Aerospace Science and Technology 63 (2017) 18–32

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Optimum active twist input scenario for performance improvement and vibration reduction of a helicopter rotor

Younghyun You, Sung N. Jung *

Department of Aerospace Information Engineering, Konkuk University, 120 Neungdong-ro, Gwangjin-gu, Seoul 05029, Republic of Korea

ARTICLE INFO

Article history:
Received 26 January 2016
Received in revised form 28 November 2016
Accepted 9 December 2016
Available online 15 December 2016

Keywords:
Active twist rotor
Optimization
Descending flight
Power consumption
Hub vibration

ABSTRACT

In this paper, the best actuation scenario is sought using a multitude of active twist control inputs taking advantage of a global search algorithm to improve performance and reduce vibration of a helicopter rotor. The active twist schemes include a single harmonic, multiple harmonic, and three different segmented non-harmonic actuation cases. An advanced particle swarm assisted genetic algorithm (PSGA) is employed for the optimizer. In addition, a comprehensive rotorcraft analysis code CAMRAD II is used to reach the trim and to predict the rotor power and hub vibratory loads. A scale-down BO-105 model is used for the reference rotor while assuming the actuator material embedded in the blade structure. Among the active twist control inputs, the non-harmonic cases show the best performance gains in reducing the hub vibrations and power consumptions. The hub vibration is reduced by up to 87% while the rotor power required is decreased by 3.3% as compared to the baseline uncontrolled rotor in low speed descending flight condition when using the non-harmonic active twist schedules. The resulting optimized actuation profiles are found for each of the active twist control cases and the physical mechanism leading to less vibration and power consumption is discussed. The Pareto optimum is also examined to illustrate the simultaneous reduction in the power required and the hub vibration of the rotor.

1. Introduction

During the past decades, high vibration and noise, and relatively low performance characteristic of a rotor in various flight regimes have been the key issues of concern in the rotorcraft aeromechanics field. A variety of active control concepts and mechanisms have been studied as potential engineering solution to tackle the problem. Among the proposed methods, the active twist rotor (ATR) concept offers clear advantages such as the fact that no hydraulic power systems and separate mechanical parts are required since the rotor blades are directly twisted using the concept of induced-strain actuation which inherently serve as a blade structure. The ATR is pioneered by Chen and Chopra [1] exploiting the benefit of direct strain components of embedded piezoceramic elements. The detailed discussion of ATR and its development are found in Chopra [2], Thakkar and Ganguli [3], and Pawar and Jung [4].

The first and the most widely explored ATR scheme uses a single harmonic type of control introduced into the rotor blade individually. In this setup, the amplitude and phase of given higher harmonic frequency are varied arbitrarily for the twist control. The representative study is NASA/Army/MIT active twist rotor [5,6] tested in the NASA Langley Transonic Dynamics Tunnel. Either of 3 to 5/rev actuation is applied to the actuator region that leads to a favorable vibration and blade-vortex interaction (BVI) noise reduction. Yeo [7] investigated the capability of the currently-available active control concepts including the active twist control. A 2/rev harmonic ATR input is used for the improvement of the rotor performance. The rotor lift-to-drag ratio is increased by about 10% at high speed conditions with slight decrease in blade loading. Recently, an international joint program called STAR (Smart Twisting Active Rotor) is formed to search the benefits of the active twist concept for performance improvement, vibration reduction, and noise alleviation of a rotor [8]. Up to 5/rev active twist harmonic inputs are applied to a variety of flight conditions and the study shows a potential in reaching the desired goals. This type of control is simple in nature, but the overall performance is essentially limited to the specified wave form of the harmonic function because it does not take any flexibility into account to counter adverse aeroelastic environments faced during the helicopter flights.

The second method uses a multi-harmonic twist input that consists of a number of higher harmonic components. Strictly speaking, the single harmonic actuation is a subset of the second type. However, they are divided into separate cases to clearly understand

---

* Corresponding author.
E-mail addresses: john82@konkuk.ac.kr (Y. You), snjung@konkuk.ac.kr (S.N. Jung).

http://dx.doi.org/10.1016/j.ast.2016.12.011

Nomenclature

A	Amplitude of twist moment	(N-m)
B_0	Steady twisting moment	(N-m)
B_n	Amplitude of the n-th harmonic frequency	(N-m)
c_{d0}	Mean airfoil drag coefficient	
H_x	Rotor drag force	(N)
M_i	Rotor hub moments	(N-m)
N_b	Number of blade	
n	Single harmonic number	
F_i	Rotor hub shear forces	(N)
P	Rotor total power required	(kW)
R	Rotor radius	(m)
T	Twisting moment	(N-m)
W_0	Rotorcraft reference weight	(N)
w	Weight factor	
$\mathbf{x}$	Design variable vector	
ρ	Air density	(kg/m^3)
$\theta_{()}$	Trim control angles	(°)
ϕ	Phase angle	(°)
ϕ_n	Phase angle of the n-th harmonic frequency	(°)
μ	Advance ratio	
σ	Rotor solidity	
ψ	Rotor azimuth angle	(°)
Ω	Nominal rotor speed	(rad/s)

the benefit of the twist control with each other. Zhang et al. [9] and Bailly et al. [10] used combined inputs comprised of up to 5/rev harmonics to demonstrate the potential improvement of ATR with respect to the rotor performance, vibration, and noise reduction. The multi-harmonic type offers a broad spectrum of harmonic inputs to enlarge the actuation authority when compared with the single harmonic counterpart, while the complexity becomes increased significantly due to larger design space in the multiple component inputs.

The final one is the non-harmonic type of twist inputs that has been studied recently. In this actuation, arbitrary waveforms such as a step or saw-type input are generated to activate the blade. Fogarty et al. [11] used a step input to examine the BVI noise characteristic according to the actuation of MFC (Macro Fiber Composites) actuator plies embedded in a portion of an Apache AH-64A blade. The step input is characterized by rotor azimuthal location to start, duration, and magnitude of actuation. A noise reduction of up to 10 dB in BVI noise is reached with the non-harmonic active control. It is indicated that the noise reduction performance is highly dependent on the choice of the initial azimuthal location and the duration in the actuation. Jain et al. [12] investigated several on-blade active controls including the active twist control for improving the rotor performance. An advancing-side-only actuation with 2/rev (twice per revolution) harmonic form is adopted in the twist control. The study reveals that the proposed waveform is effective in improving the performance of a rotor particularly in high speed flight where the outboard tip region is subjected to a negative loading. These non-harmonic actuation studies show great potential in reducing BVI noise and increasing performance gains. However, only single step or simple harmonic waveform has been introduced in the actuation. To maximize the actuation performance, there is a need to make use of more general forms of harmonic or non-harmonic waveform shapes suited to the rotorcraft operation environment in different flight regimes.

The objective of the current work is to find the best actuation deployment scenario using various types of ATR inputs taking advantage of a global search algorithm for performance improvement and vibration reduction. The actuation scenarios include a single harmonic, multiple harmonic, and several segmented non-harmonic inputs. An advanced particle swarm assisted genetic algorithm (PSGA) [13] is employed for the optimizer, and the comprehensive rotorcraft analysis code CAMRAD II [14] is used to compute the behavior of a rotor. The numerical simulation is conducted first to verify the present optimum vibration/performance results as compared with the predictions from the parameter sweep study computed over the whole design space (e.g., frequency contents, amplitudes, and phases). Next, either the rotor performance improvement or vibration reduction is studied in low speed descent and high speed forward flight conditions. Finally, a simultaneous vibration reduction and performance improvement is sought using the multi-objective function approach.

2. Analysis methods

The analytical approaches and optimization algorithms adopted in the present study are described in the following subsections. The active twist input schedules to reduce vibration and improve performance are also discussed.

2.1. Rotorcraft aeromechanics analysis

A comprehensive rotorcraft dynamics analysis code CAMRAD II [14] is used to analyse the rotor. The code is characterized by multibody dynamics, nonlinear finite elements, and various levels of rotorcraft aerodynamic models. For the structural analysis, the blade motion is expressed as the summation of the rigid body motion and the elastic motion. The rigid body motion describes the motion of end of the beam element, and the elastic motion is measured relative to the rigid body motion. They consist of 6° of freedom (DOF) for the rigid motion and 9 DOF for elastic motion (3 axial, 2 flap, 2 lead-lag, and 2 torsion) resulting in a 15 DOF per beam element. The aerodynamic model of CAMRAD II is based on the lifting-line theory combined with the airfoil table look-up as well as various levels of the vortex wake representations. In this study, the blade structure is discretized into 18 nonlinear beam finite elements along the blade span. The ONERA-EDLIN unsteady aerodynamic theory along with C81 airfoil table look-up is used to calculate the aerodynamic loads acting on the blade. In addition, a rolled-up free wake model is introduced to the non-uniform induced inflow of the rotor. The rolled-up wake model is based on the feature that a tip vortex forms at the blade tip and convects to the flow field behind the rotor. Only an isolated rotor condition is considered to simplify the analysis.

CAMRAD II is not equipped with the option to model the induced strain actuation of the piezoelectric actuator. Therefore, the active twist model is implemented by applying torsional moments with equal and opposite magnitudes at both extremities over the actuator region of the blade. Fig. 1 shows the schematic of the active twist control mechanism under the application of the torsional moments. It is assumed that the MFC actuator is embedded in the skin of the blade structure, spanning from 24% to 96% of the blade radius. It is also assumed that the applied torsional couple results in a linear variation of twist angle along the blade span while no twist variation exists in the free-actuation region (see Fig. 1). Note that a positive twist couple produces nose-up pitch motion. The actuator region in the blade is modeled with 6 beam finite elements. The effect of the embedded piezoelectric actuators on the structural properties of the blade is ignored.