

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**BLADE OPTIMIZATION OF UNMANNED HELICOPTER
FOR VARIABLE ROTOR SPEED**



M.Sc. THESIS

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Department of Aeronautical and Astronautical Engineering

Aeronautical and Astronautical Engineering Programme

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**DEĞİŞKEN ROTOR HIZI İÇİN
İNSANSIZ HELİKOPTERİN PALA OPTİMİZASYONU**

YÜKSEK LİSANS TEZİ

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To my family,



FOREWORD

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ABBREVIATIONS

BECAS	: Beam Cross Section Analysis Software
BFGS	: Broyden- Fletcher-Goldfarb-Shanno Algorithm
CAD	: Computer Aided Design
CFRP	: Carbon Fibre-reinforced Polymers
GA	: Genetic Algorithm
QP	: Quadratic Programming
RCAS	: Rotorcraft Comprehensive Analysis System
SQP	: Sequential Quadratic Programming
UMARC	: University of Maryland Advanced Rotorcraft Code
UAV	: Unmanned Aerial Vehicle
VABS	: Variational Beam Sectional Analysis
VAM	: Variational Asymptotic Method
1D	: One Dimensional
2D	: Two Dimensional
3D	: Three Dimensional



SYMBOLS

c	: Chord
f	: Equivalent Wetted Area
A	: Rotor Disk Area
C_P	: Coefficient of Total Power
C_{P_0}	: Coefficient of Profile Power
C_{P_i}	: Coefficient of Induced Power
C_{P_p}	: Coefficient of Parasite Power
C_T	: Coefficient of Thrust
D	: Diameter
N_b	: Number of Blades
F_C	: Centrifugal Force
P	: Total Power
P_0	: Profile Power
P_i	: Induced Power
P_p	: Parasite Power
V_∞	: Free-stream Velocity
C_{d_0}	: Drag Coefficient Zero lift
C_{l_α}	: Lift Curve Slope
ρ	: Density
κ	: Induced Power Factor
Ω	: Rotor Speed
σ	: Rotor Solidity
θ	: Blade Twist
λ	: Induced Inflow Ratio
μ	: Advance Ratio
ω_i	: Natural Frequency
n/rev	: Rotor Harmonics



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BLADE OPTIMIZATION OF UNMANNED HELICOPTER FOR VARIABLE ROTOR SPEED

SUMMARY

Helicopter unmanned aerial vehicle systems are preferred in many areas due to their vertical landing, take-off and hovering capabilities. In addition, manned helicopters are converted to unmanned systems and used for activities such as cargo and surveillance. Helicopter rotor systems operate at a constant rpm and change the angle of the blades to create the required forces and moments. However, operating the rotor at the ideal speed for the flight condition is one of the concepts studied to increase performance and efficiency.

This thesis aims to improve the performance of a helicopter unmanned aerial vehicle rotor system with variable rotor speed and to optimize the rotor blade vibration in the determined rotor speed range. It is aimed to reduce the power required by reducing the speed of the rotor system. In addition, by creating an optimization process, it is aimed to avoid vibration problems due to reducing the rotor speed.

Within the scope of the thesis, first of all, literature research was carried out about variable rotor speed and rotor blade optimization. In line with the researches, it was decided to model the rotor blade with the Variational Asymptotic Method instead of using three-dimensional elements in commercial finite element analysis software such as Ansys, Abaqus and Nastran. The Variational Asymptotic Method is used for the analysis of slender structures such as blades, rotor blades and wind turbines. This method, developed by Berdichevski, transforms a three-dimensional problem into a two-dimensional cross-sectional analysis and a one-dimensional nonlinear beam analysis problem. The modelling effort and computational cost are reduced by using this modeling method.

A finite element model of the blade cross-section was created to perform cross-sectional analysis for the rotor blade. In order to create the finite element model of the blade section, PreVABS input files were created using cross-section design parameters. In these input files, the section profile, geometric dimensions, material layout and material properties are defined. By using the input files prepared in this way, the section finite element model was obtained parametrically with the PreVABS software. This finite element model was solved with VABS software. As a result of the analysis with VABS, the cross-sectional mass and stiffness properties were calculated.

After the cross-sectional analysis, the rotor blade is modeled as a flexible beam with Dymore, a finite element based multibody dynamics software. In this study, a simple model was created with Dymore to be included in an optimization process. Only the blade is modeled as flexible, other components of the rotor are assumed as rigid. The dominant force acting on the rotor blades is the centrifugal force. In addition, with

the increase in rotor speed, the centrifugal force also increases, causing the natural frequencies to change. The blade natural frequencies should be calculated in the rotor operating speed range. In this direction, the variation of natural frequencies according to rotor speed should be examined by creating a fan diagram. Centrifugal force was applied to the blade flexible beam model created with Dymore in 10% increments, and natural frequencies were obtained according to the rotor speed and a fan diagram was created. Thus, the rotor blade analysis was carried out in two stages by cross-section and beam analysis.

The main objective of this study is to increase the performance by changing the rotor speed. For this purpose, the rotor power required should be calculated. In this study, rotor power equations derived from the blade element momentum theory are used to estimate the rotor power. Using these equations, rotor power estimation was performed under different load and forward flight speed conditions.

By reducing the rotor speed, the drag force of the rotor profile can also be reduced. However, as the rotor speed decreases, the lifting force also decreases. The angle of attack of the blades can be increased to provide the required lifting force. However, the increase in angle of attack is limited due to the stall limit of the blade. To avoid stall, reduction of rotor speed should be limited and the flight conditions should be determined to be applied reduced rotor speed. In this study, considering the torque and power curve of the engine, it was decided to limit the reducing of the rotor speed by 20%. In this study, it is assumed that the rotor system will operate at two different rotor speeds, which are the baseline rotor speed and 20% reduced rotor speed. In this direction, power required calculations were carried out for both the baseline rotor speed and the reduced rotor speed. Calculations were performed under different gross weight and forward flight speed conditions to determine the flight conditions which reduced rotor speed is applicable.

According to the power estimation results, the flight conditions in which the rotor speed can be reduced by 20% have been determined. It is concluded that reducing the rotor speed is not applicable in low and high speed forward flight conditions. However, it has been observed that the power required can be reduced by reducing the rotor speed in the cruising speed condition. It has also been observed that as the gross weight increases, reduced rotor speed can be applied in a more limited range of flight speeds. When the percentages of the power required reduction is examined, it is observed that it is the highest at low gross weight and cruising speed. As a result, in this flight condition, it is possible to reduce the power required by about 10% by reducing the rotor speed by 20%.

In the final stage, it is aimed to reduce vibrations by creating an optimization process. There are different approaches to reduce vibration in rotors. In rotor optimization studies, it is aimed to reduce vibration by reducing the forces and moments on the rotor hub or by tuning the natural frequencies. In this thesis, it is aimed to calculate natural frequencies and separate them from rotor excitations in the optimization process.

Sequential Quadratic Programming(SQP), which is a gradient-based algorithm, was preferred as the optimization algorithm. By choosing a gradient-based algorithm, it is aimed to reach the result quickly and with low computational cost. SQP requires low

number of function calculations than other gradient-based algorithms. The gradient of functions were calculated numerically by using finite difference method.

The optimization aim was determined as increasing the difference between natural frequencies and rotor operating frequency multiples (rotor harmonics). For this purpose, the difference between each natural frequency and the closest rotor harmonic is calculated. The smallest of these differences is defined as the optimization objective function. In this study, the objective function and constraints are calculated for both baseline and 20% reduced rotor speed.

Geometric properties and location of the nonstructural mass were used as optimization design variables. The cross-section dimensions, spanwise and chordwise location of the nonstructural mass are defined as the design variable. Bounds are defined for these design variables, taking into account the geometric limits. In addition, constraints for optimization are defined. Centrifugal force and non-structural mass are constrained to satisfy performance and structural strength criteria with optimized blade design. In addition, optimized blade design, a constraint is defined for the difference between the natural frequencies and it is aimed to avoid undesired vibrations due to coupling of natural frequencies.

As a result of the optimization, the difference between the blade natural frequencies and rotor harmonics has been increased by about 48%. In addition, the nonstructural mass and centrifugal force are also reduced. According to the result of the optimization, optimized design have better vibration and performance characteristic than baseline rotor blade design.



DEĞİŞKEN ROTOR HIZI İÇİN İNSANSIZ HELİKOPTERİN PALA OPTİMİZASYONU

ÖZET

İnsansız hava araçları, uygulama alanları ve kabiliyetleri bakımında son yıllarda hızlı bir gelişim göstermektedir. Dikey iniş kalkış ve askıda kalabilme kabiliyetleri sebebiyle helikopter insansız hava aracı sistemleri pek çok alanda tercih edilmektedir. Ayrıca, mevcut helikopterler de insansız sistemlere dönüştürülüp, kargo ve gözetleme gibi faaliyetler için kullanılmaktadır. Helikopter rotor sistemleri, bir eksen etrafında dönen kanatlardan ve bu kanatların kontrol mekanizmalarından oluşmaktadır. Rotor sistemleri, sabit bir açısal hızda döner ve kanatların açılarını değiştirerek gerekli kuvvet ve momentleri oluşturur. Ancak, rotorun uçuş koşuluna göre ideal devirde çalışması, performans ve verimliliği artırmak için üzerinde çalışılan konseptlerdendir. Bu bağlamda, değişken rotor hızı konsepti ile rotor performansının geliştirilmesi amaçlanmaktadır. Rotorun devri azaldığında, rotor palaları üzerindeki dinamik basınçta azalmaktadır. Dinamik basıncın azalması ile profil sürüklenme kuvvetleri ve kaldırma kuvveti de azalmaktadır. Bu durumda, gereken kaldırma kuvveti, rotor pala hücum açısı artırılarak sağlanabilir. Profil sürüklenme kuvvetindeki azalışın ötürü rotor profil güç gereksiniminde de azalış olmaktadır. Rotor güç gereksinimindeki azalış, yakıt tüketimini düşürmektedir. Yakıt tüketiminin düşürülmesi sonucunda, menzil ve havada kalış süresi gibi performans özellikleri artmaktadır. Öte yandan, rotor hızının değiştirilmesi, rezonans ve istenmeyen titreşimlere sebep olabileceği için mevcut rotor tasarımları oldukça kısıtlı bir devir aralığında çalışabilir.

Bu tez çalışması, bir helikopter insansız hava aracı rotor sistemi için değişken rotor hızı ile performansının geliştirilmesini ve belirlenen rotor hızı aralığında rotor palasının titreşim bakımından en iyilenmesini amaçlamaktadır. Mevcut rotor sisteminin devrinin düşürülerek, güç gereksiniminin azaltılması hedeflenmiştir. Ayrıca bir optimizasyon döngüsü oluşturularak rotor devrinin değişmesi sonucu olacak titreşim sorunlarının önüne geçilmek istenmiştir.

Tez kapsamında, öncelikle değişken rotor hızı ve rotor pala optimizasyonu hakkında literatür araştırması yapılmıştır. Literatürde yapılan çalışmalar ve kullanılan yöntemler incelenmiştir. Yapılan araştırmalar doğrultusunda, rotor palasının Ansys, Abaqus ve Nastran gibi ticari sonlu eleman analizi yazılımlarındaki üç boyutlu elemanlar kullanılarak modellenmesi yerine Varyasyonel Asimptotik Metot ile modellenmesine karar verilmiştir. Varyasyonel Asimptotik Metot, kanat, rotor palası ve rüzgar türbini gibi ince ve uzun yapıların analizi için kullanılan yöntemdir. Berdichevski tarafından geliştirilen bu metot, üç boyutlu bir problemi, iki boyutlu kesit analizi ve bir boyutlu doğrusal olmayan kiriş analizi problemine dönüştürmektedir. Bu modelleme yöntemi kullanılarak, hem model oluşturmak için harcanan çaba hem de gereken hesaplama maliyeti azaltılmaktadır.

Rotor palası için kesit analizi gerçekleştirmek amacıyla pala kesitinin sonlu elemanlar modeli oluşturulmuştur. Pala kesitinin sonlu elemanlar modelini oluşturabilmek için kesit tasarım parametreleri kullanılarak, PreVABS girdi dosyaları oluşturulmuştur. Bu girdi dosyalarında, kesit profili, geometrik ölçüler, malzeme dağılımı ve malzeme özellikleri tanımlanmıştır. Böylelikle hazırlanan girdi dosyaları kullanılarak, kesit sonlu elemanlar modeli, PreVABS yazılımı ile parametrik olarak elde edilmiştir. PreVABS ile oluşturulan kesit modeli, VABS yazılımı ile çözdürülmüştür. VABS ile yapılan analiz sonucunda, kesit kütle ve direngenlik özellikleri hesaplanmıştır.

Kesit analizinden sonra, hesaplanan kesit direngenlik ve kütle özellikleri kullanılarak, rotor palasının bir giriş olarak modellenmesi gerekmektedir. Bu aşamada, sonlu elemanlar tabanlı çoklu cisim dinamik yazılımı olan Dymore ile rotor palası esnek bir giriş olarak modellenmiştir. Bu çalışmada, oluşturulacak olan rotor modeli, bir optimizasyon döngüsüne dahil edileceği için basit bir model oluşturmaya gayret gösterilmiştir. Dymore ile sadece pala esnek olarak modellenmiş, rotorun diğer elemanları katı olarak kabul edilmiştir. Rotor palalarına etkiyen kuvvetlerden baskın olan, merkezkaç kuvvetidir. Ayrıca, rotor devrinin artması ile birlikte merkezkaç kuvveti de artarak, doğal frekansların değişmesine neden olmaktadır. Pala doğal frekans değerlerinin, rotor çalışma hızı aralığında hesaplanması gerekmektedir. Bu doğrultuda doğal frekansların, rotor hızına göre değişimi fan diyagramı oluşturularak incelenmelidir. Dymore ile oluşturulan pala esnek giriş modeline, merkezkaç kuvveti% 10 artışlarla uygulanarak, rotor devrine göre doğal frekanslar elde edilmiş ve fan diyagramı çizdirilmiştir. Bu çalışmada, hem aerodinamik kuvvetlerin etkisi, merkezkaç kuvvetine göre az olduğu için modele dahil edilmemiştir. Böylelikle rotor palası, kesit ve giriş analizi ile iki aşamalı olarak çözülmüştür.

Bu çalışmanın ana hedefi olan, rotor hızının değiştirilerek performansın artırılması amacına yönelik olarak, rotor güç gereksiniminin hesaplanması gerekmektedir. Bu kapsamda, rotor gücünü tahmin etmek amacıyla pala elemanı momentum teorisi ile türetilen rotor güç denklemleri kullanılmıştır. Bu denklemler kullanılarak, farklı yük ve ileri uçuş hızı koşullarında, rotor güç tahmini gerçekleştirilmiştir.

Rotor devri azaltılarak, rotor profil sürüklenme kuvveti de azaltılabilmektedir. Ancak rotor devrinin azalması ile birlikte kaldırma kuvveti de azalmaktadır. Gereken kaldırma kuvvetini sağlamak için palaların hücum açısı artırılabilir. Ancak hücum açısı artışı, pala üzerindeki hava ayrışması sebebiyle sınırlıdır. Bu sebeplerden ötürü rotor hızının düşürülmesi sınırlandırılmalı ve düşük rotor hızının uygulanabileceği uçuş koşulları belirlenmelidir. Bu çalışmada motorun tork ve güç eğrisi de dikkate alınarak, rotor devrinin en fazla %20 düşürülmesi kararlaştırılmıştır. Bu çalışmada, rotor sistemi için asıl rotor devri ve %20 azaltılmış rotor devri olmak üzere iki farklı rotor devrinde çalışacak kabulü yapılmıştır. Bu doğrultuda hem asıl rotor devri hem de %20 düşürülmüş rotor devri için güç hesaplamaları yapılmıştır. Düşük rotor hızının, uygulanabilir olduğu uçuş koşullarını belirlemek için farklı yük ve ileri uçuş hızı koşullarında hesaplamalar gerçekleştirilmiştir.

Yapılan güç tahmini sonuçları doğrultusunda, motorun üretebildiği güç değerleri de göz önünde bulundurularak, rotor devrinin %20 düşürülebileceği uçuş koşulları belirlenmiştir. Bu bağlamda, rotor hızının düşürülmesinin, düşük ve yüksek ileri uçuş koşullarında, uygulanabilir olmadığı sonucuna varılmıştır. Ancak, seyir hızı

koşulunda, rotor devrinin azaltılarak, güç gereksiniminin azaltılabileceği görülmüştür. Ayrıca, yük arttıkça düşük rotor devrinin daha kısıtlı bir uçuş hızı aralığında uygulanabileceği görülmüştür. Rotor devrinin azaltılması ile güç gereksiniminin oransal olarak düşürülmesi incelendiğinde, düşük yük ve seyir hızında en fazla olduğu gözlemlenmiştir. Sonuç olarak, bu uçuş koşulunda, rotor hızının %20 düşürülmesi ile güç gereksinimi yaklaşık %10 düşürmek mümkündür.

Son aşamada, bir optimizasyon döngüsü oluşturularak titreşimlerin azaltılması amaçlanmıştır. Rotorlarda titreşim düşürmek için farklı yaklaşımlar bulunmaktadır. Rotor optimizasyon çalışmalarında, rotor başına gelen kuvvet ve momentleri düşürerek veya doğal frekansları düzenleyerek titreşimi düşürmek hedeflenmektedir. Bu tez çalışmasında da optimizasyon sürecinde doğal frekansların hesaplanması ve rotor uyarılarından ayrıştırılması amaçlanmıştır.

Optimizasyon algoritması olarak gradyan tabanlı bir algoritma olan SQP tercih edilmiştir. Gradyan tabanlı bir algoritma tercih edilerek hızlı ve düşük hesaplama maliyetiyle sonuca ulaşmak amaçlanmıştır. SQP gradyan tabanlı algoritmalar içinde düşük fonksiyon hesaplama sayısı ile öne çıkmaktadır.

Optimizasyon amacı, doğal frekanslar ile rotor çalışma frekansı katları (rotor harmonikleri) arasındaki farkın artırılması olarak belirlenmiştir. Bu amaca yönelik olarak, her doğal frekans ile en yakın rotor çalışma frekans katı arasındaki fark hesaplanmıştır. Bu farkların en küçük olanı, optimizasyon amaç fonksiyonu olarak tanımlanmıştır. Bu çalışmada, amaç fonksiyonu ve kısıtlamalar hem asıl rotor devri hem de %20 düşürülmüş rotor devri için hesaplanmıştır. Böylelikle, rotor hızı düşürülerek performansı geliştirilmiş rotor için mevcut titreşim karakteristiği geliştirilmiştir.

Optimizasyon tasarım değişkenleri olarak, pala yapısal olmayan kütlelerin geometrik ve konum özellikleri kullanılmıştır. Bu kapsamda, yapısal olmayan kütlelerin kesit ölçüleri, veter ve rotor yarıçapındaki konumu, tasarım değişkeni olarak tanımlanmıştır. Bu tasarım değişkenleri için geometrik sınırlar göz önünde bulundurularak sınırlar tanımlanmıştır. Ayrıca, optimizasyon için kısıtlamalar tanımlanmıştır. Optimizasyon sonucunda elde edilecek tasarımın, mevcut pala tasarımına göre daha kötü performans ve yapısal dayanıma sahip olmaması için merkezkaç kuvveti ve yapısal olmayan kütle sınırlandırılmıştır. Ayrıca, optimizasyon sonucu elde edilen pala tasarımında, doğal frekansların birbirleri arasındaki fark için kısıtlama tanımlanarak, doğal frekansların birbirleri ile etkileşiminden ötürü oluşabilecek istenmeyen titreşimleri önlemek amaçlanmıştır.

Optimizasyon sonucunda, pala doğal frekansları ile rotor harmonikleri arasındaki fark yaklaşık %48 artırılmıştır. Ayrıca yapısal olmayan kütle ve merkezkaç kuvveti de düşürülmüştür. Bu sonuçlara göre, optimizasyon sonucunda, mevcut rotor pala tasarımına göre hem titreşim hem de performans bakımından daha iyi bir tasarım elde edilmiştir.



1. INTRODUCTION

Today, the use of unmanned aerial vehicles(UAV) is increasing rapidly with the development of electronics and communication systems. Unmanned aerial vehicles have been actively used in many different fields, both military and civilian. In recent years, the unmanned aerial vehicles are used more frequently in research and can be mentioned with different names as seen in Figure 1.1 [1].

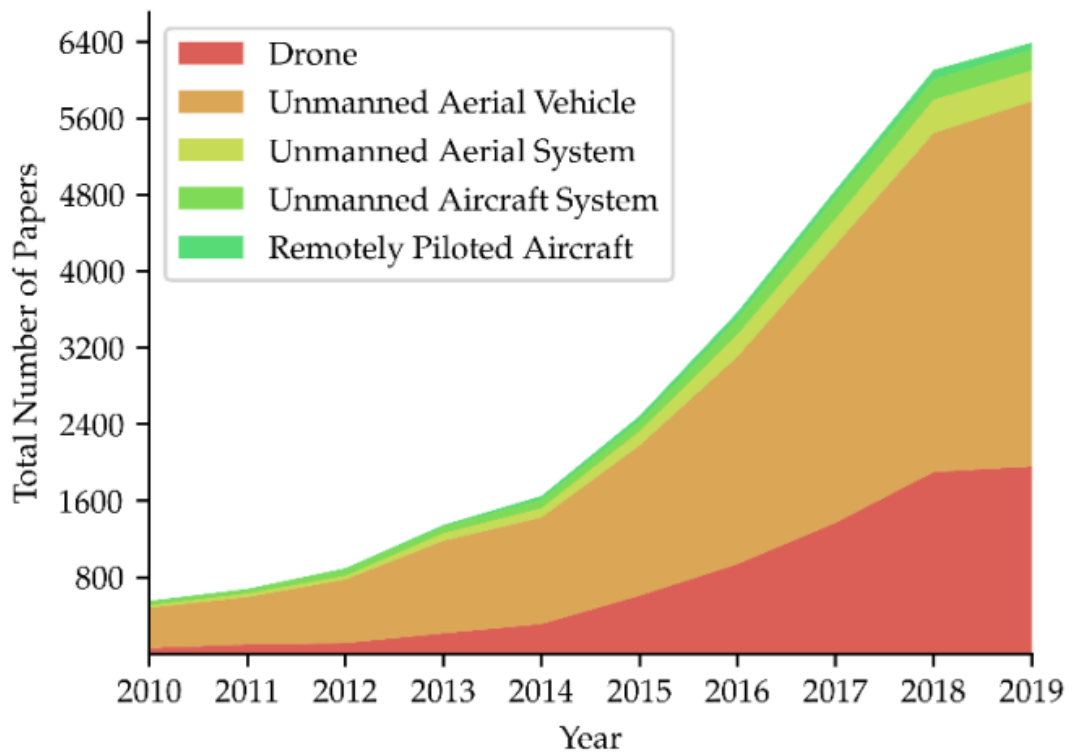


Figure 1.1 : Usage of different words that are used in literature for unmanned aerial vehicles [1].

The UAV systems can be classified fixed-wing or rotary-wing platforms. The fixed-wing or rotary-wing platform can also be divided subcategories because they can be in different configurations as seen in Figure 1.2. In different applications, fixed or rotary wing platforms can be preferred due to their advantages.



Figure 1.2 : Unmanned aerial vehicle configurations [2].

Rotary wing UAVs or unmanned helicopters have a wide range of applications such as cargo delivery and surveillance, as they have vertical take-off and landing capability and the ability to hover. For these different purposes, rotary wing UAV systems can have different types and number of rotor configurations. The rotary wing UAVs can be helicopter or multi-copter type.

Unmanned helicopters can be developed by converting manned helicopters. Figure 1.3 shows the Robinson R-22 helicopter, which is a manned helicopter, converted into an unmanned helicopter [3]. For this reason, unmanned helicopters can be analysed and designed using the same methods as manned helicopters.

The helicopter UAVs provide the forces and moments required for flying and control with the forces and moments produced by the rotors. These forces and moments are the aerodynamic forces created by the rotation of the blades in the rotor at a certain angle



Figure 1.3 : Unmanned Robinson-22 helicopter [3].

and angular speed. In this way, helicopters can generate aerodynamic forces and fly while hovering or at different flight speeds. Helicopters control the angle of the blades to achieve the desired force equilibrium. However, in the variable rotor speed concept, which is one of the concepts studied to improve the performance of helicopters today, it is aimed to change not only the angle of the rotor blades but also the rotor speed [4].

Rotor systems are constantly operating at high speeds, so their dynamic characteristics are important. Rotor systems are generally designed to operate at a constant speed, and the dynamic properties at this speed are taken into account. At this rotor operating speed, the absence of resonance in the rotor is an important design criterion. With the variable rotor speed concept, it is necessary to avoid vibration problems in case the rotor speed is changed during flight. For this purpose, the dynamic behavior of the rotor at different speeds should be examined by creating a fan diagram.

1.1 Literature Review

In this thesis, variable rotor speed and rotor blade optimization were focused as the main points and these were included in the literature review section.

1.1.1 Variable rotor speed

Karem [5] revealed the effect of variable rotor speed on rotor performance with his patent called optimum speed rotor. The advantages and effects of variable rotor speed are advocated and illustrated.

Miste [6] has developed codes to calculate helicopter performance and to simulate turbo-shaft engine. Using these codes, the variable speed rotor concept has been studied on the UH-60 helicopter. It was aimed to reduce fuel consumption and for this purpose, ideal rotor speed was determined according to the flight condition. With the determined ideal speeds, the power required could be reduced as in Figure 1.4. In this context, studies were carried out in two different concepts, in which the engine speed was changed and the transmission ratio was changed.

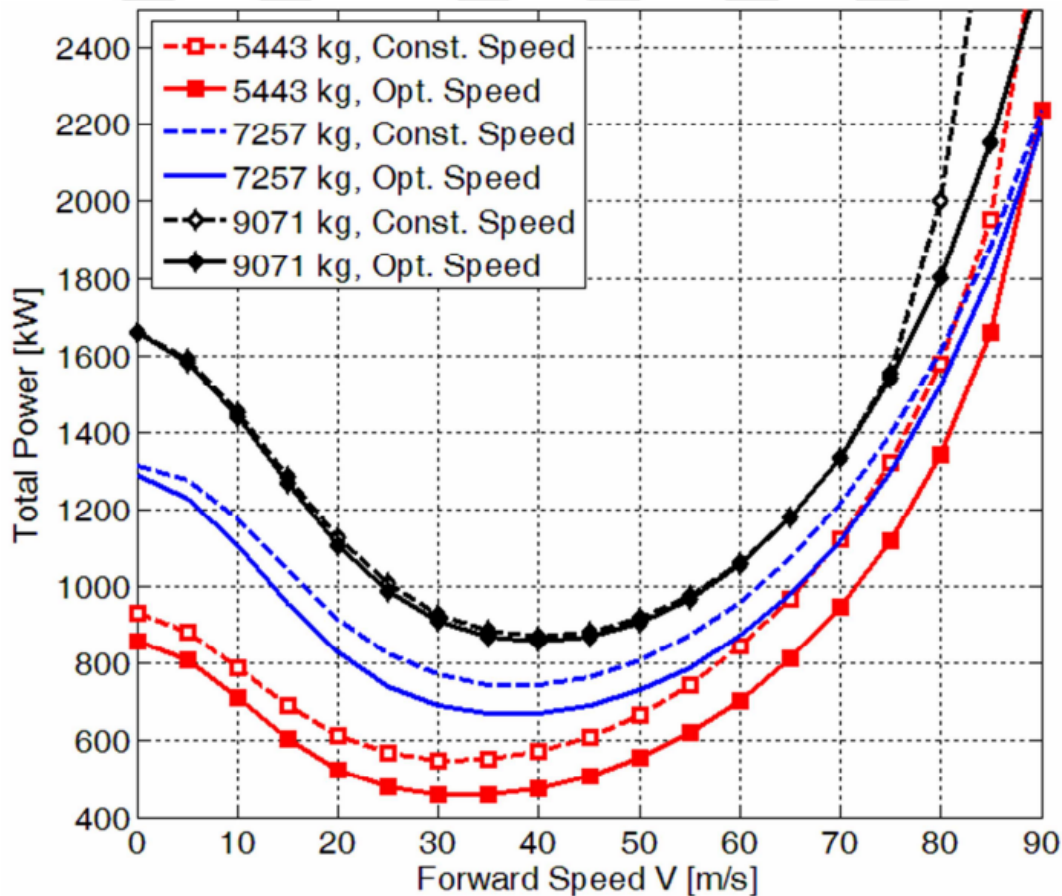


Figure 1.4 : Total power for different gross weights and rotor speed [6].

Mistry and Gandhi [7] investigated the effect of rotor speed and diameter variation on helicopter performance in their study. In their study, it is aimed to reduce the rotor

required power. It is determined that different flight conditions with altitude, weight and speed. The effect of rotor speed and diameter examined in these conditions. In their research, a four-blade articulated rotor system model is used, assuming the rotor blades as rigid for analysis. They agreed that rigid blade model is sufficient because the aim of this research is on rotor power improvements and not rotor strength. As a result of the study, it is concluded that reducing the rotor speed effectively reduces the power requirement under the condition of low altitude, low gross weight and cruise speed. However, in low speed condition, they found that the reduction in power requirement was limited with increasing altitude and gross weight. In the low-weight condition, the power can be reduced by decreasing the rotor speed, as in Figure 1.5. They concluded that significant power reductions at low and medium gross weight, low altitude, and cruise speed, with only the change in rotor speed, can also be achieved at higher altitudes and in a wider range of velocity by using the change in rotor radius and speed.

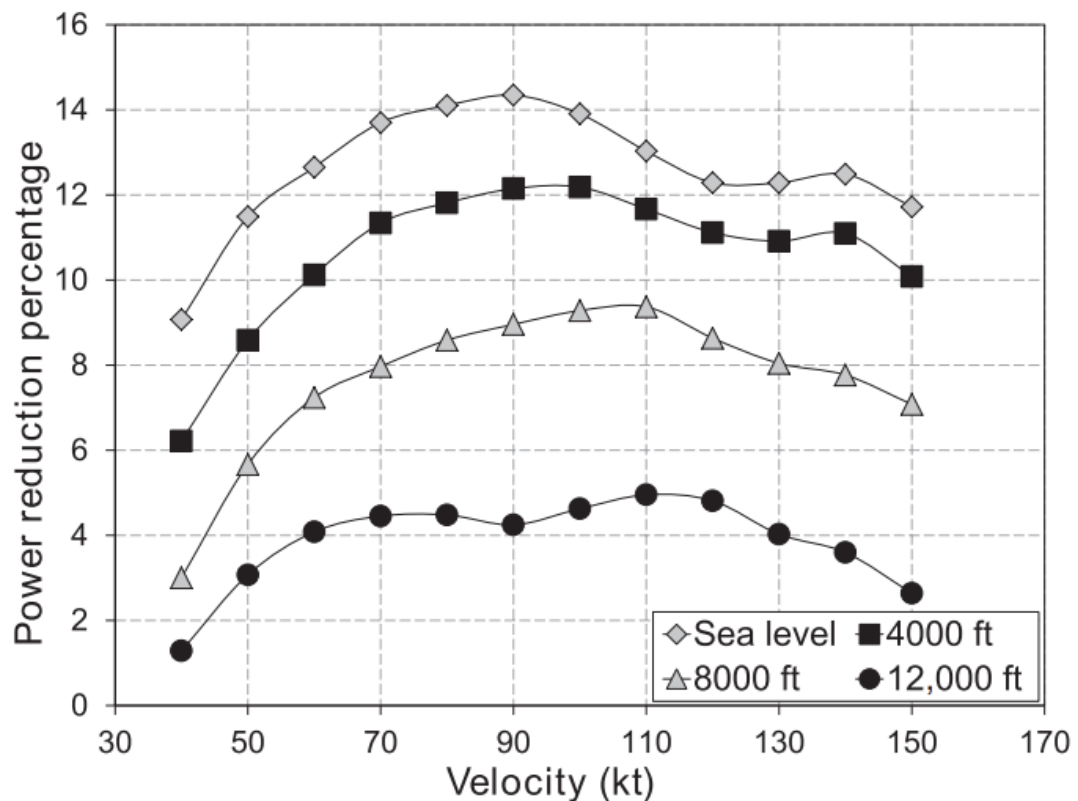


Figure 1.5 : Power reduction with variable rotor speed [7].

Bowen-Davies [4] evaluated the effects of rotor radius or rpm change on the rotor up to high advance ratios. For this purpose, using the UMARC code, comprehensive analysis of the UH-60 rotor model were performed and discussed in terms of vibration, aerodynamics and performance. As a result of the analysis, it was concluded that when the rpm is decreased and the torque on the rotor is increased, a decrease in power is obtained. When rotor speed and trim are applied for minimum power, the torque increase is obtained as in Figure 1.6. In addition, it has been observed that the vibrations and the acting forces on the rotor increase with the decrease of rotor speed.

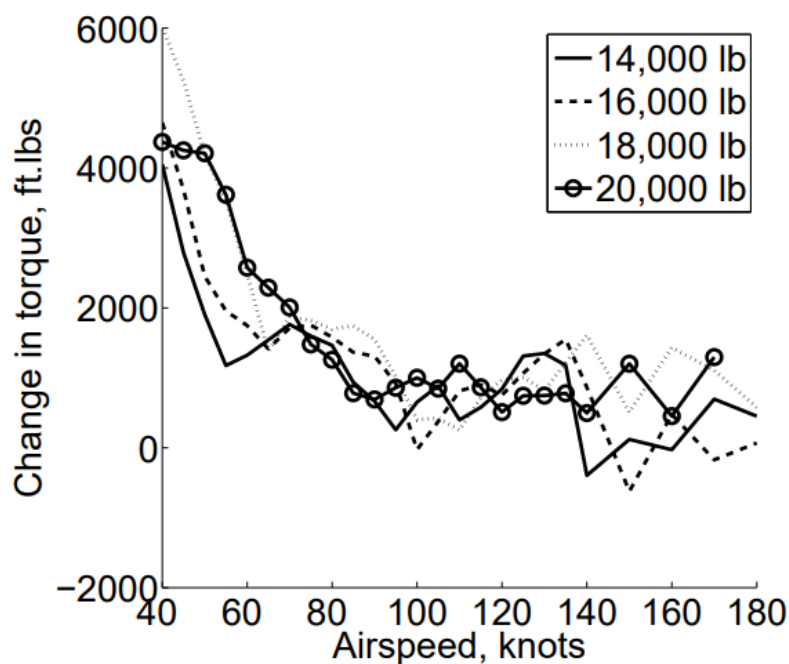


Figure 1.6 : Change in torque with variable rpm [4].

Han et al. [8] studied the effects of variable blade twist and rotor speed on performance parameters. In the study, research was carried out on the improvement of the performance of these two concepts of the helicopter. Calculations were made with two different aerodynamic models, empirical and computational. In the analysis results, it was obtained that as long as the forward speed is not too high, the required power can be reduced by reducing the rotor speed. It has been calculated that the reduction in required power can be increased by the variation of blade twist with rotor speed. However, rotor speed was found to be more effective as in Figure 1.7. On the other

hand, it has been seen that variable twist can be used to reduce the load on the rotor blade with variable rotor speed applied.

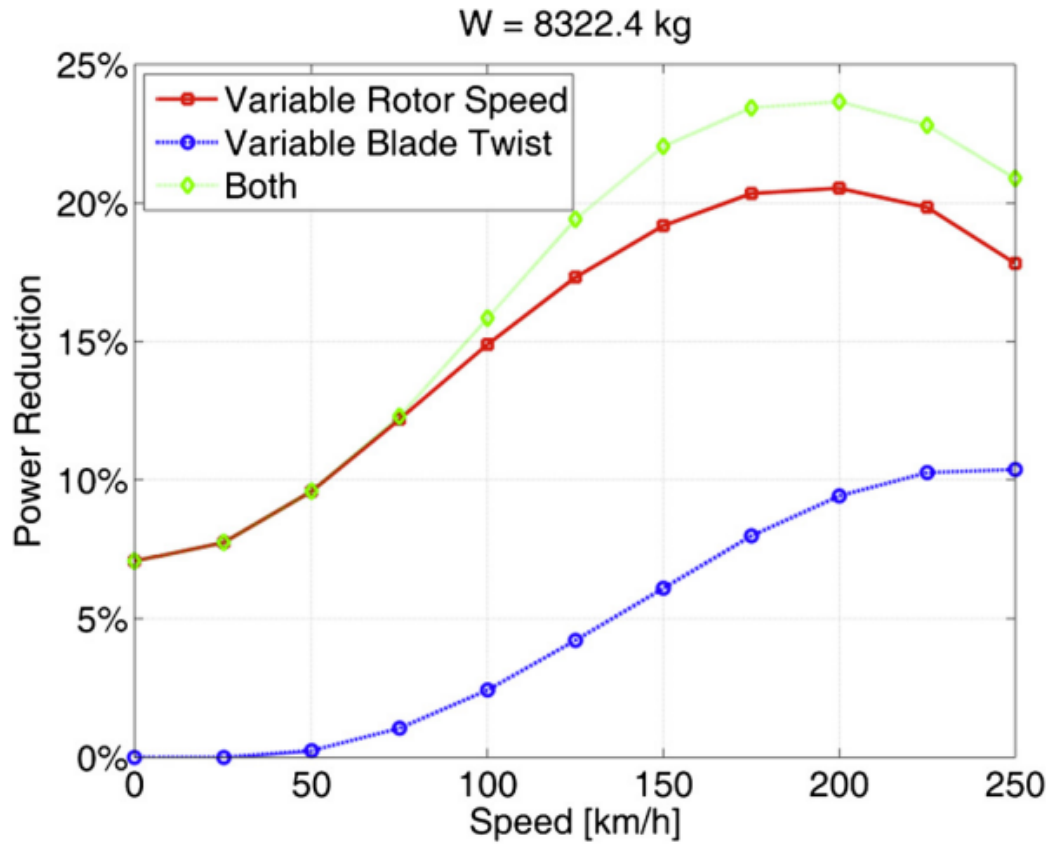


Figure 1.7 : Power reduction with variable twist or rotor speed [8].

Dibble [9] aimed to prevent vibration problems that may occur due to variable rotor speed in his thesis. In order to prevent vibration and resonance problems, the application of compression force to the blade was investigated. In this context, he examined the relationship between the natural frequencies of rotor blade and its resonance behavior with the compression force. In the study, models with different fidelity were established and the effect on the calculations was also observed. Also, the effect of compression force on damping was observed. The influence of the compression force on the vibration response of the rotor blade can be improved, as in the example in Figure 1.8. With this study, it has been concluded that the application of compression force will make the application of variable rotor speed more convenient with its effect on natural frequencies and damping.

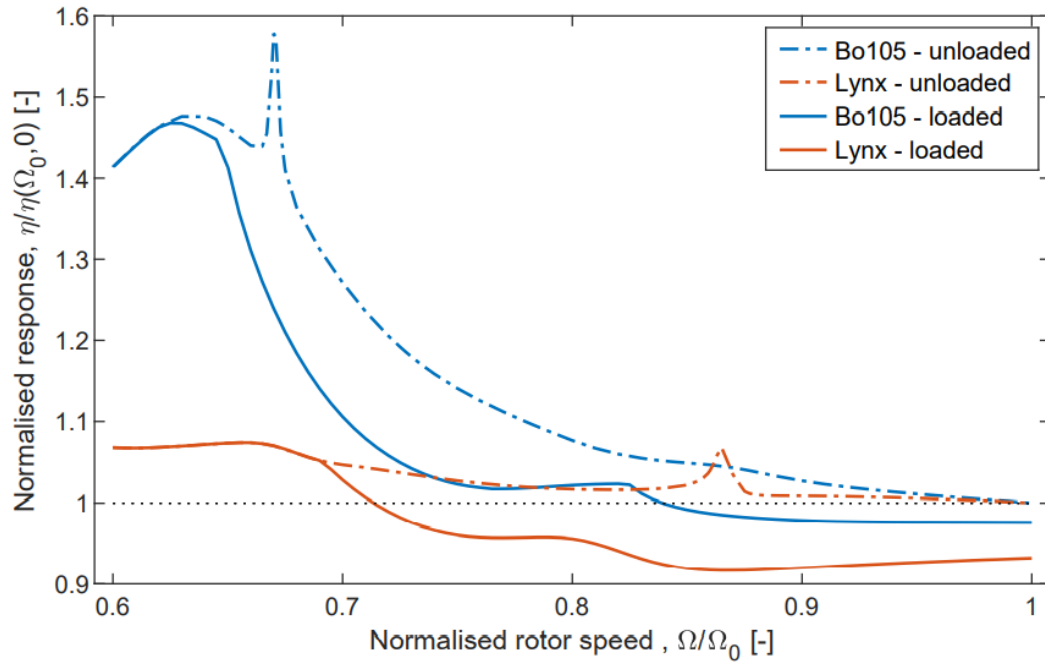


Figure 1.8 : Effects of the rotor speed and compression load on blade response [9]

1.1.2 Rotor blade analysis and optimization

Friedmann and Shanthakumaran [10] studied on optimizing rotor blades for a helicopter in the forward flight condition. They created and applied the optimization process for rotor blade. Nonstructural mass and spar properties were used as design variables for the optimization process. They defined natural frequencies as optimization constraints. In addition, aeroelastic stability was also used as a constraint. With the optimization, the forces and moments at the rotor head were calculated and they aimed to minimize the maximum values of their obtained force results. At the end of the study, they concluded that by tuning the natural frequencies, vibration can be reduced significantly. The benefits of using non-structural mass have demonstrated for vibration reduction purposes. In addition, weight of the blade design they obtained as a result of optimization was lower than the baseline blade design.

Pritchard and Adelman [11] created an optimization cycle to minimize vibrations in the helicopter rotor. With this optimization process, they aimed to find the optimum tuning masses and locations that reduce vibration. For this purpose, the rotor blade is modeled as in Figure 1.9 by using beam elements with freedom to flap at its root. However,

lead-lag and torsion degree of freedoms in the root of the blade were restricted. Using the finite element model, dynamic analyses were performed and modal parameters were calculated. As a result of the optimization, they aimed to minimize both the shear in the root of the blade and the nonstructural mass in the blade. For this purpose, three different nonstructural masses and their positions were used as variables. CONMIN was used, which is a gradient-based algorithm, as an optimization algorithm.

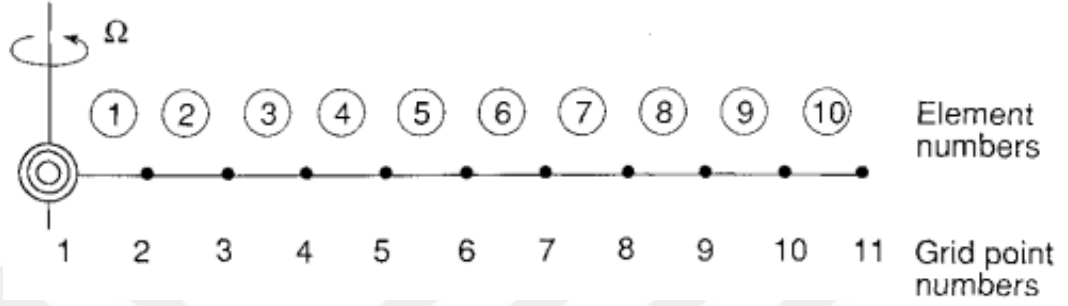


Figure 1.9 : Rotor blade finite element model [11].

Li et al. [12] have created an optimization loop with constraints on manufacturability and section properties for rotor blade optimization. In this optimization cycle, the geometric parameters of the section and the properties of the composite layers were used as variables. Cross-section parameters were calculated using VABS software for section analysis. Gradient-based and non-gradient-based two different methods are used together as algorithms for the optimization cycle. By using sequential quadratic programming as a gradient-based algorithm, the optimum region was reached quickly, and they obtained suitable results for generating with a non-gradient genetic algorithm. Additionally, the effectiveness of the design variables was investigated by sensitivity analysis.

Gündüz [13] studied on creating an automated design cycle instead of the traditional analysis and design cycle for rotors. With this study, it was aimed to reduce the time spent in the blade development process and the optimization process in Figure 1.10 was created. As the analysis method, firstly, the cross-section mass and stiffness matrices were calculated with VABS software. The multibody dynamic model of the rotor system was created using Dymore software, and modeled the blades with beam elements in this model. While creating these beam elements, cross-section matrices calculated with VABS were used. In addition, it has automated the creation

of a computer added design (CAD) model with CATIA. In this way, it has been avoided to spend time on drawing a model again for optimum design. The geometrical properties of the blade such as rotor radius and chord are also included in the study. Conjugate Gradient Method was used as the optimization process and an improvement was achieved in the blade design obtained as a result of the optimization.

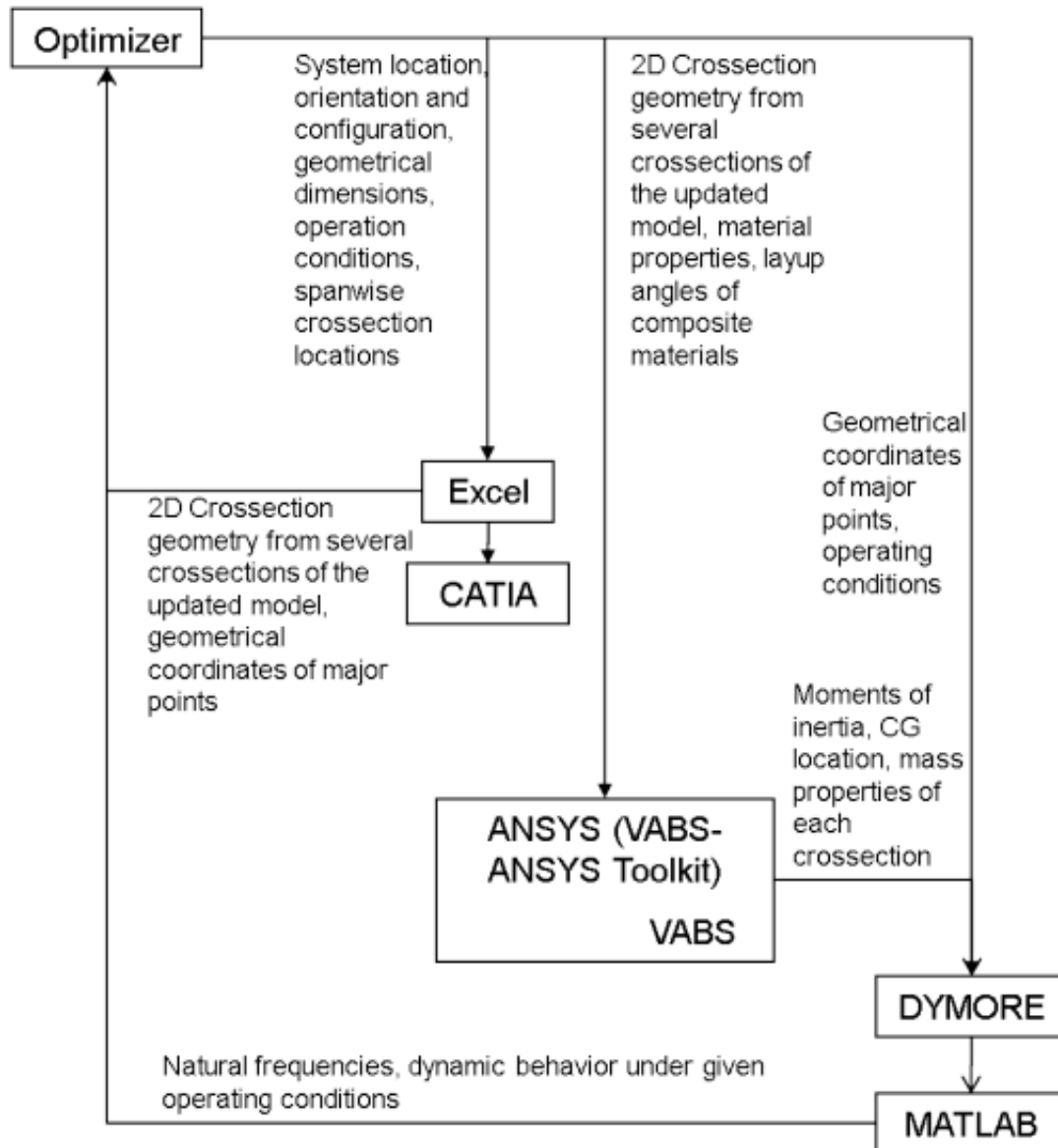


Figure 1.10 : Optimization loop [13].

Kumar [14] carried out an optimization study for rotor blades with both passive and active vibration control. Aeroelastic analyses were used in optimization studies and the optimization process was established as in Figure 1.11. Cross-section analyses

were performed with VABS and aeroelastic analyses were performed using RCAS. In these analyses, the forces and moments acting on the rotor center were calculated and aimed to minimize them. In the optimization, for this purpose, composite layer properties and non-structural mass properties are defined as variables. In addition, the Efficient Global Optimization algorithm was preferred and maximum strain, torsional frequency, center of gravity, mass per unit length and shear center were defined as constraints. The created optimization cycle was applied to the widely used UH-60 helicopter and the forces of vibration sources could be reduced by optimization.

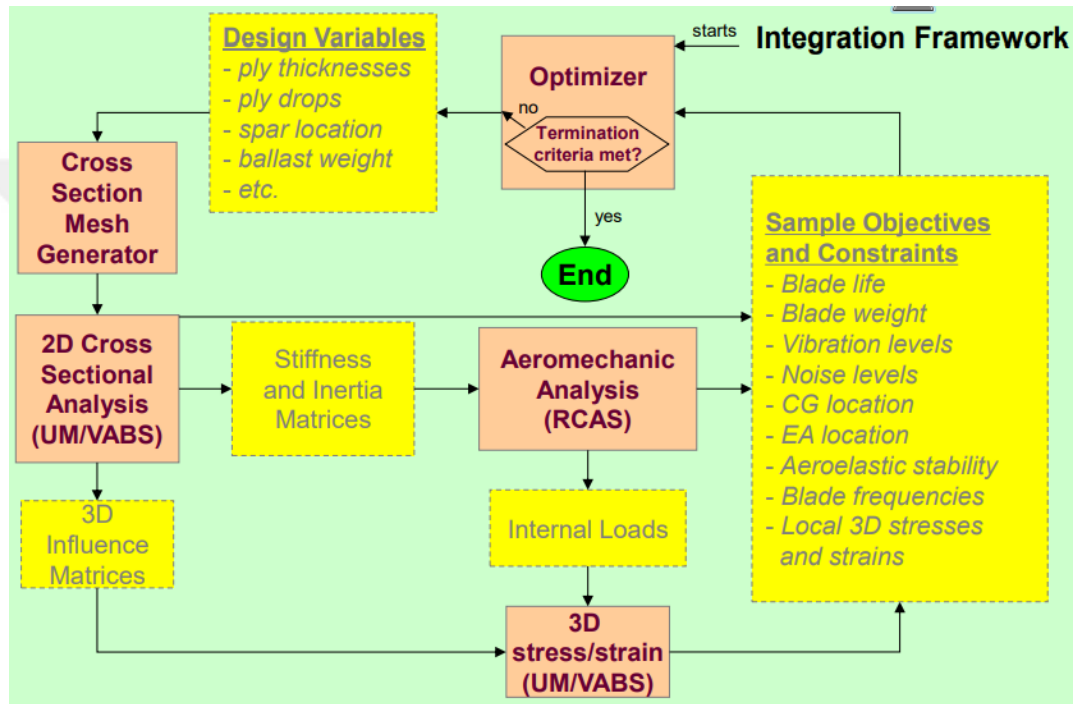


Figure 1.11 : Optimization process for rotor blade
Optimization process for rotor blade [14].

Taymaz [15] carried out a helicopter optimization study for the forward flight condition. In the thesis study, the reduced vibration formula was used to examine the vibration. Optimization has been carried out to minimize the resultant force calculated with the reduced vibration formula. For this purpose, spar and composite layer properties were used as variables. Using VABS and Dymore software, analyses were performed, and Tsai-Hill was chosen as the composite failure criteria and defined as a constraint. The natural frequencies and autorotation were calculated analytically and their values were also used as constraints. For the optimization algorithm,

gradient-based and non-gradient algorithms were combined and used. By applying optimization process to the UH-60 helicopter, vibrations in the rotor are reduced.

1.2 Motivation of the Thesis

The main purpose of this thesis is to improve the performance of an unmanned helicopter. For this purpose, it is aimed to improve the performance of the rotor system by applying variable rotor speed concept. In the concept of variable rotor speed, it is possible to improve performance parameters by applying different rotor speeds according to the flight condition. Accordingly, in some flight conditions, the required power can be reduced by reducing the rotor speed. However, in current helicopters, turbo-shaft engines are generally used. These turbo-shaft engines are designed to operate effectively in a restricted rev range. However, unmanned helicopters with internal combustion engines are suitable for the application of this concept. In this thesis, this variable rotor speed concept will be applied to an unmanned helicopter with an internal combustion engine. Thus, it is aimed to decrease the rotor and engine speed of the unmanned helicopter and reduce the required power.

The variation of rotor speed changes the structural dynamic characteristic of the blade. The blade has different dynamic properties at different rotor speeds. The change in these dynamic properties can cause vibration problems. The aim of this thesis is to minimize these disadvantages that arise as a result of the change in rotor speed. As a result of optimization, it is aimed that to make this concept applicable. For this purpose, the other aim of the thesis is to create an optimization cycle, to optimize the blade in terms of vibration and to avoid undesired vibrations that may occur as a result of rotor speed change. Thus, as a result of this study, it is desired to make it possible to change the rotor speed and improve performance of unmanned helicopter.

1.3 Structure of Thesis

In the first chapter of this thesis, first of all, a general introduction is made. The literature research on variable speed rotor and rotor blade optimization is included in this section. In the following, the motivation of the thesis is mentioned.

Chapter 2 covers the modeling methods used in this thesis. In this context, the theory of modeling methods is mentioned. The software used in the thesis study and the capabilities of these software are given. In addition, the method used for optimization is also explained in this chapter.

In Chapter 3, firstly, the theory of helicopter performance calculations is explained. In this context, the power estimation of the helicopter in hover and forward flight conditions is explained theoretically. In the second part of this chapter, power estimates are made for different payloads and forward flight conditions, and the results are shared. These power estimations for different rotor speeds are examined and flight conditions to which reduced rotor speed will be applied are determined.

Chapter 4 describes the optimization framework established in the thesis for vibration reduction. The design variables, constraints, and objective function of the optimization are explained. Afterwards, the optimization results are given and compared with baseline design.

In the last chapter, the thesis is summarized and evaluated in general. The obtained achievements and disadvantages of the methods in this study are discussed. Finally, recommendations for future studies are given.



2. METHODOLOGY

2.1 Modelling of Rotor Blade

Modern helicopters have rotor blades that take advantage of different materials. In modern rotor blades, different materials are used together, mostly composite materials. In addition, helicopter blade designs have complex designs as in Figure 2.1 [16] due to both variety of material and geometry. The use of composite materials has led to an increase in blade design parameters and simulation studies. The fact that composite materials have design parameters such as stacking, fiber direction and number of layers has also increased the optimization studies [15,17,18].

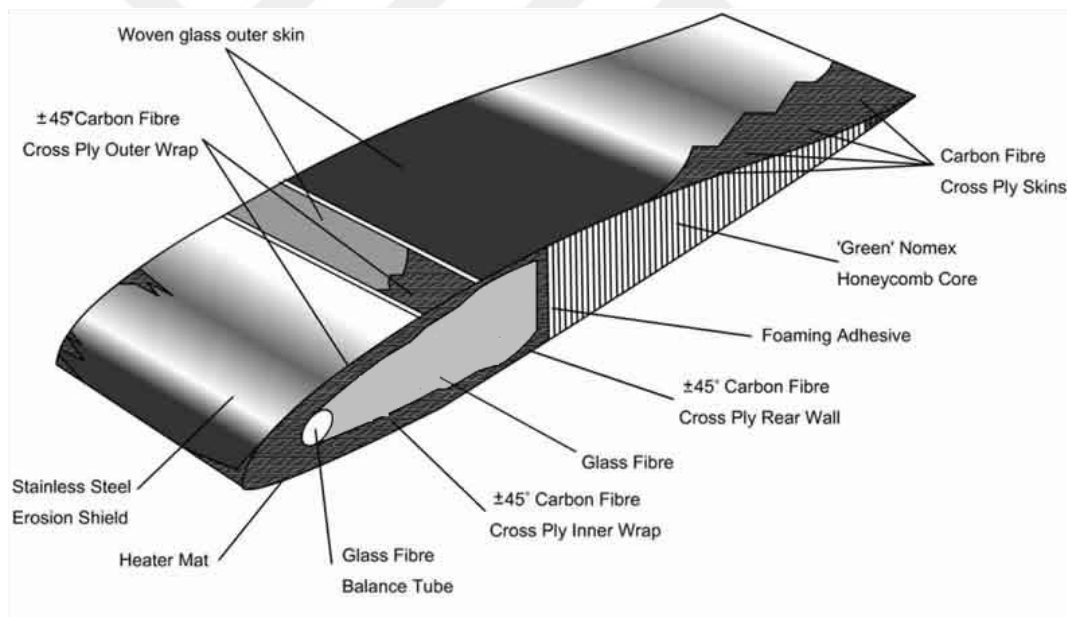


Figure 2.1 : Typical composite rotor blade [16]

The structure of the rotor blades is long and thin to provide sufficient aerodynamic efficiency and performance. As can be seen in the example blade geometry in Figure 2.2 , they have high aspect ratio. The cross-section of the rotor blades is in the form of an airfoil and the thickness of the airfoils is small.

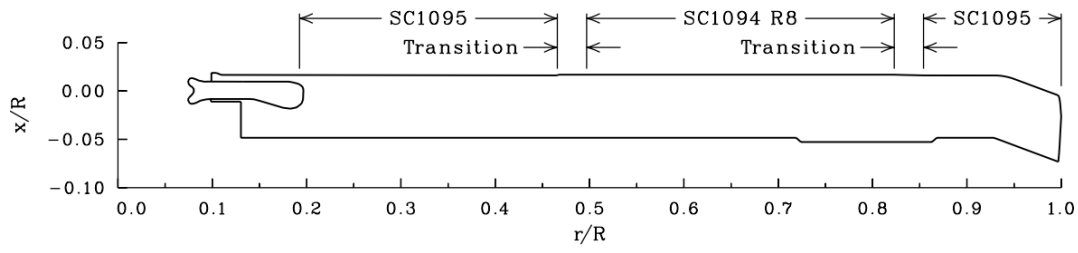


Figure 2.2 : UH-60 rotor blade geometry [19]

In particular, composite rotor blades have very small cross-section dimensions and layer thicknesses compared to their lengths. Due to these topological properties of rotor blades, it is very difficult to model with traditional 3D finite element analysis methods. Generally, slender structures such as rotor blades are modeled using beam elements. When this type of slender structures are modeled as beams, modeling difficulties due to cross-section are avoided, while maintaining accuracy. On the other hand, there are different difficulties in modeling rotor blades, which have composite anisotropic structure. When modeling composite rotor blades with beam models in commercial 3D fea codes, elastic couplings cannot be obtained correctly [20].

Berdichevski [21] developed a two-stage method called variational asymptotic method(VAM) for the analysis of beam-like structures such as rotor blades. With this method, a 3D structural problem can be solved by using linear 2D section analysis and 1D nonlinear beam analysis. The figure below shows the transformation of the problem into cross-section analysis and beam analysis problem.

In the first step, a cross-section finite element model is created and the cross-section stiffness and mass matrices are calculated. In the next step, the rotor blade is modeled with beam elements. When defining the beam for the rotor blade, the cross-section matrices which calculated in the previous step are used. Finally, dehomogenization is performed by taking the internal moments and forces obtained from the analyses with beam elements and applying them to the cross-section model. Thus, the stress and strain distribution in the cross-section can be obtained.

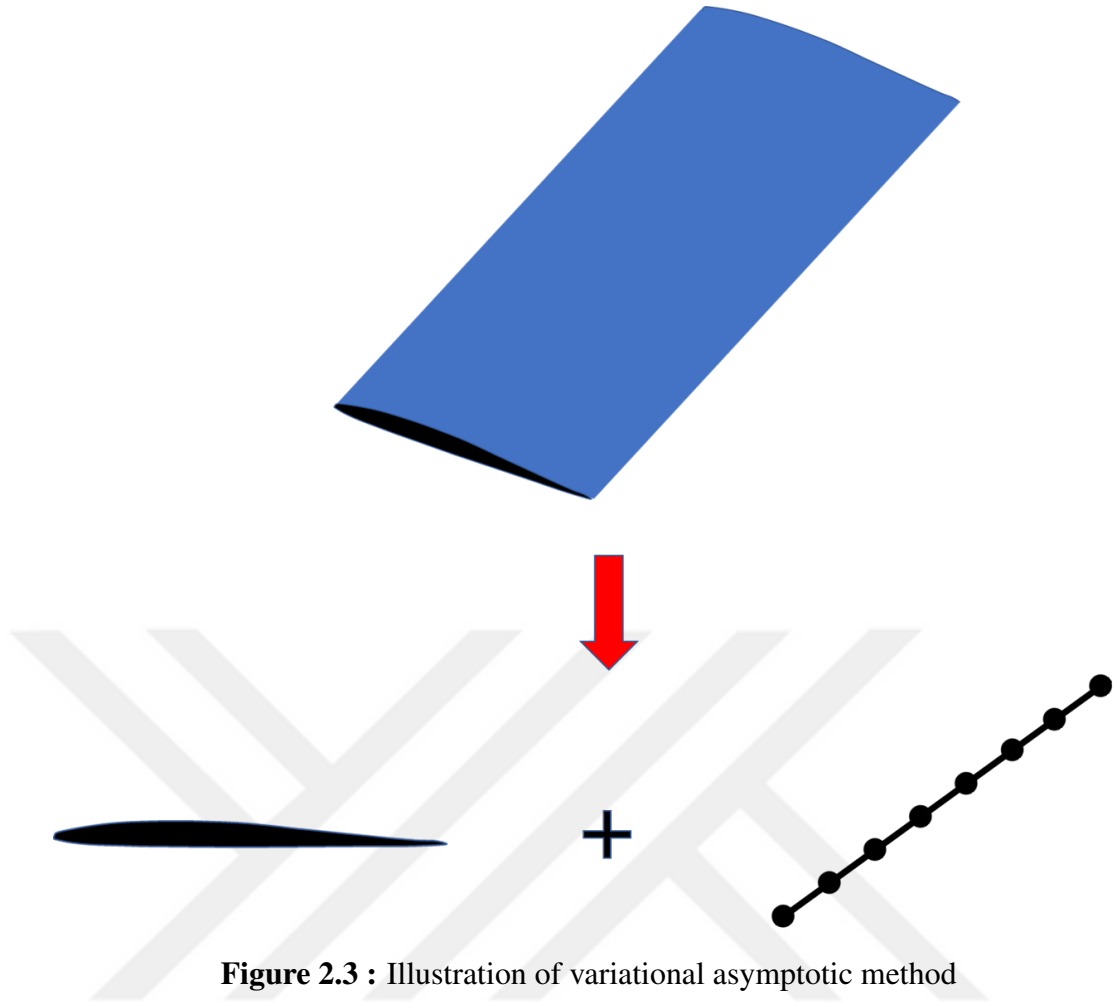


Figure 2.3 : Illustration of variational asymptotic method

2.1.1 Cross-sectional analysis

In order to model the rotor blade with the variational asymptotic method, first of all, 2D cross-section analysis should be performed. With this cross-section analysis, mass and stiffness matrices should be obtained. These calculated matrices will be used as input to the 1D beam analysis in the next step. Software such as BECAS, NuMAD/BPE, or VABS are available for cross-section analysis. In this thesis, VABS was preferred as the cross-section analysis solver due to its accuracy and efficiency advantages [20]. In addition, it was decided to use the PreVABS software developed for VABS for the cross-section finite element model required for VABS. Using PreVABS, it is possible to parametrically construct a cross-section finite element model for rotor blades [22].

2.1.1.1 PreVABS

PreVABS [22] is preprocessor software for VABS software. PreVABS is a software suitable for designs with complex composite section features such as wind turbine blade in Figure 2.4. With PreVABS, the time spent for design and optimization can be reduced by creating models parametrically. The model created with PreVABS can be used both for calculating the cross-section stiffness and mass matrices (homogenization) and for calculating the stress distribution in the section (dehomogenization) using the results of 1D beam analysis.

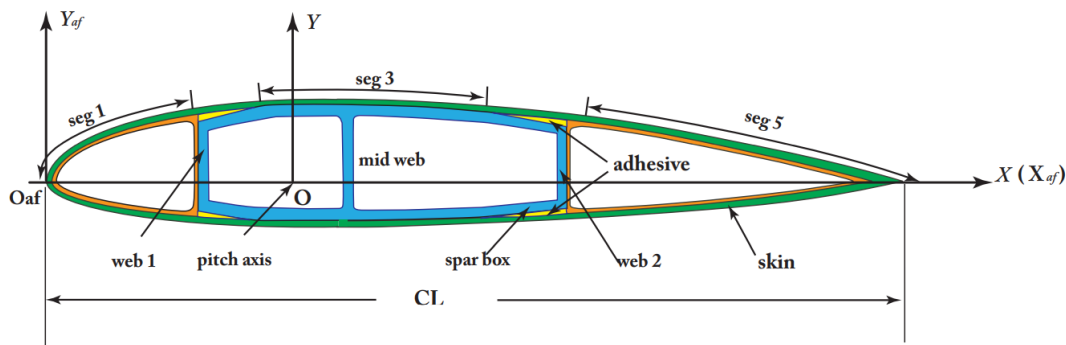


Figure 2.4 : Example layout of a blade cross-section [22].

PreVABS [23] software is a program that runs on the command line and can be run automatically. In order to create the section finite element model with PreVABS, first of all, input files must be created. One of these input files is required to create the geometry of the section. In addition to this geometry file, a separate input file can be created for the airfoil data. Second, an input file is created to define the layup of composites. Another input file is required to define material properties. Input files containing these generated geometry, material and layup information are called into a main input file.

This main input file is used to define the general properties of the cross-section and to combine all the input files. Analysis are performed by calling this main input file. In this main input file, the position, twist angle and size of the cross-section can be determined in the input file with the commands in figure 3. In addition

to these geometric parameters, mesh properties such as element type and size are determined. However, the PreVABS 1.4.3 version used in this thesis only allows the use of triangular elements [23].

In the input file created for the geometric features, first of all, the points required to define the section must be defined. These base points are the points that define the airfoil for the rotor blades and the points necessary to define the contours of the section. Using these points, the baselines are again determined in the geometry input file. PreVABS has the ability to create straight, circle and arc lines for baseline creation. The base points of the blade section are created as an example with the PreVABS parametric geometry input file in the figure below [23].

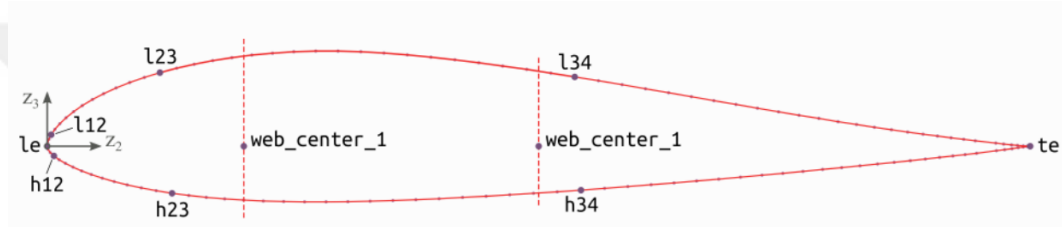


Figure 2.5 : Example base points for blade cross-section [23].

The baselines of example cross section can be created as in Figure 2.6.

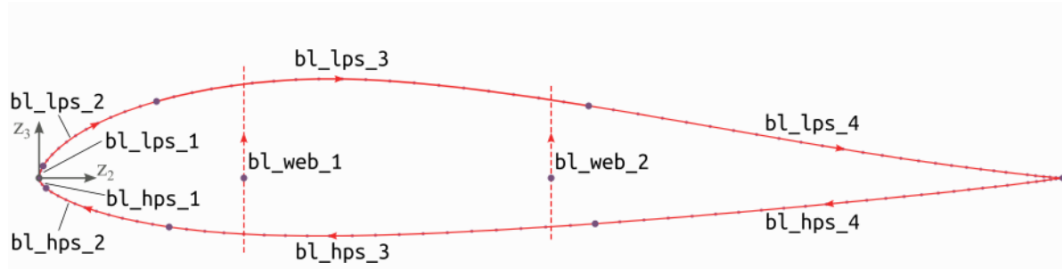


Figure 2.6 : Example baselines for blade cross-section [23].

In the material input file of PreVABS, the material and lamina properties can be defined. Density, elastic and strength properties of materials are defined in the material input file. Elastic properties of materials can be formed as isotropic, orthotropic and anisotropic depending on the type of material [22]. In addition, lamina properties can be created by entering material and thickness information in this input file.

In another input file, layup input file, the layer arrangement of composite materials and the directions of the layers are defined. While defining the layers, the angle between the baseline direction and the composite fiber direction is defined as shown in the example in Figure 2.7.

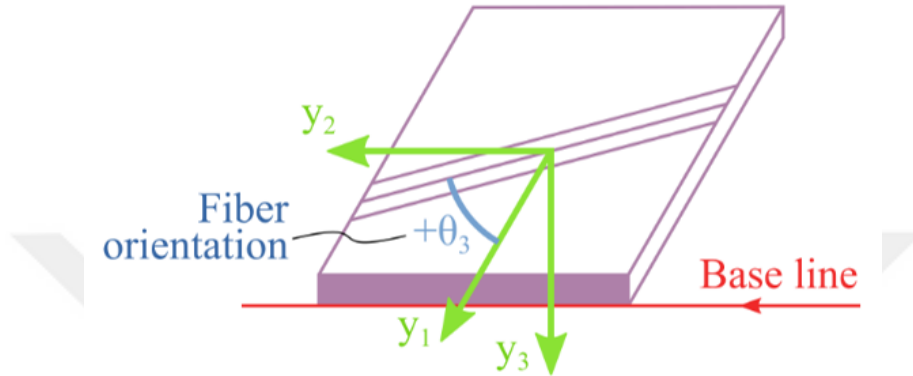


Figure 2.7 : Definition of composite fiber orientation.

In this thesis, a finite element model was created for helicopter UAV rotor blades with PreVABS. The material layout of blade cross-section is illustrated with different colors in Figure 2.8.

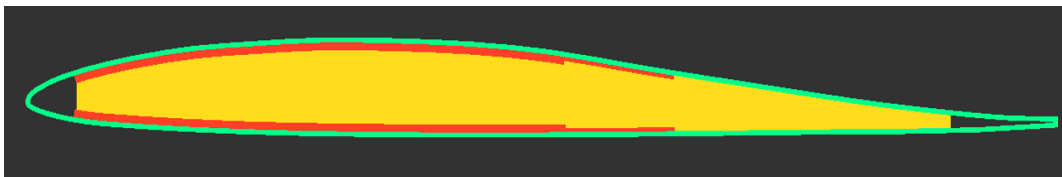


Figure 2.8 : Material layout of the blade cross-section.

The details of material layout of cross-section is given in Table 2.1

Table 2.1 : Cross-section materials.

Region	Material	Property
Green	Fabric CFRP	$+45^{\circ}/-45^{\circ}$
Red	UD CFRP	0°
Orange	Foam	Isotropic

The input files were created for PeVABS with an hierarchy. In this thesis, five different input files were created to create the finite element model for section analysis with PreVABS.

As the first step for the section analysis, the Airfoil.dat file containing the airfoil coordinates was created. Then the Baseline.xml file was created, the Airfoil.dat file was called with the include command and base points and baselines were defined based on the airfoil coordinates. Two more input files named Materials.xml and Layups.xml were created and materials and layups of layers were defined respectively. A main input file was created and general geometric properties, mesh properties and components of crosssection were defined. The hierarchy of the input files for section analysis is visualized in Figure 2.9.

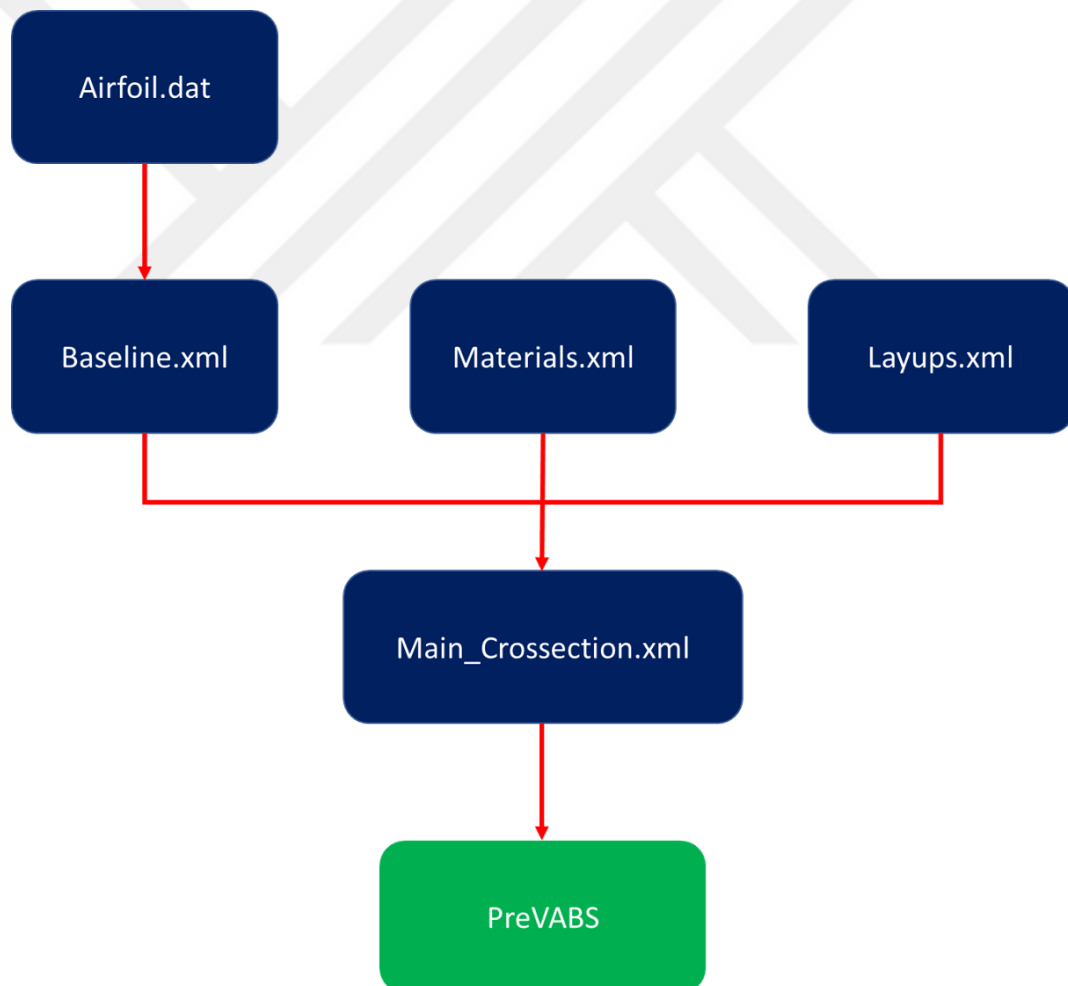


Figure 2.9 : Input files of PreVABS.

PreVABS was run with the command line and the finite element model of the section was obtained using the created input files. The view of the cross-section finite element model obtained by using parametric inputs is as in Figure 2.10.

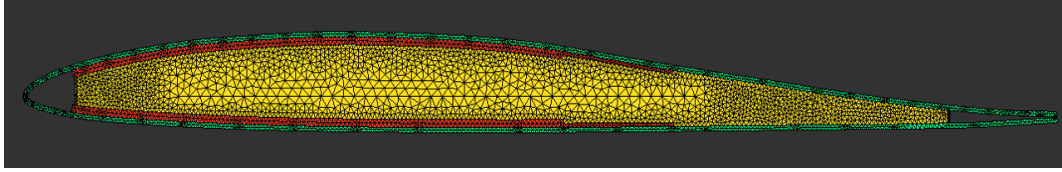


Figure 2.10 : Cross-section finite element model

2.1.1.2 VABS

In the previous section, the finite element model created with PreVABS needs to be solved with the help of a solver. Cross-sectional analysis is performed with VABS, which was mentioned in the previous sections. The homogenization process flow can be visualized in Figure 2.11 with the cross-sectional analysis method using PreVABS and VABS software. In addition, forces and moments obtained in beam analysis can be defined as input to VABS and by using VABS software, displacements and stresses on the section can be calculated [24].

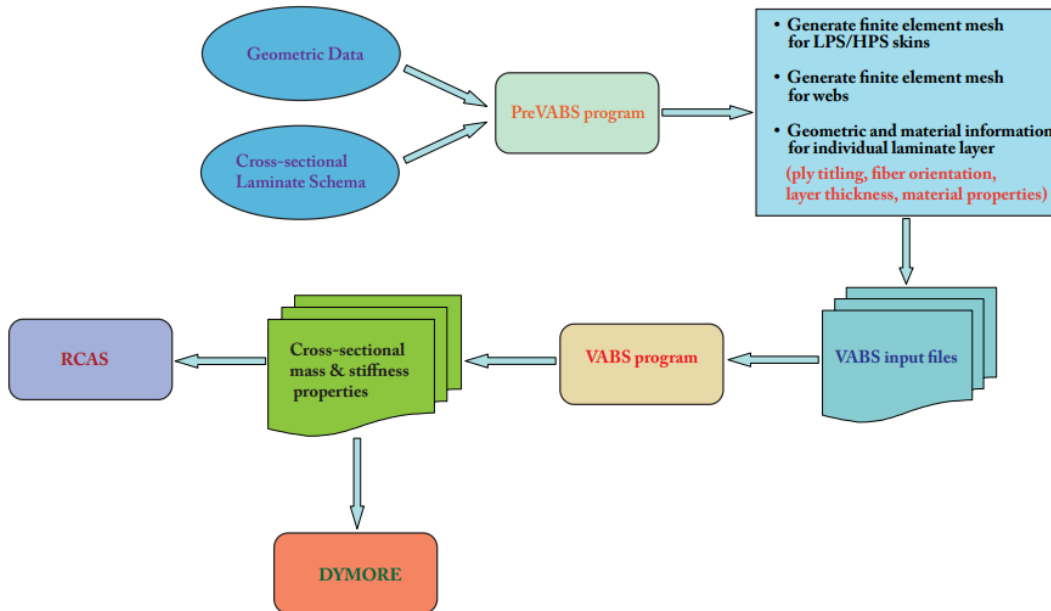


Figure 2.11 : Flow of cross-sectional analysis [22].

The finite element model of cross-section, which was created for this thesis, was solved with VABS software and homogenization was performed for the rotor blade section. After this process, mass and stiffness matrices of the cross-section were obtained. In addition, center of gravity, neutral axis and shear center were calculated at the end of this process. The properties that determine this section characteristic should be calculated according to the same coordinate system as the beam analysis, otherwise coordinate transformation should be applied [22]. In this study, the origin of cross-section is used the same as reference axis of the beam.

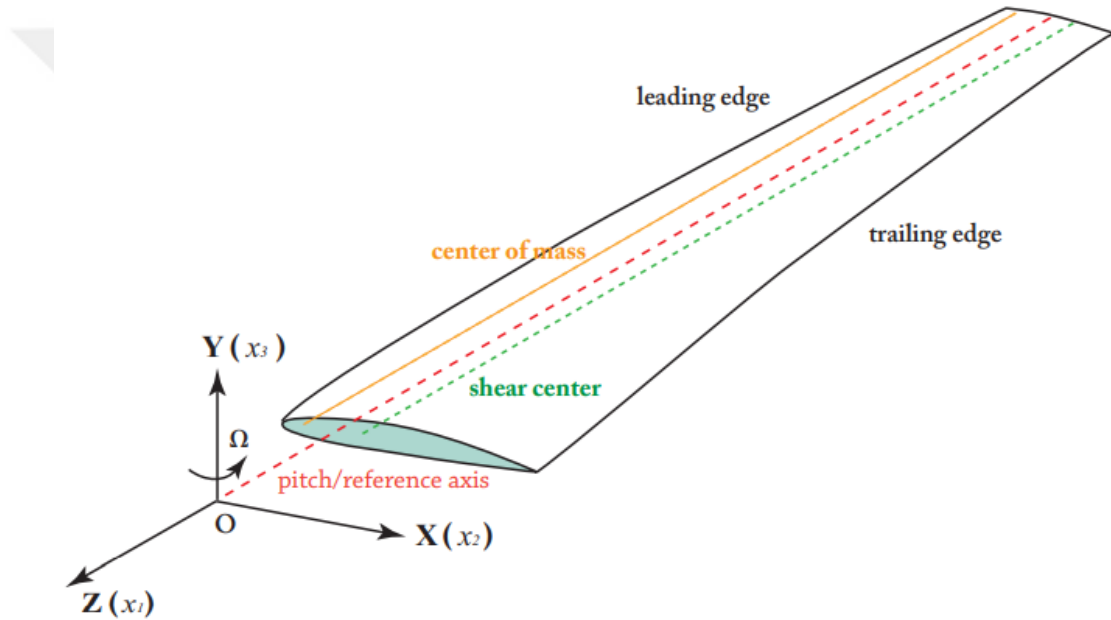


Figure 2.12 : Rotor blade coordinates. [22]

2.1.2 Modelling of rotor blade via beam elements

Dymore [25] is a comprehensive analysis tool for multibody dynamics problems. Dymore is a flexible multibody dynamics software with finite element formulation. It is used for modeling dynamic systems such as helicopter rotors and wind turbines. Dymore includes structural models, aerodynamic models and control models and offers advantages for modeling different interdisciplinary interactions. It allows

building aerodynamic models and interacting with structural analysis. In addition, controller elements can be defined to simulate trim condition [25].

In this thesis, the model to be created with Dymore has been simplified since an optimization study will be carried out. The model was created considering the optimization objective function and constraints. It is aimed to create a model that calculates the natural frequencies required for the optimization process with sufficient accuracy. At operating speeds for rotor blades, centrifugal force is dominant for natural frequency calculations. In addition, the critical force for the structural strength criteria on the blade is the centrifugal load. As the rotors rotate at high angular speeds, the centrifugal force causes stress on the blade root. The helicopter UAV which is discussed in this study has a hingeless rotor system. In the modeling phase, this rotor system was assumed to be rigid except for the blade. In addition, the feathering hinge is assumed to be rigid.

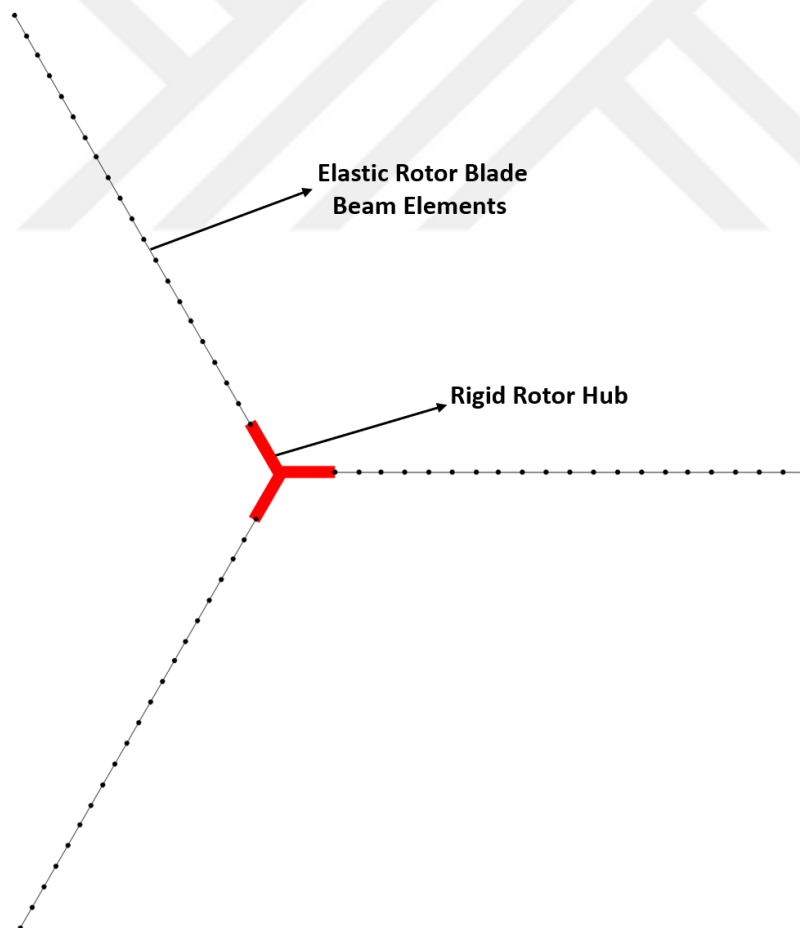


Figure 2.13 : Illustration of Dymore rotor model.

Dymore is software that runs with pre-made input files. In this direction, in the input file to be prepared, a curve passing through the reference axis of the beam is defined in order to create an elastic beam model. This curve is required to define the beam geometrically. In addition, the division of the beam into elements is defined by the mesh parameters when creating this curve. Then an edge with a topological entity associated with this curve is created. As in Figure 2.14, a beam property definition is created to define the section properties perpendicular to the curve that defines the beam. The beam is defined using this property and edge definition .

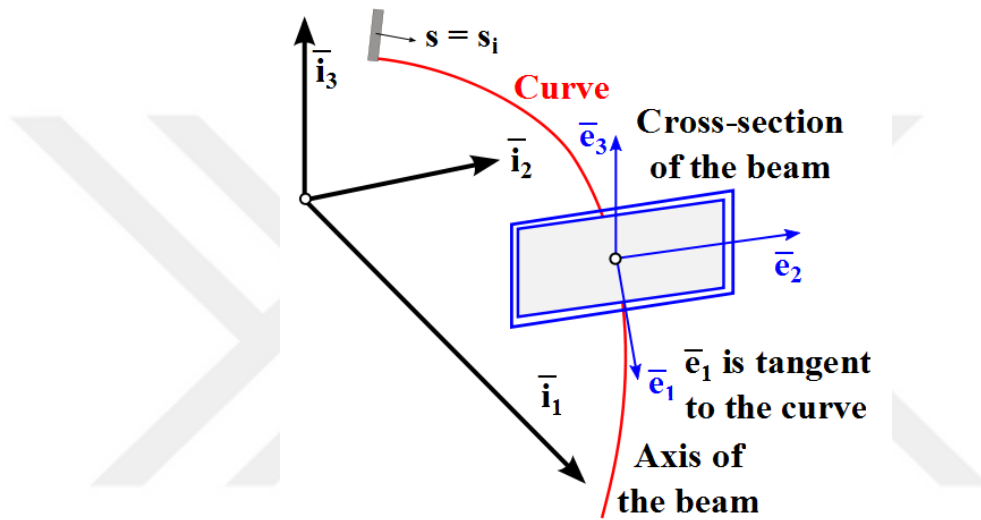


Figure 2.14 : Beam geometry in Dymore. [25]

During the modeling phase, the rotor blade was modeled using third order beam elements. To be conservative, 40 beam elements were used. The beam root is rigidly connected to the rotor hub. The section mass and stiffness properties obtained with VABS have been added to the input file as beam property.

Srinivasan et al. [26] examined vibration characteristic of a rotor blade using the finite element method and experimental methods. Including centrifugal and inertial effects, analysis results were able to correlate with experimental results without including aerodynamic effects. It was also observed that the first flapping mode was significantly affected by the centrifugal force. Tamer [27] studied on an optimization process to reduce vibrations in the rotor system and natural frequencies were calculated

without including aerodynamic effects. Dibble [9] studied on the concept of variable rotor speed and observed that the unsteady aerodynamic effects on undamped natural frequencies is minimal. For the optimization process, it is important to simplify the models both in order to give results with sufficient accuracy and to reduce the computational costs. Therefore, natural frequencies were calculated without including aerodynamic forces in this study. In natural frequency calculations, only centrifugal and inertial effects are included.

As a result of this analysis, the rotor blade natural frequencies will be calculated and the fan diagram will be created, so the static analysis mode is used [13]. In this study, analysis were carried out under vacuum condition, without aerodynamic effects, and only centrifugal force was applied as load. Centrifugal force was applied in time steps in order to create a fan diagram and to avoid convergence problem. In this direction, time steps were defined in the analysis with 10% force increments. Thus, natural frequencies were calculated as in Table 2.2 for all rotor speeds from zero to operating speed.

Table 2.2 : Natural frequencies of rotor blade.

Rotor Speed	Mod 1 Hz	Mod 2 Hz	Mod 3 Hz	Mod 4 Hz	Mod 5 Hz	Mod 6 Hz
0Ω	2.947	16.796	20.907	26.824	63.049	106.004
0.1Ω	3.559	16.831	21.543	26.863	63.766	106.081
0.2Ω	4.942	16.938	23.343	26.982	65.855	106.269
0.3Ω	6.600	17.114	26.047	27.179	69.157	106.506
0.4Ω	8.351	17.356	27.440	29.397	73.457	106.768
0.5Ω	10.138	17.660	27.780	33.163	78.536	107.056
0.6Ω	11.939	18.022	28.186	37.210	84.199	107.374
0.7Ω	13.745	18.437	28.653	41.445	90.284	107.732
0.8Ω	15.553	18.900	29.178	45.809	96.659	108.142
0.9Ω	17.358	19.407	29.756	50.264	103.160	108.682
1Ω	19.151	19.962	30.380	54.784	108.158	110.915

A graph was created to examine the relationship between the calculated natural frequencies and rotor speed as in Figure 2.15. The flapping modes were increased with rotor speed such as first and fifth mode. The second mode, first lead-lag mode, is almost the same for rotor speed range. The Mode 6 is torsion mode and it is not increased with rotor speed.

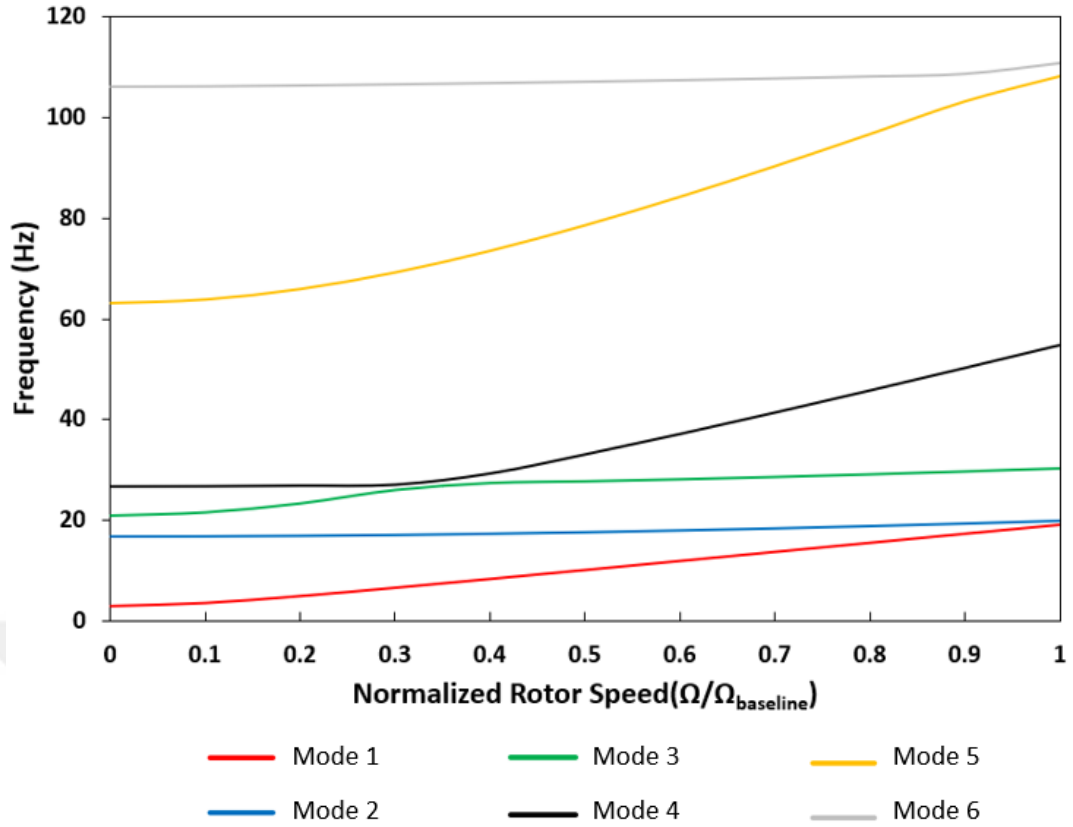


Figure 2.15 : Natural frequencies of baseline design.

2.2 Optimization Method

Optimization algorithms have started to be applied more in engineering studies with the increase in computational capabilities. These optimization studies can be carried out using different optimization methods. There are many studies comparing the advantages and disadvantages of optimization approaches.

Vanderplaats [28], in his book, explained and illustrated different optimization techniques for engineering. The SQP which is used in this thesis is also explained theoretically and compared with other optimization algorithms. Vanderplaats performed a comparison on the beam optimization problem in Figure 2.16. In this problem, the geometric properties of the beam are defined as variable and it is aimed to reduce its volume. Geometric limits, displacement and stress are used as constraints. This problem has been solved with gradient-based and non-gradient optimization approaches, and a similar optimum objective function value has been

reached. However, there were serious differences between optimization methods in the number of iterations and objective function calculations. It has been concluded that SQP is the approach that requires the least number of function calculation among the seven different methods applied. Körpe and Kanat [29] also preferred SQP in their aerodynamic optimization study due to the advantage of low number of function calculations.

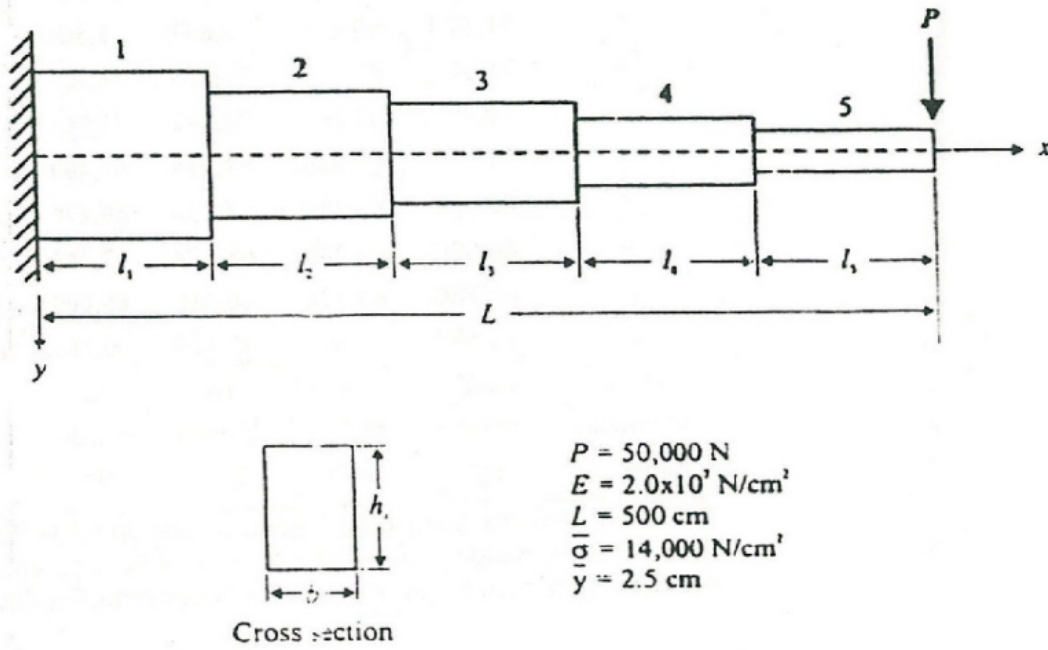


Figure 2.16 : Example optimization problem [28].

Li et al. [12] have used SQP in their studies because of the fast convergence advantages. SQP was used together with GA in the optimization process for the rotor blade section. Thus, the disadvantage of SQP that convergence at local minima is avoided by combining GA.

The general constrained optimization problem can be defined for n design variables(x).

$$\min f(x) \quad x = x_1, x_2, \dots, x_n \quad (2.1)$$

The $f(x)$ is the objective function and the design variables have lower and upper bounds.

$$x_l \leq x \leq x_u \quad (2.2)$$

The optimization problem is considered to have number of m equality and inequality constraint. The problem subject to

$$G_i(x) = 0 \quad (i = 1, \dots, m_e) \quad (2.3)$$

$$G_i(x) \leq 0 \quad (i = m_e + 1, \dots, m) \quad (2.4)$$

2.2.1 Sequential quadratic programming

In this study, SQP was chosen as the optimization method and the optimization process was created with the help of MATLAB toolbox [30]. The SQP method is a gradient-based algorithm that can be used to optimize nonlinear constrained functions. The SQP algorithm of MATLAB toolbox is described briefly in sections below.

In this method, the quasi-Newton updating method is used to calculate the Hessian matrix of the Lagrangian function. This Hessian matrix calculation is performed for each iteration. This Hessian matrix is used to construct the QP subproblem. The created QP subproblem is solved and used to create the search direction to be used for line search. The general constrained optimization problem is transformed into the QP subproblem. This process is performed using a Lagrangian-based approach [30].

$$L(x, \lambda) = f(x) + \sum_{i=1}^m \lambda_i g_i(x) \quad (2.5)$$

The constraints are linearized to transform the problem to the QP subproblem. The quadratic subproblem can be written as

$$\min \frac{1}{2} d^T H_k d + \nabla f(x_k)^T d \quad (2.6)$$

The QP subproblem constraint equations are

$$\nabla g_i(x_k)^T d + g_i(x_k) = 0, \quad i = 1, \dots, m_e \quad (2.7)$$

$$\nabla g_i(x_k)^T d + g_i(x_k) \leq 0, \quad i = m_e + 1, \dots, m \quad (2.8)$$

After the QP subproblem is solved, it is used to calculate the values in the new iteration.

$$x_{k+1} = x_k + a_k d_k \quad (2.9)$$

In order to minimize the merit function, the step length parameter a_k is determined by a line search method. It is possible to solve the positive Hessian matrix H_k with a quasi-Newton method such as BFGS [30]. The SQP algorithm can be illustrated as in Figure 2.17.

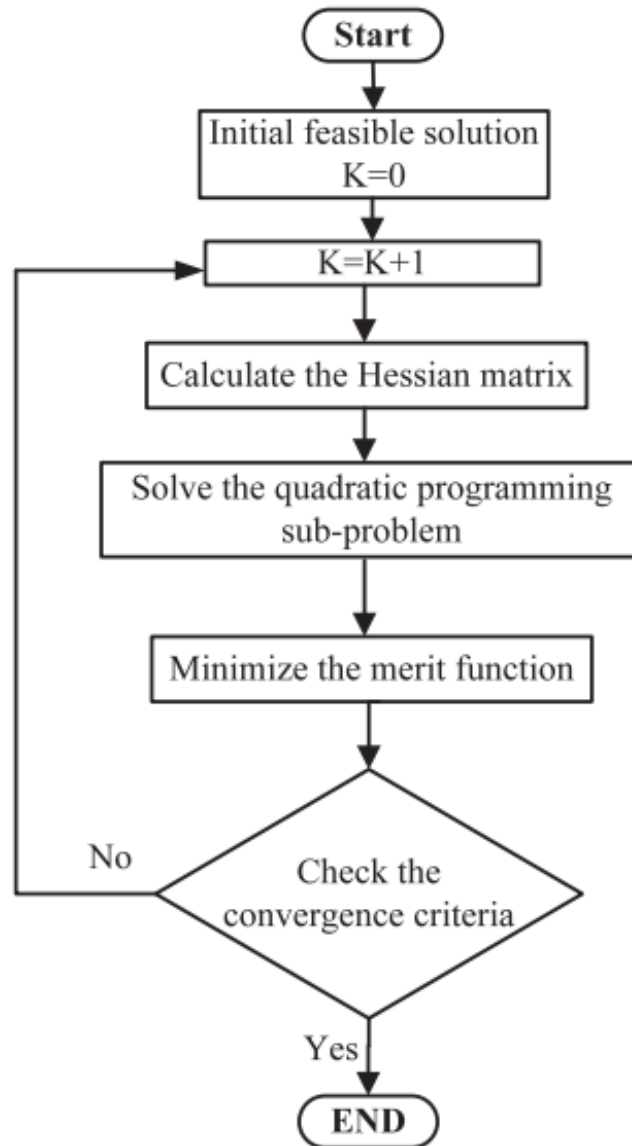


Figure 2.17 : SQP process [31].

The algorithm of the SQP can be summarized as following, with respect to [32].

- The original problem is converted to a QP subproblem. In the first iteration, the Hessian matrix of Lagrangian function is considered an identity matrix.

- The QP subproblem is solved and Lagrange multipliers are found.
- A line search is performed for the QP subproblem. Penalty function is calculated. The step size is changed until the penalty function is reduced. The weight of the violated constraints is applied according to the Lagrange multipliers.
- The Lagrangian gradient is calculated and the new Hessian matrix of Lagrangian is found using the BFGS method.
- Convergence is checked. If the convergence criteria are not satisfied, return to the first step.





3. PERFORMANCE IMPROVEMENT WITH VARIABLE ROTOR SPEED

Variable rotor speed is one of the main concepts studied for performance improvement purposes. The variable rotor speed is able to improve performance in terms of power, noise and control. In order to analyze the effects of this concept on performance parameters, these parameters need to be calculated and examined. In this scope, helicopter power required has been calculated and compared for different flight conditions. Many performance parameters are directly affected by the decrease in power required. Therefore, the power required should be estimated and the effects of variable rotor speed should be revealed.

3.1 Theory of Power Estimation

The blade element and momentum methods is used to estimate rotor performance. Using these methods, reliable estimations for rotor power can be performed. Hover and forward flight conditions have different assumptions and performance parameter derivations. In this study, power required was estimated with separate equations for hover and forward flight.

3.1.1 Power estimation in hover

Rotor power in hover can be estimated using modified momentum theory [33]. In hover, the total power required can be calculated with sum of profile power (P_0) and induced power (P_i). The total rotor power required is calculated by using equation below.

$$P = P_0 + P_i = \rho A (\Omega R)^3 \left(\frac{\sigma C_{d0}}{8} \right) + \frac{\kappa W^{3/2}}{\sqrt{2\rho A}} \quad (3.1)$$

The induced power factor κ is,

$$\kappa = \frac{2(n+1)^{3/2}}{(3n+2)} \quad (3.2)$$

The power induced factor is used to include effect of inflow distribution over the rotor radius. In ideal, the inflow is uniform $n = 0$ and $\kappa = 1$. It can be obtained experimentally, but it is taken as 1.15 in this study [33].

3.1.2 Power estimation in forward flight

In forward flight, the total power required is obtained by summing the profile, induced and parasite power (P_p).

$$P = P_i + P_0 + P_p \quad (3.3)$$

The coefficient of induced power (C_{P_i}) is calculated by using equation below.

$$C_{P_i} = \frac{\kappa C_w^2}{2\sqrt{\lambda^2 + \mu^2}} \quad (3.4)$$

Induced inflow ratio, λ , can be approximated with numerical solution. The initial induced inflow ratio is taken as

$$\lambda_i = \sqrt{\frac{C_T}{2}} \quad (3.5)$$

Then the inflow ratio is found with iterative solution by using this equation

$$\lambda = \mu \tan\alpha + \frac{C_T/2}{\sqrt{\lambda^2 + \mu^2}} \quad (3.6)$$

The advance ratio(μ) and thrust coefficient(C_T) of helicopter are known from the equations given below.

$$\mu = \frac{V_\infty \cos\alpha}{\Omega R} \quad (3.7)$$

$$C_T = \frac{T}{\rho A (\Omega R)^2} \quad (3.8)$$

Then, the induced power in forward flight can be written as

$$P_i = (\rho A (\Omega R)^3) \frac{\kappa C_w^2}{2\sqrt{\lambda^2 + \mu^2}} \quad (3.9)$$

The profile power coefficient (C_{P_0}) can be estimated by using the blade element theory [33]. The profile power coefficient and the profile power in forward flight can be calculated as

$$C_{P_0} = \left(\frac{\sigma C_{d0}}{8} \right) + (1 + K\mu^2) \quad (3.10)$$

$$P_0 = \left(\rho A (\Omega R)^3 \right) \frac{\sigma C_{d0}}{8} (1 + K\mu^2) \quad (3.11)$$

The numerical value of K varies from 4 to 5 depending on the advancing ratio [33].

The parasitic power, P_P , is the power requirement due to viscous effects on structural components such as the fuselage in forward flight. The coefficient of parasite power (C_{P_p}) can be approximated as

$$C_{P_p} = \frac{1}{2} \left(\frac{f}{A} \right) \mu^3 \quad (3.12)$$

$$P_P = \left(\frac{1}{2} \rho V_\infty^2 S_{ref} C_{D_f} \right) V_\infty \quad (3.13)$$

3.2 Application of the Power Estimation

The power required of helicopter rotors changes with different flight conditions. The power required changes with the change of parameters such as forward speed, altitude and gross weight. With the variable rotor speed concept, it is aimed to change the rotor speed according to the change of this power required. In this direction, it is necessary to calculate the power required of the helicopter for different flight conditions. Using these calculated power required values, the rotor speed can be determined for different flight conditions.

The rotor blade has a rectangular shape without twist or taper. The rotor blade has a unique airfoil shape that is not change along the spanwise. In the calculations, it is assumed that the profile drag coefficient and lift curve slope are constant. The design parameters of rotor is given as in Table 3.1.

Table 3.1 : Rotor properties.

Parameter	Symbol	Value
Number of blades	N_b	3
Rotor speed (rpm)	Ω	1000
Chord (mm)	c	93
Diameter (mm)	D	3065
Solidity	σ	0.058
Taper	t	None
Twist	θ	None
Induced power factor	κ	1.15
Equivalent wetted area (m^2)	f	0.35
Profile drag coefficient	C_{d0}	0.007
Lift curve slope(/deg)	$C_{l\alpha}$	0.11

First, thrust and power calculations were carried out for the hover condition to examine the applicability and limitations of variable rotor speed. By using the Blade Element Momentum Theory code [34], thrust and power graphs were obtained for different gross weight conditions.

In the hover condition, the graphs were examined considering that the thrust and gross weight were equal. According to these results, when the rotor speed is reduced by 20%, the power available is limited to 164kg gross weight as in Figure 3.1. However, according to the stall limit, the thrust force is limited to 178kg at reduced rotor speed as in Figure 3.2.

According to these results, it is concluded that the variable rotor speed concept is predominantly constrained by the power available value of the engine. In the next steps, calculations were performed for variable rotor speed, considering only the power available limit of the engine.

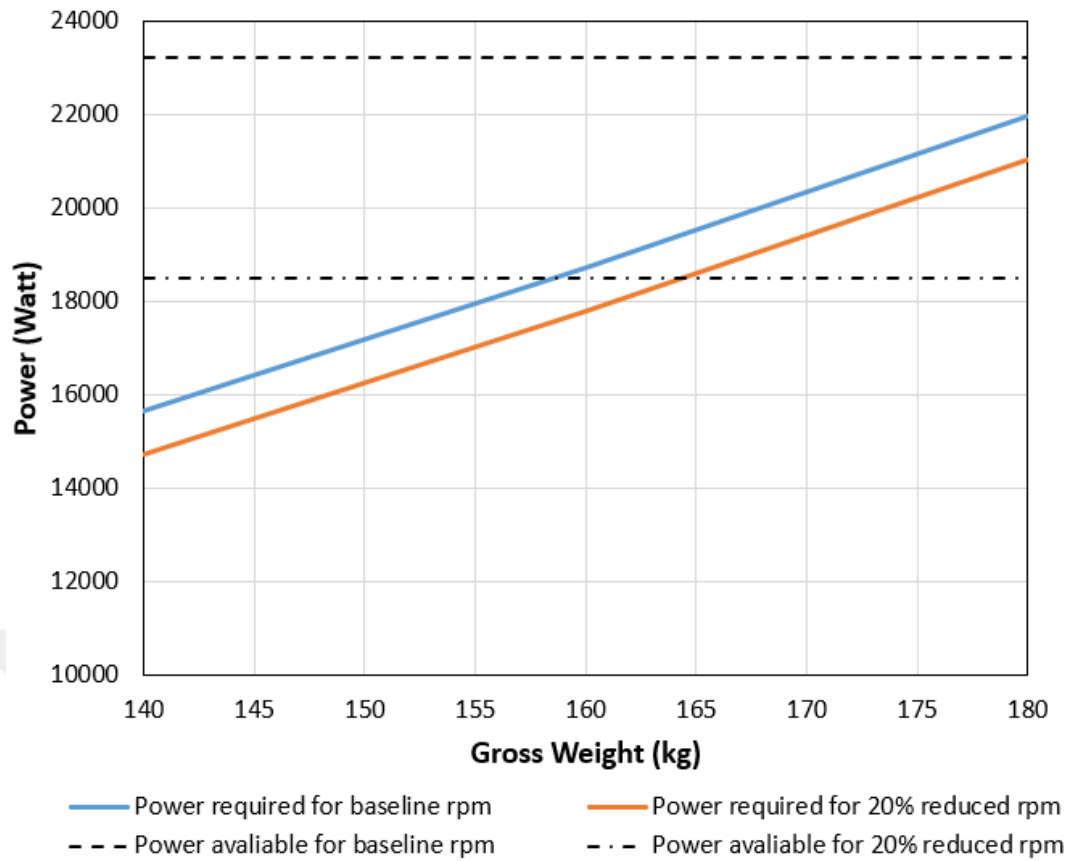


Figure 3.1 : Rotor power required in hover.

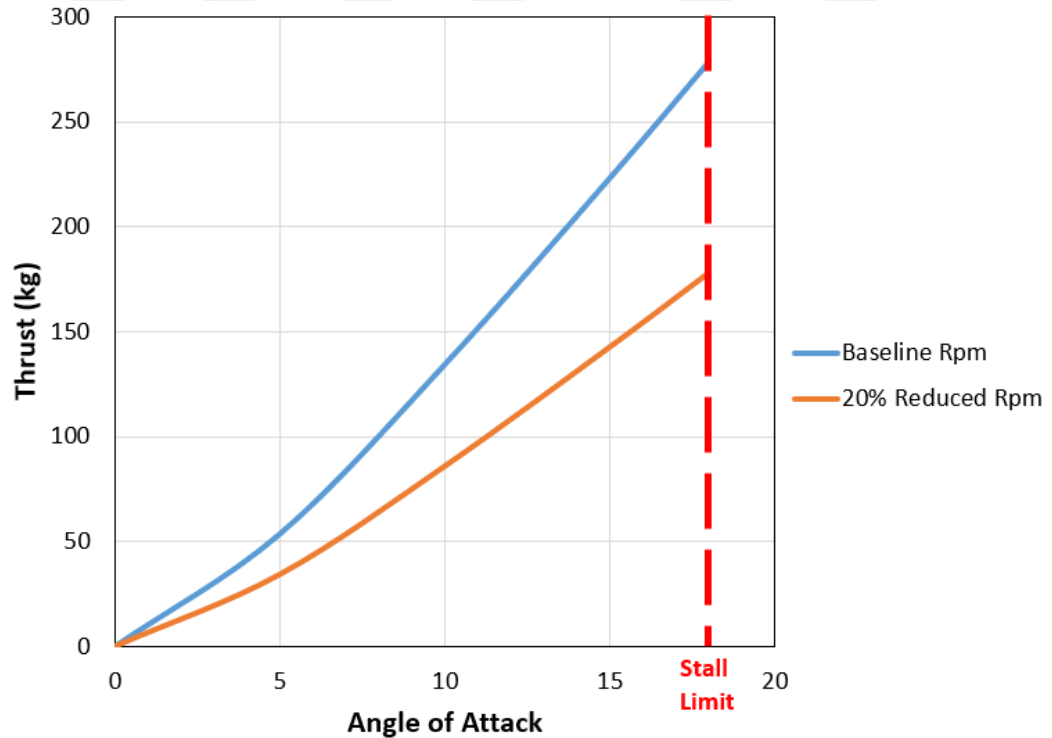


Figure 3.2 : Thrust in hover.

The power required estimations were carried out for different gross weight and velocity conditions. In addition, for this study, the rotor speed was reduced by 20% to examine the relationship between the rotor speed and the power required. Therefore, power calculations were carried out for baseline and 20% reduced rotor speed. The power required values were calculated as in Figure 3.3

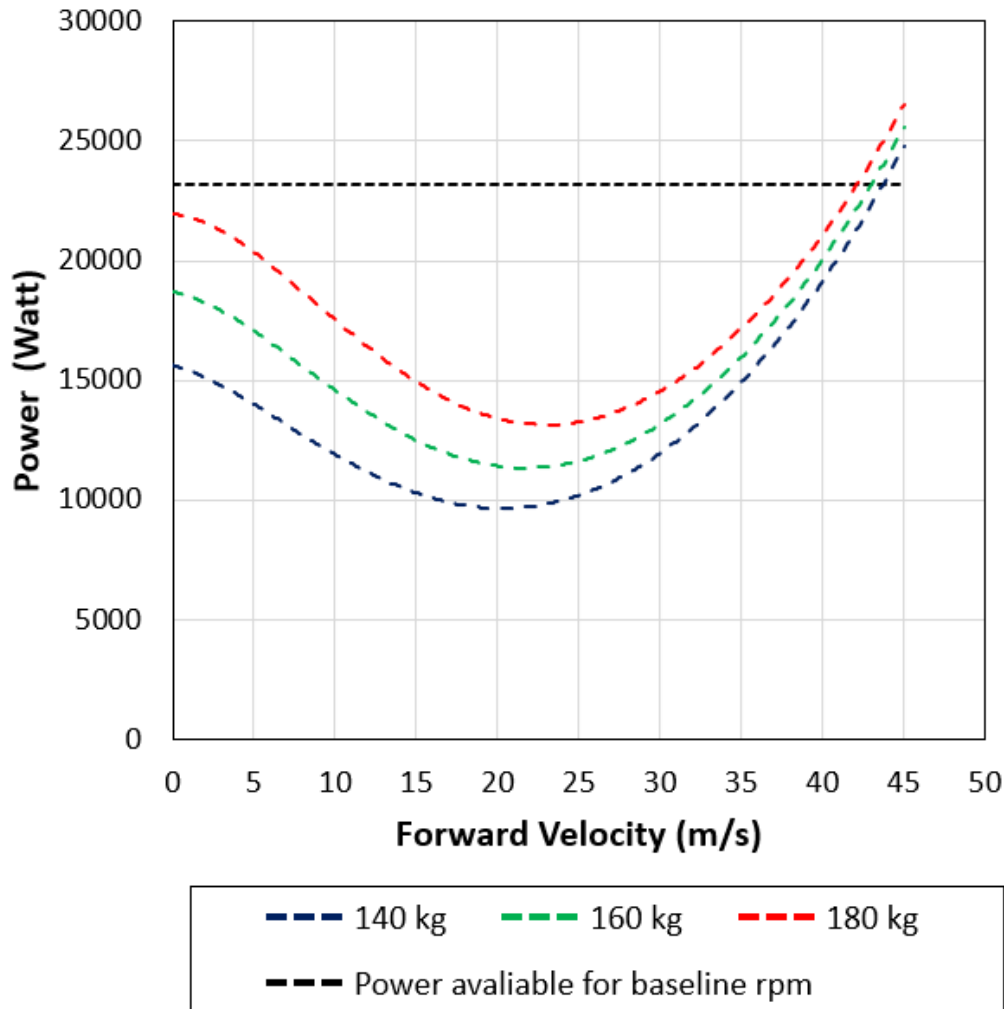


Figure 3.3 : Rotor required power in forward flight for baseline rpm.

It is assumed that single ratio transmission is used for this rotor. Thus, rotor speed and available power will change with engine rpm. The variation of engine power available has been taken into account according to engine speed and the reduction for engine speed has been limited to 20 percent. The rpm range of the engine was determined by considering rpm values that produce maximum torque. The torque and power data of the helicopter UAV engine is given in Appendix A.

Power is calculated for different gross weight and forward speed condition with reduced rotor speed by 20 percent. A reduction in power required was achieved by decreasing the rotor speed. However, due to the constant transmission ratio of the rotor system, the decrease in power available is also noteworthy. Therefore, it is not possible to reduce the rotor speed in every flight condition.

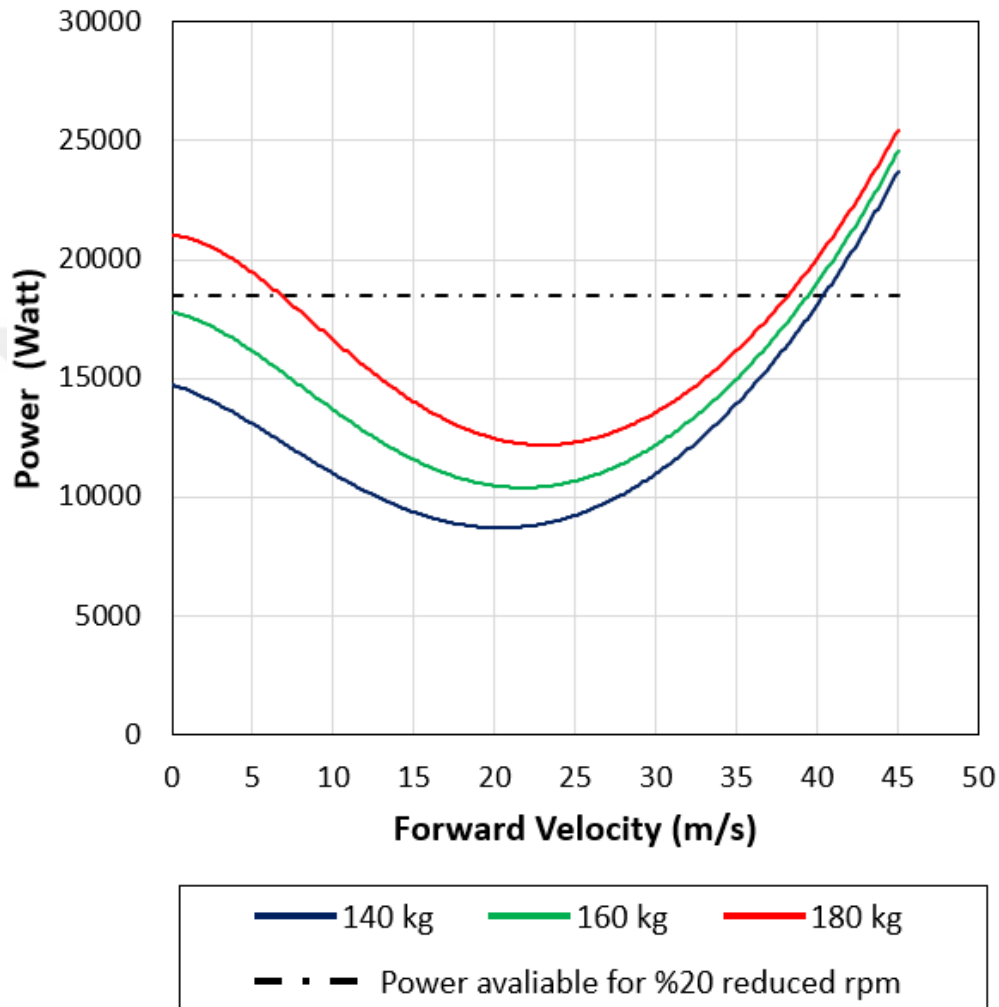


Figure 3.4 : Rotor required power in forward flight for reduced rpm.

According to the power estimation graphs, the variable rotor speed concept can be used for low gross weight and cruise velocities. For reduced rotor speed, power required is decreasing and it is applicable for low gross weight and cruise velocities. The reduced rotor speed can not be used for high and low forward velocity conditions. In addition, the reduced rpm is not applicable for high gross weight conditions.

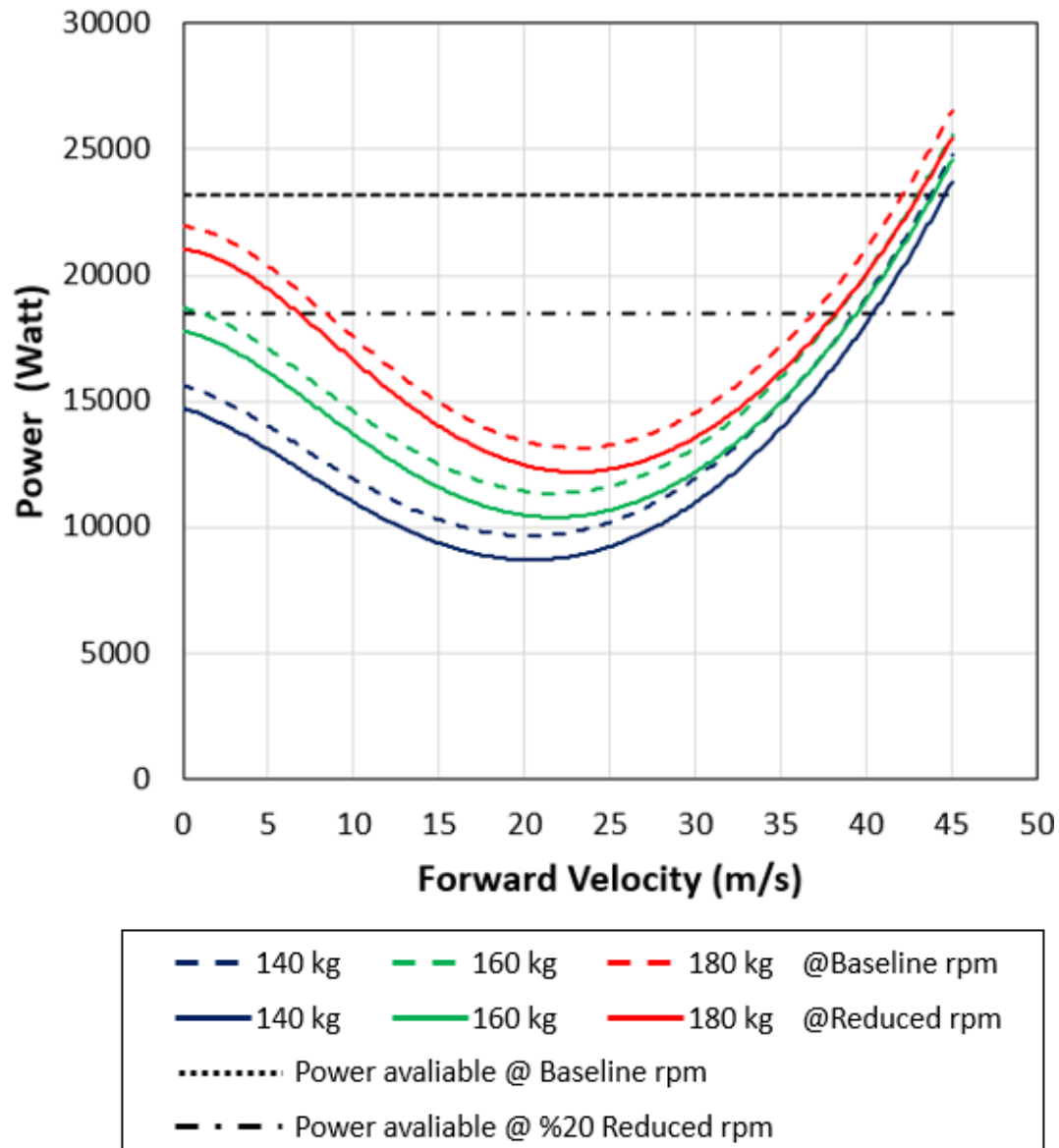


Figure 3.5 : Rotor power for different weight, velocity and rpm.

The range in which the rotor speed can be reduced is determined using these graphs. In addition, the percentage of power reduction that occurs with the change of rotor speed is also examined. As can be seen in the Figure 3.6, the largest power reduction is obtained for low gross weight and cruise velocities (20-25m/s). However power reductions are decreasing with low and high-speed flight cases. In addition, power reduction is decreasing with high gross weight conditions.

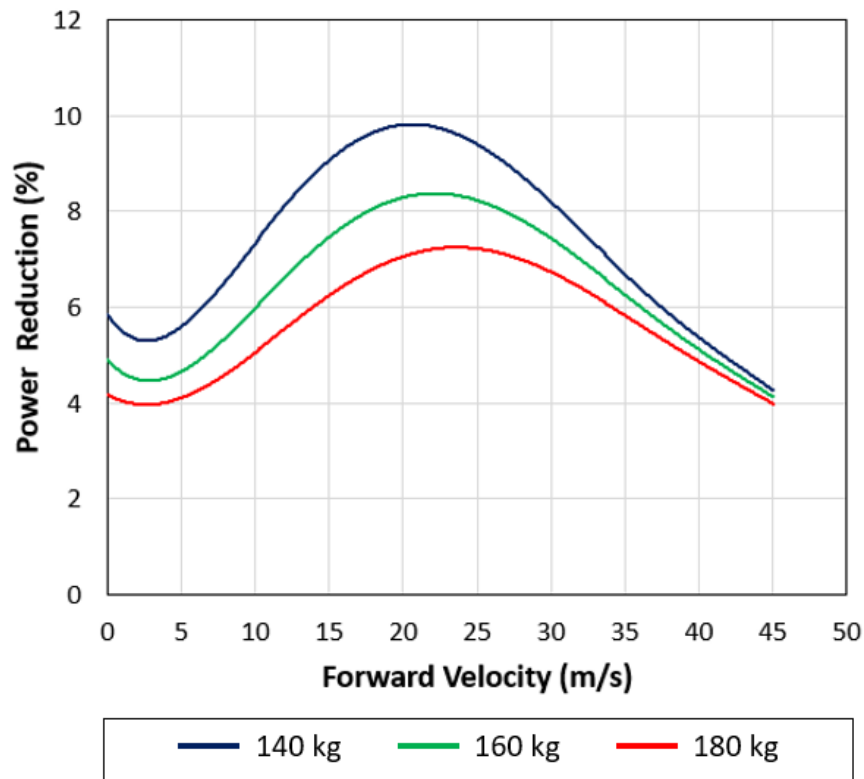


Figure 3.6 : Power reduction percentages with 20% rotor speed reduction.

According to the power estimations, for power reduction, the rotor speed intervals were determined as Figure 3.7. Within the scope of variable rotor speed, it is aimed for the rotor to operate at two different speeds for different flight conditions. Using power calculations, it has been determined under which flight conditions baseline or 20% reduced rpm will be preferred.

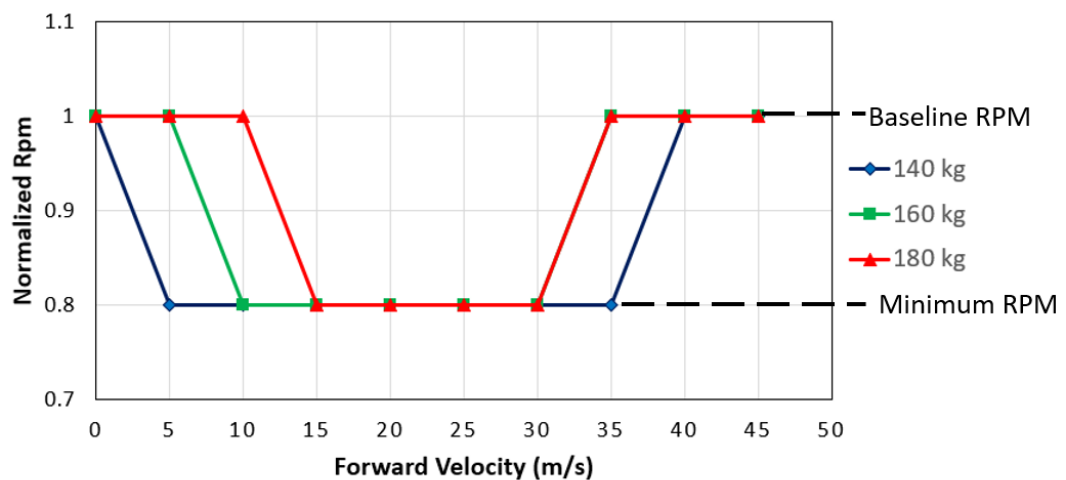


Figure 3.7 : Rotor speed for minimum power required.

For minimum power, the rotor rpm varies with forward velocity and gross weight. To reduce power required, the variable rotor speed concept can be applied for this rotor design by using Figure 3.7. However, according to the fan plot diagram in Chapter-3, the variable rotor speed concept can not be used directly, because rotor blade design should be optimized to avoid resonance and vibration for reduced rotor speed. In the next Chapter, an optimization process will be created to optimize the rotor blade design. The Dymore model of the rotor blade will be included the optimization cycle and the optimum rotor blade design will be obtained for variable rotor speed interval.



4. BLADE OPTIMIZATION TO REDUCE VIBRATION

4.1 Optimization Approach

In this study, it is aimed to optimize the rotor blade, which performance has been improved with variable rotor speed, in terms of vibration. An optimization process has been established to achieve this aim. Baseline design of rotor blades are designed to operate at a single rotor speed. However, it has been shown in the previous chapter that the performance of the blades can be improved by reducing the rotor speed. It has been seen with the fan diagram that the rotor harmonics and natural frequencies are closer with reduced the rotor speed. At both baseline rotor speed and reduced rotor speed, the rotor blade design must be optimized for vibration because vibration is the root cause of many problems such as fatigue.

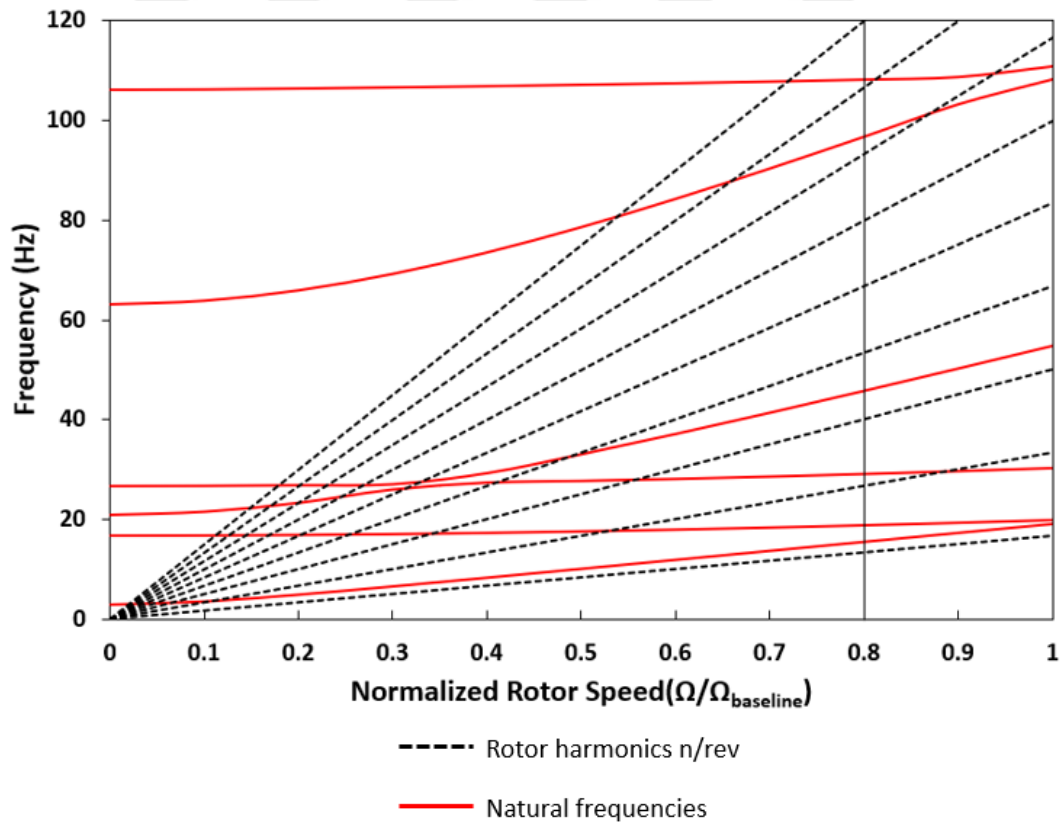


Figure 4.1 : Rotor blade fan diagram for baseline design.

The most basic method to reduce vibration of rotor systems is to optimize the rotor blade. This method aims to change the blade design parameters and reduce the vibration. Rotor vibrations can be reduced with Hub Loads Minimization or Natural Frequency Separation method [27]. In this study, natural frequency separation method was used due to its advantages such as fast and easy applicability. This method basically deals with separation of rotor harmonics and natural frequencies. In any rotary system, natural frequency placement is important. Crossing or close to natural frequencies and rotor harmonics can cause resonance or undesired vibrations. For this reason, it is important to calculate the natural frequencies, fan plot diagram, correctly at operating speeds in rotary systems. By calculating the natural frequencies, the dynamic behavior of the rotor blade can be examined. In line with this information, the optimization process was created within the framework of natural frequency separation. In this scope, optimization process aims to increase the difference between rotor harmonics and natural frequencies by changing the non-structural mass properties.

4.2 Design Variables

In the optimization process, the difference between natural frequencies and harmonics will be increased to reduce vibration. Therefore, natural frequencies need to be tuned according to harmonics. Natural frequencies can be tuned by varying the mass or stiffness values. In this study, the mass properties of the blade are used as variables, because if the stiffness values are included in the optimization, time of optimization process is increases. Therefore, blade composite layer properties were kept constant and only nonstructural mass properties were defined as variable. In this way, the dynamic properties of the blade were adjusted by changing only the mass properties without changing the stiffness properties.

The variables of the nonstructural mass were determined according to the baseline design. In the baseline design of the rotor blade, the nonstructural mass has a rectangular cross section and extends from the middle of the rotor blade towards the blade tip, in the form of a strip. To change the mass properties of the rotor blade, the weight of this nonstructural mass or the position of the center of gravity can be

changed. The design variables of optimization was determined as in Table 4.1 Its dimension of cross-section, spanwise and chordwise location have been defined as variables in order to be able to change both the weight of the nonstructural mass and the position of the center of gravity.

Table 4.1 : Design variables.

Design Variable	Property of Nonstructural Mass
X(1)	Inner Spanwise Location
X(2)	Outer Spanwise Location
X(3)	Chordwise Location
X(4)	Cross-section Width
X(5)	Cross-section Height

The spanwise location of nonstructural mass was defined as design variables in Figure 4.2. The design variables X(1) and X(2) represent the start-end locations along the span of the nonstructural mass.

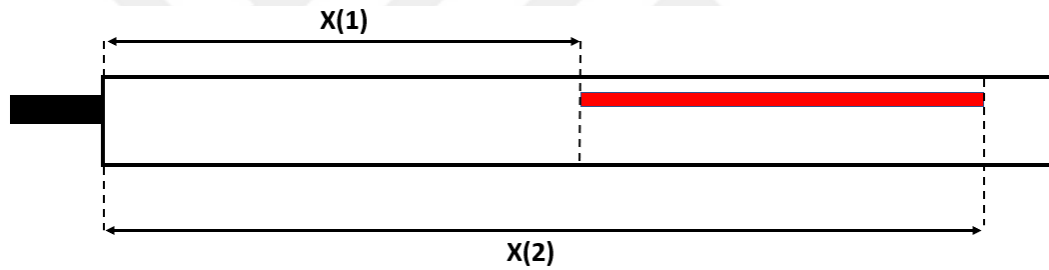


Figure 4.2 : Spanwise design variables of nonstructural mass.

The cross-section properties and chordwise location of nonstructural mass was defined as design variables in Figure 4.3. The design variables X(3) defines the distance between center of the nonstructural mass and leading edge of the blade. The design variables X(4) and X(5) represent the width and height of the nonstructural mass.

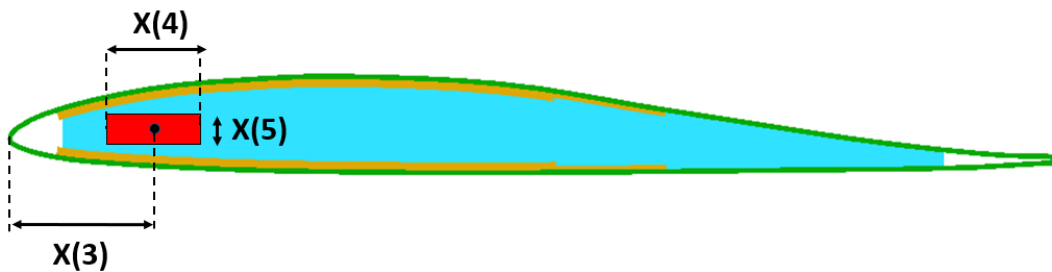


Figure 4.3 : Cross-section design variables of nonstructural mass.

4.3 Constraints

In an optimization process, constraints are defined to determine the feasible region. The area within the feasible region can represent where the constraints are satisfied. In order to obtain usable design as a result of an optimization, optimized design must be located in the feasible region. It is ensured that the design obtained as a result of optimization with the determined constraints does not have lower performance in terms of determined parameters than the baseline design. Therefore, it is important to properly define constraints in order to achieve a usable optimized design.

In this study, it is desired that the optimized blade design should not be weaker than the initial design in terms of performance, strength and vibration. For this optimization process, three different constraints were determined and the optimized blade design was ensured to meet the requirements.

In rotor blades, the main load considered for structural strength is centrifugal force (F_C). In this study, since the stiffness of the blade is constant during optimization, it is requested that the loads acting on the blade do not increase. Since the main load, centrifugal force acting on the blade was not more than the centrifugal force of baseline design ($F_{C_{baseline}}$), the structural strength could be satisfied for the optimized design. For this purpose, the constraint for centrifugal force is defined as follows.

$$F_C \leq F_{C_{baseline}} \quad (4.1)$$

The weight of the rotor blades is important in terms of performance and dynamic characteristics. During this optimization study, the weight of the nonstructural mass in the blade is changed in order to change the natural frequencies of the blade. Due to this weight change, the total weight of the rotor blade also changes. In this study, the weight of the nonstructural mass is constrained as follows in order not to have a negative effect on the performance and dynamic properties of the rotor.

$$Weight \leq Weight_{baseline} \quad (4.2)$$

In this study, since the aim of the optimization is to minimize the vibrations in the rotor, it is desired that there is no negative effect in terms of vibration in the optimized design compared to the baseline design. With the optimization process, the natural frequencies

of the rotor blade are changed and separated from the rotor harmonics. However, as a result of this process, it can have a negative effect on the dynamic characteristic of the rotor as a result of the intersection of natural frequencies(ω_i). In the optimized blade design, a constraint has been created as follows to avoid such an effect.

$$\min(\omega_i - \omega_{i-1}) \leq \text{baseline} \quad (4.3)$$

To determine the values to be used in the constraints, analysis were performed for the baseline design before the optimization process. Constraint values were defined using these analysis results and the optimization process was run.

4.4 Objective

The aim of the optimization is to reduce the vibration level of rotor blade. To achieve this aim, increasing the difference between natural frequency of blade and rotor harmonics was used as a method. The difference between natural frequencies and rotor harmonics represents the difference between the excitation frequencies and the natural frequencies of the rotor blade. By increasing this difference, resonance and undesired high vibrations are avoided.

In this optimization study, the calculated natural frequencies were normalized by dividing the rotor speed. The difference with the closest rotor harmonic(n/rev) is calculated for all normalized natural frequency values. The minimum of these calculated difference values is defined as the objective of this optimization study.

$$F_{obj} = \min \left(\frac{\omega_i}{\Omega} - n/rev \right) \quad (4.4)$$

4.5 Optimization Framework

In this optimization study, an optimization framework was created by using the modeling approach mentioned in Chapter 2 for analysis. The entire optimization flow is automated with MATLAB. MATLAB codes were created to generate the input and output files of the analyses. Thus, the analyses and optimization algorithm in the entire optimization flow were controlled via MATLAB. Before the optimization loop, analysis were carried out for the baseline design. These obtained values are used to define constraints. The optimization framework was crated as Figure 4.4

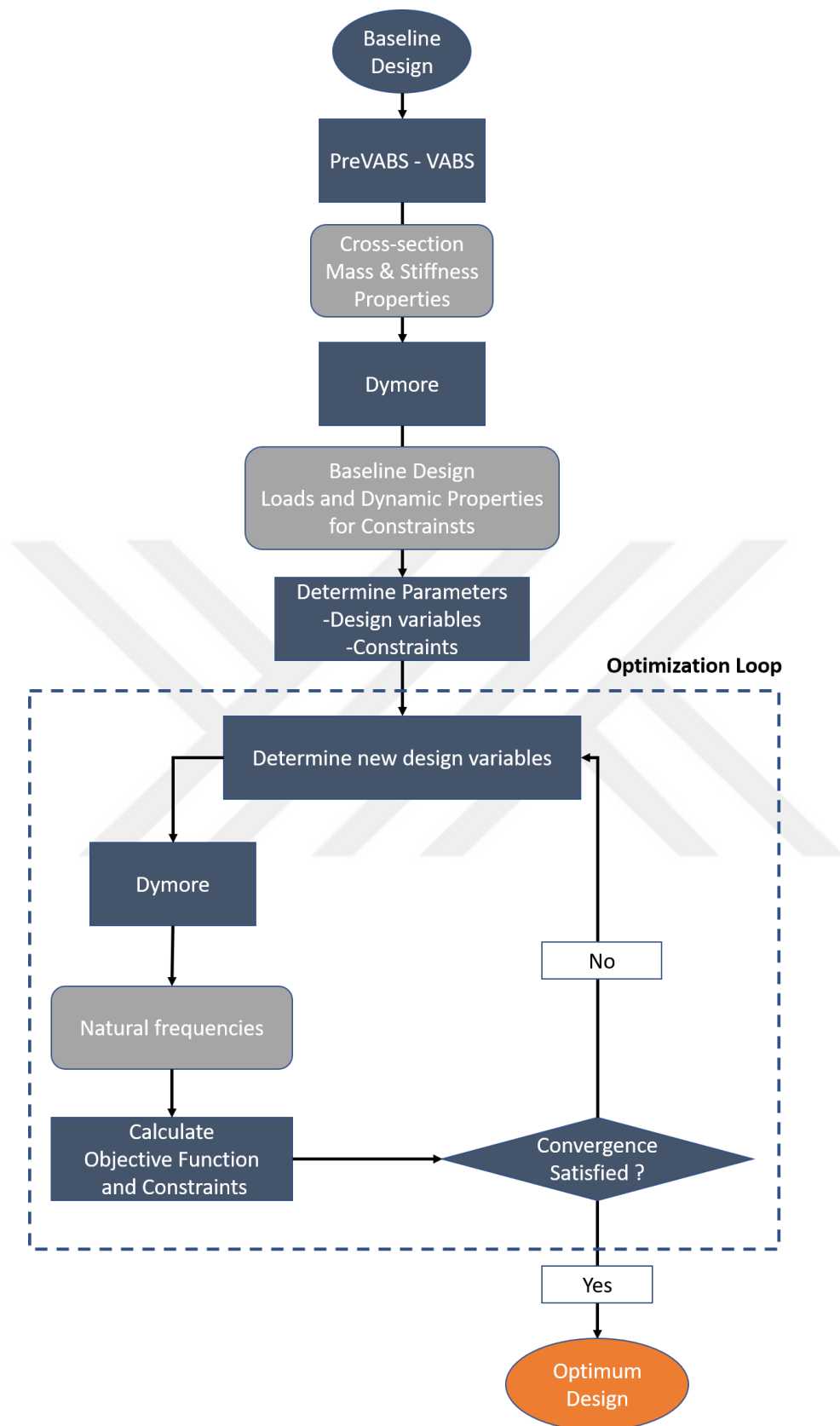


Figure 4.4 : Optimization flow chart.

In the first step, the rotor blade cross-section was modeled with PreVABS for baseline design. For the created section model, the section mass and stiffness matrices were calculated with VABS. These section mass and stiffness matrices will be used as input to the beam model created with Dymore. In the next step, rotor blade model was created with Dymore. Using this Dymore blade model, centrifugal force and natural frequencies were calculated for the baseline design and rotor speed. Based on this calculated centrifugal force value, a centrifugal force constraint was created for the optimization loop. The baseline design variables were taken as the initial design values of optimization and the created optimization loop was run.

4.6 Results

In the first step of optimization process, analyses were run for the baseline blade design. As a result of these analyses, the centrifugal force and natural frequencies were calculated at the baseline rotor speed. Normalized natural frequencies was calculated by dividing baseline rotor speed. The nonstructural mass and centrifugal force were also calculated as in Table 4.2.

Table 4.2 : Analysis results of baseline design.

Parameter	Result
Mode 1	1.149
Mode 2	1.197
Mode 3	1.822
Mode 4	3.287
Mode 5	6.489
Mode 6	6.654
Centrifugal Force	4.147kN
Nonstructural Mass	0.323kg
Difference Between Normalized Modes	0.048

The constraints were defined by considering the characteristics of the baseline design. The centrifugal force is constrained with baseline value, because the high centrifugal force cause a failure at the blade root. Therefore, defining the constraints, the strength and performance of optimized blade design will be sufficient. Using baseline analysis results, constraints values were determined as in the Table 4.3.

Table 4.3 : Design constraints.

Constraints
Centrifugal Force $\leq 4.15\text{kN}$
Nonstructural Mass $\leq 0.35\text{kg}$
Difference Between Normalized Modes ≥ 0.048

The natural frequency results were examined for both baseline rotor speed and reduced rotor speed in Table 4.4. The normalized difference between rotor harmonics and natural frequencies is lower at reduced rotor speed. Therefore, when the rotor speed is reduced by 20 percent with the variable rotor speed concept, the vibration level of the rotor are expected to be higher than the baseline rotor speed. This result confirms that rotor blade should be optimized in terms of vibration for rotor blade performance improvement with variable rotor speed.

Table 4.4 : Normalized differences between natural frequency and rotor harmonics for baseline blade design.

	Baseline Rotor Speed	20% Reduced Rotor Speed
	$\frac{\omega_i}{\Omega} - \frac{n}{rev}$	$\frac{\omega_i}{\Omega} - \frac{n}{rev}$
Mode 1	0.149	0.166
Mode 2	0.197	0.417
Mode 3	0.178	0.188
Mode 4	0.287	0.435
Mode 5	0.489	0.249
Mode 6	0.346	0.110

The design variables were determined in the optimization structure described in Chapter 2, as in the table below. The lower and upper bounds of the design variables were determined according to the physical limits as in Table 4.5.

Table 4.5 : Bounds of design variables.

Design Variable	Lower Bound	Baseline	Upper Bound
X(1)	0.025R	0.5R	0.925R
X(2)	0.05R	0.95R	0.95R
X(3)	0.1c	0.2c	0.3c
X(4)	0.5mm	4mm	4mm
X(5)	0.5mm	12mm	20mm

Optimization was carried out and the rotor blade was improved in terms of vibration. The baseline and optimized parameter were compared as in the Table 4.6. As a

result of optimization, the objective function of optimization was increased. Since the normalized difference between natural frequency and rotor harmonics, objective function, was increased, rotor vibrations was reduced. In addition, the weight of nonstructural mass and centrifugal force were obtained lower than the baseline design. It is better than the baseline design in terms of structural strength because the centrifugal force is reduced.

Table 4.6 : Parameters for baseline and optimized design.

Parameter	Baseline Design	Optimized Design
X(1)	0.5R	0.516R
X(2)	0.95R	0.845R
X(3)	0.2c	0.246c
X(4)	4mm	3.84mm
X(5)	12mm	11.96mm
Centrifugal Force	4.147kN	2.763kN
Nonstructural Mass	0.323kg	0.227kg
Difference Between Modes	0.048	0.172
Objective Function	0.110	0.163

When the optimization results were examined, it was observed that the nonstructural mass changed both chordwise and spanwise locations. The nonstructural mass is reduced as a result of optimization by decreasing the its spanwise length. The optimized mass per unit span of rotor blade was obtained as Figure 4.5.

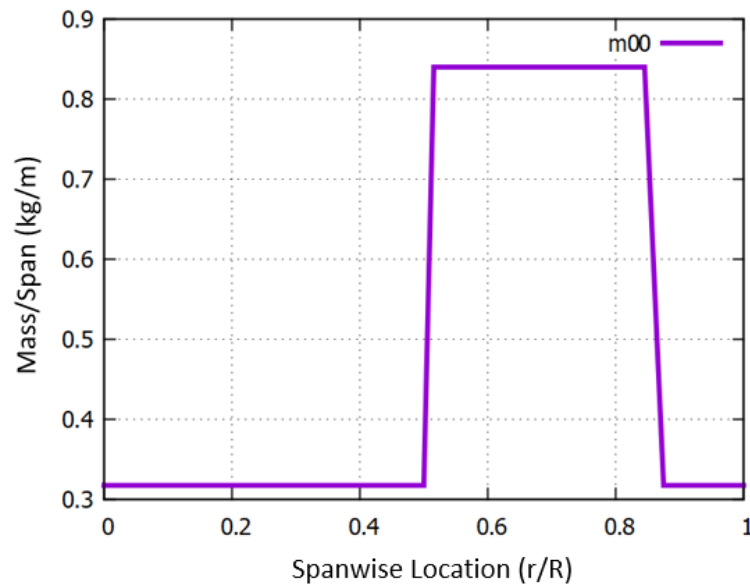


Figure 4.5 : Mass per unit span distribution.

In optimization process, objective function is obtained with calculating the minimum difference between normalized natural frequency(ω_i/Ω) and closest harmonic(n/rev). The baseline and optimized natural frequencies were obtained as following table.

Table 4.7 : Normalized natural frequencies for baseline and optimized design.

	Baseline Design		Optimized Design	
	@Baseline	@Reduced	@Baseline	@Reduced
	Rpm	Rpm	Rpm	Rpm
	ω_i/Ω	ω_i/Ω	ω_i/Ω	ω_i/Ω
Mod 1	1.149	1.166	1.163	1.182
Mod 2	1.197	1.417	1.335	1.596
Mod 3	1.822	2.188	2.288	2.785
Mod 4	3.287	3.435	3.287	3.479
Mod 5	6.489	7.249	6.439	7.166
Mod 6	6.654	8.110	8.390	10.27

The difference between normalized natural frequency and closest harmonic were calculated for all natural frequencies as in the Table 4.8.

Table 4.8 : Differences between normalized natural frequencies and rotor harmonics.

	Baseline Design		Optimized Design	
	@Baseline	@Reduced	@Baseline	@Reduced
	Rpm	Rpm	Rpm	Rpm
	$\frac{\omega_i}{\Omega} - \frac{n}{rev}$	$\frac{\omega_i}{\Omega} - \frac{n}{rev}$	$\frac{\omega_i}{\Omega} - \frac{n}{rev}$	$\frac{\omega_i}{\Omega} - \frac{n}{rev}$
Mod 1	0.149	0.166	0.163	0.182
Mod 2	0.197	0.417	0.335	0.404
Mod 3	0.178	0.188	0.288	0.215
Mod 4	0.287	0.435	0.287	0.479
Mod 5	0.489	0.249	0.439	0.166
Mod 6	0.346	0.110	0.390	0.279

As can be observed from the results in Table 4.8, the blade design that obtained as a result of the optimization has higher differences between normalized natural frequencies and rotor harmonics. The objective function of the optimization was increased by about 48 percent over the initial design. Therefore, with the optimized blade design, the objective function at reduced rotor speed is even better than the baseline rotor speed and design. As a result of the increasing of objective function, the undesired vibration will be reduced.

The fan diagram of optimized rotor blade was created by using calculated natural frequencies as in the Figure 4.6. The fan diagram of optimized blade was compared with fan diagram of baseline design. As a result of comparison, increasing of the difference between natural frequencies and harmonics is observed with optimized design. In addition, with optimized design, the intersection between third mode and 2/rev harmonic was avoided in rotor operation speed range.

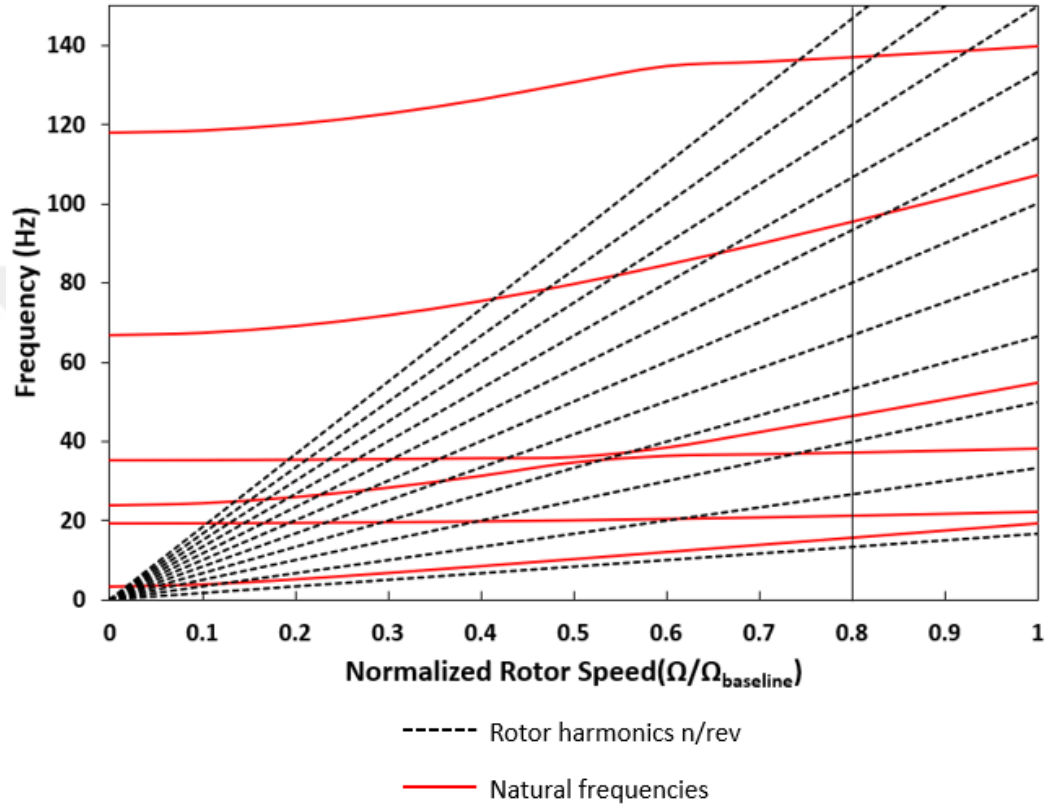


Figure 4.6 : Fan diagram of optimized blade.



5. CONCLUSIONS

In this thesis, it has been studied to improve the performance of a helicopter UAV. In this context, it is aimed to improve the rotor performance of helicopter with variable rotor speed. Secondly, it is aimed to optimize the rotor blade in order to reduce the vibration problems that may occur as a result of these performance improvements.

First of all, the studies in the literature were searched and the methods and tools used were examined. In line with the researches, rotor blade modeling with the variational asymptotic method has been studied. A finite element model was created for cross-section analysis using PreVABS software. By using the created cross-section finite element model, cross-section stiffness and mass characteristics were obtained with VABS. In the next step, the rotor blade is modeled as a flexible beam with Dymore using finite element formulation. Thus, the 3D rotor blade is solved in two stages as a 2D cross section and a 1D beam problem. With the analysis made with Dymore, natural frequencies were calculated at different rotor speeds and a fan diagram was created.

In order to improve the rotor performance, the relationship between rotor speed and rotor power has been investigated. In this context, it is carried out for rotor power estimation under different load and speed conditions. Power estimation formulas derived from blade element theory and momentum theory were used for power estimation.

In line with the power estimation results, it was concluded that the rotor speed is applicable under low load and cruise speed conditions. At the end of this study, by reducing the rotor speed by 20%, the rotor power required can be reduced by approximately 10% in cruising speed and low load conditions.

In the final stage, an optimization cycle is established. In this optimization process, it is aimed to separate the natural frequencies and rotor excitation. For this, the geometry

and position of the non-structural mass in the rotor are used as design variables. Mass and centrifugal force are considered as constraints. As a result of the optimization, the difference between the normalized blade natural frequencies and rotor harmonics has been increased by approximately 48%. In addition, non-structural mass and centrifugal force are also reduced. As a result of the optimization, a better design has been achieved in terms of both vibration and performance compared to the initial design.

5.1 Recommendations for Future Work

In this study, rotor power estimation was calculated by blade element momentum theory based equations. In order to examine the effects of rotor speed on performance in more detail, computational fluid dynamics software or rotor comprehensive analysis codes such as Dymore and CAMRAD II can be used for required power estimation.

In this thesis, vibrations on the rotor were studied with natural frequencies and rotor harmonics. In further studies, an optimization process can be created that considers both the natural frequencies and the forces acting on the rotor hub. In addition, aerodynamic forces can be included in the analysis and their effects on vibration and damping can be observed.

Structural design variables such as composite layer properties can be included as well as non-structural mass to enhance optimization studies. In addition, when structural variables are included, strength constraints can be defined by determining failure criteria for composite materials.

In optimization studies, gradient-based and non-gradient algorithms can be used together to reach the global minimum efficiently.

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APPENDICES

APPENDIX A : Engine Specifications





APPENDIX A : Engine Specifications

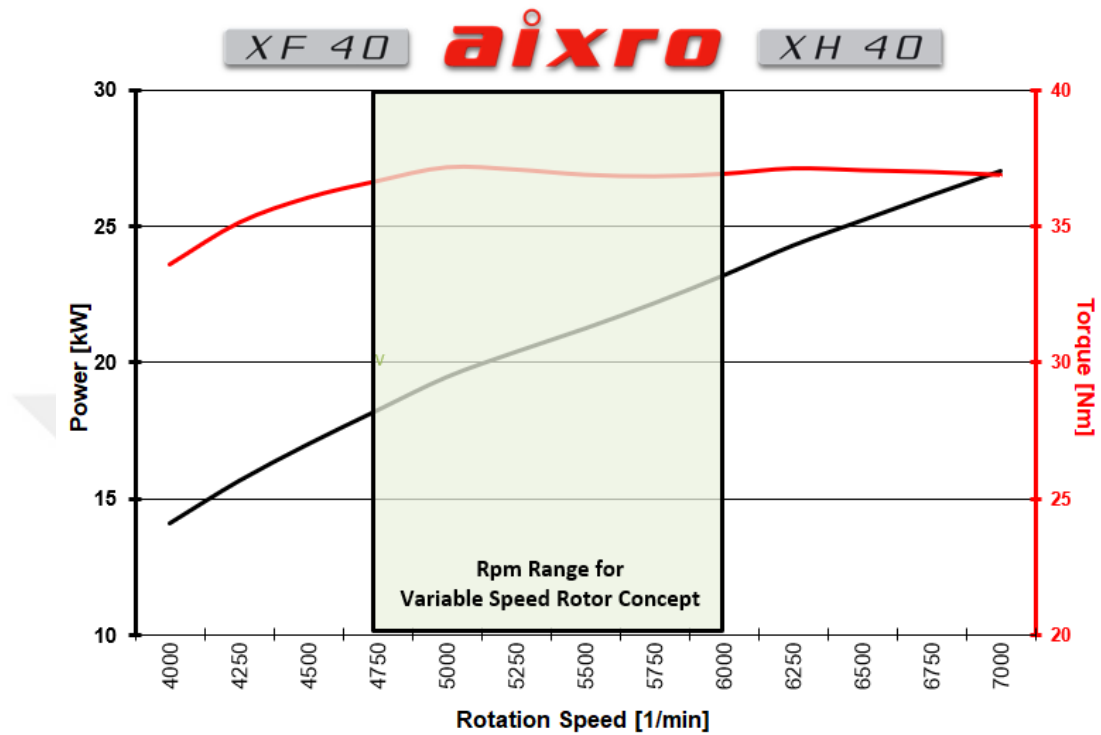


Figure A.1 : Torque and power curves of Aixro XH40 engine [35].



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