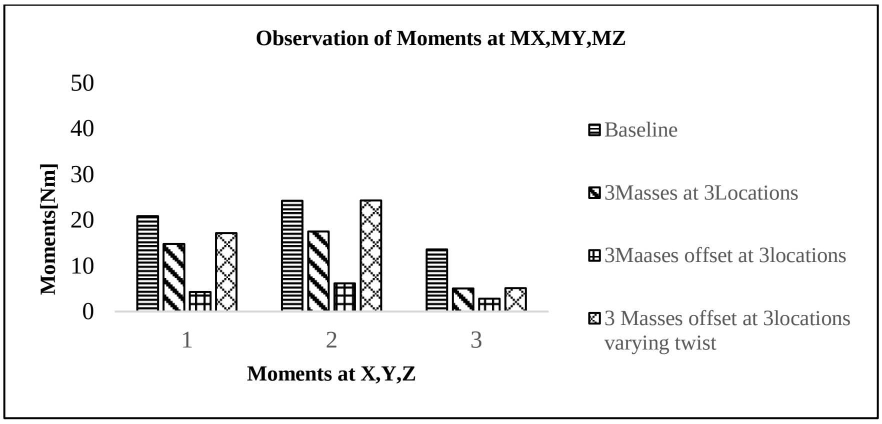

Figure 18. Comparing the Moments [M_X, M_Y, M_Z] of baseline with the forces obtained through Optimization

RCE itself cannot trigger the tool and terminates after its execution, so batch files are to be used for integrating the tools and executing them and the Python in RCE is only compatible with Python 2.7, other library files, and the rest of the commands for scripting cannot be performed for developed versions in RCE, if these can be updated in RCE, it will be more user-friendly to work on RCE.

Coming to the case of working with VAST, as arbitrary blade shapes can be configured and computed, the feature has not been thoroughly tested yet. Most verification and validation cases use straight rectangular blades, so this feature is still experimental and configured in GUI currently it is not very clear which models or model combinations are needed and the usage of the inter-model dependencies.

7. KEY FINDINGS FROM DESIGN OF EXPERIMENTS & OPTIMIZATION

The key findings from the design of experiments and optimization processes to understand the behavior of vibration and minimizing the vibration loads at rotor hub are as follows:

- From the design of experiments where the single tuning mass in the increments of 0.01kg is placed on the elastic axis of the rotor blade at the location between 0.46m to 2.0m from the center of rotor blade, the decline of vibration is observed while increasing the tuning mass with the increase of distance from the center of the rotor blade. Especially at the tip of the rotor blade (i.e;1.829m from the rotor center), a clear decline of the objective function is observed when the mass of 0.23kg is placed. This experiment result also led to the study of the behavior of the objective function when the mass is placed offset to the elastic axis to compare the objective function's behavior when the mass is placed near the center of the rotor blade and away from the center of the rotor blade.
- From the design of experiments where the single tuning masses of 0.02kg, 0.1kg, and 0.23kg are placed offset to the elastic axis between the range of -0.0060 to +0.0060 at locations of 0.794m, 1.270m, 1.524m,1.829m, and 2.0m to observe the objective function behavior. Initially, the decline of the objective function is observed with the increase of masses placed above the elastic axis at the locations 0.794m, and 1.270m from the center of the rotor blade. Gradually the least objective function is observed when the increase of masses is placed below the offset axis at 1.829m from the center of the rotor blade. Compared with the objective function when the masses are placed offset at 2.0m, the least objective function is observed at the 1.829m location. Through this design of experiments the observation in the behavior of vibration is the vibration will be less when the tuning mass is placed near the tip of the rotor blade than the tuning mass is placed at the tip of the rotor blade
- When the optimization process is carried out to attain the minimization of the objective function to reduce the vibration at the rotor hub placing three tuning masses at three different locations placing offset to the elastic axis with a varying twist at forward descent flight condition a significant vibration reduction is observed while it is compared to the baseline objective function where there was no tuning mass is placed. This builds confidence to carry out the optimization process in other flight conditions and also involving other parameters as design variables could be useful to study the minimization of the vibration at the rotor blade.

8. CONCLUSION

Rotor blade vibration is one of the major hazards for the helicopter affecting the flight's performance. For this purpose, an optimization procedure was developed which involves integrating VAST (Versatile Aerodynamic Simulation Tool) into the workflow-integrated environment RCE (Remote Control Environment) using a Single-Objective Genetic optimization algorithm.

The whole optimization process is performed by carrying out three experiments at the forward flight descent condition by placing three tuning masses whose total weight of the three tuning masses is the summation of 10% weight of the rotor blade. The experiments carried out for minimizing the objective function are placing the three tuning masses at varying locations on the elastic axis of the rotor blade, the other experiment when the masses are placed offset to the elastic axis at varying positions, and the last experiment when the masses placed offset to the elastic axis at varying locations with varying twist angle. The design variables are three masses, the locations on the rotor blade, the distance offset to the elastic axis, and the twist angle. The resulting best objective function is compared to the objective function with the baseline condition where the masses are not placed on the helicopter rotor. The results from the experiments to achieve the vibration reduction using tuning masses are successful. The objective function has been minimized to 65.37% when it is compared to the baseline objective function.

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