9th ANKARA INTERNATIONAL AEROSPACE CONFERENCE **AIAC-2017-071**
20-22 September 2017 - METU, Ankara TURKEY

VIBRATION REDUCTION IN A HELICOPTER USING ACTIVE TWIST ROTOR BLADE METHOD INCORPORATING DIFFERENT PIEZOELECTRIC FIBER COMPOSITES

Mürüvvet Sinem SİCİM [1]
Turkish Technich
istanbul/TURKEY

Levent Ünlüsoy [2]
Roketsan A.Ş.
Ankara/TURKEY

ABSTRACT

During the takeoff, landing, climb and descend a helicopter move in almost any direction. Due to the several flight envelopes characterizing a helicopter mission, it is nearly impossible to meet the different design requirements by using fixed blade configuration. This is why recent technologies study on influence the flow conditions by passive and active means. In this paper, implementations of morphing technologies to reduce vibration levels due to rotor aerodynamics at helicopters are observed. By using Active Twist Rotor method, the effects of varied actuators such as MFC (Macro Fiber Composite), AFC (Active Fiber Composite) and single crystal piezoelectric fiber composite on vibration reduction are examined. The actuation performance of the different piezoelectric materials for the active twist rotor blade is exhibited.

[1] Postgraduate Student , sinemsicim@gmail.com
[2] Aerospace Engineer, Dr.,levent.unlusoy@roketsan.com.tr

INTRODUCTION

Helicopters are exposed to complex unsteady aerodynamic conditions during different mission cycles. The main rotor experiences highly unsteady aerodynamic loads, which cause the vibrations and noise. The rotor region on helicopter is divided by two parts which are named as advancing side and retreating side. In forward flight, asymmetric flow condition occurs due to due to different wind flow velocity between advancing side and retreating side. Forward airspeed of the helicopter increase the relative wind on advancing side, while it decreases the relative wind on retreating side. Therefore, more lift is produced on the advancing side because of relative wind speed. Producing unequal lift is called as dissymmetry of lift which causes the vibratory loads on rotor region. Dissimilarities between lift cause additional vibration, performance, stability, and rotor blade tracking problems. Figure 1 shows that rotary-wing flight vehicle aerodynamic environment in forward flight.

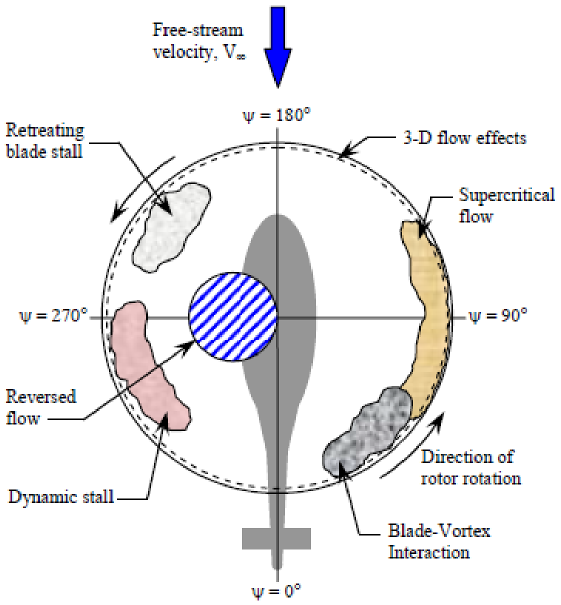

Figure 1: Aerodynamic environment in forward flight for helikopter [Matthew L. Wilbur and W. Wilkie K., 2004]

The other aerodynamic phenomena which lead to vibration is retreating side stall which is the major reason of limiting forward speed. When blade moves opposite direction of the flight, relative wind diminishes while forward speed increases. The angle of attack (AOA) must be increased to obtain equal lift with advanced side. If AOA continue to increase, retreating side will stall despite the fact that advance side continue to produce lift with some forward speed.
Figure 2 shows that angle of attack distribution on retreating blade stall. Stall angle of attack equals to 14 degree. Helicopter rotors design with twisted blade and twist angle decreases root to tip region. However, AOA is higher at the tip due to induced flow. Major problems due to retreating side stall are noticeable vibration, pitchup of the nose etc.

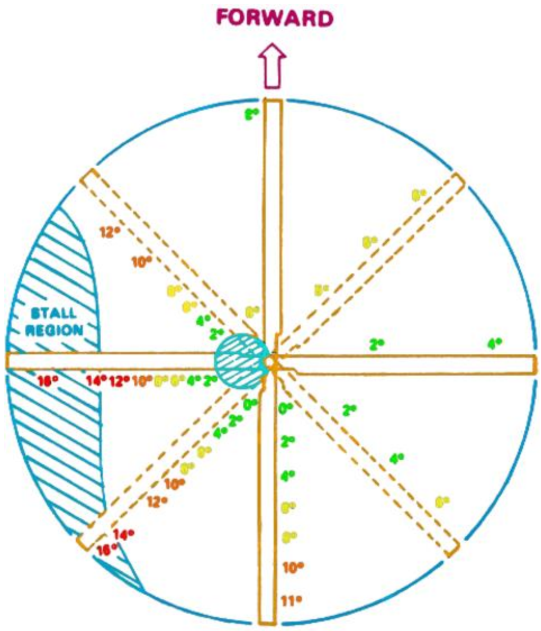

Figure 2: Angle of attack distribution

Vibration is reduced by applying passive and active techniques to influence aerodynamic conditions. Passive approach which is a traditional vibration reduction technique is used to alleviate for many years by applying vibration isolators and absorbers. However, well accepted solutions which can decrease effects of these problems have yet to be established. On the other hand, the source of aerodynamics loads can be directly interfered using active techniques. Therefore they are more effective solution for vibration reduction when compare the passive methods. General approach for active method is to change the blade pitch at harmonic frequencies above the rotational frequency. Higher harmonic control (HHC), Individual Blade Control (IBC), active trailing-edge flap and active-twist rotor methods are types of the active approach. HHC starts to use in 1970s and has results in vibration and noise reduction by using swashplate to change the pitch angle. [Wood, E. R., Powers, R. W., Hammond, C. E., and Cline, J. H., "On Developing and Flight Testing A Higher Harmonic Control System," Journal of the American Helicopter Society, Vol. 30, (1), January 1985, pp. 3-20.] IBC uses hydraulically actuated pitch motion to control pitch angle of each blade individually. Applications of these methods are difficult due to complex and heavy hydraulic system. In addition to these systems, on-blade actuators used to control vibration in rotor is widespread method.

On-blade actuator systems reduce vibration more safety ways and its failure would not affect the flight safety as much as HHC and IBC. These systems don't include many motion parts so consume less energy. Discrete actuators and continuous / embedded actuation are two major types of on-blade systems. In this paper active twist rotor system which is one of the continuous / embedded actuation methods is used to reduce vibration. In this concept active material is embedded directly cross section of the blade.

In this paper, application of active twist rotor method to reduce vibration on helicopter rotor blade by using different active materials is observed. The main aim of the paper minimizes the vibration due to aerodynamic loads. The effects of three different piezocomposite (Active-Fiber Composites,_Macro-Fiber Composite and Single Crystal Macro Fiber Composite) are compared to efficiency on reduction. Beginning of the design process, Shark-120 model which is an unmanned helicopter is selected to use as a design parameters. The appearance and specification of helicopter can be seen in Figure 1 and Table 1.

Figure 3: Shark-120 Helikopteri [Choi K., Lee J., Lee I. and Kim J.,2012]

Table 1. Specifications of the Shark-120 [Choi K., Lee J., Lee I. and Kim J.,2012]

Main Rotor	4 Rotors, diameter 3.12 m
Motor	294cc 35HP, 6,500rpm
Weight	83kg
Payload	40 kg
Operational Range	15 km
Flight Time	1 hour

Number of main rotor, total weight and rotor diameter are major properties of Shark-120 used in design. Rotor blade has a NACA 23012 airfoil with a rectangular shape as seen in Figure 3. It includes D-spar which is made of unidirectional Glass Fiber Reinforced Polymer and +45^0/–45^0 GFRP skin. To improve the strength of the blade, foam parts are added inside of the blade. Blade chord equals to 0.121 meter and blade radius is 1.56 with 0.35 meter hub region. The skin has a four composite layer.

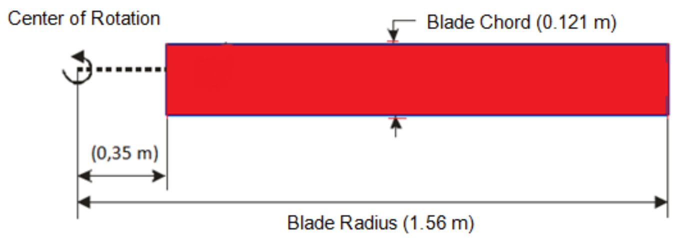

Figure 4: Dimensions of the helicopter rotor blade.

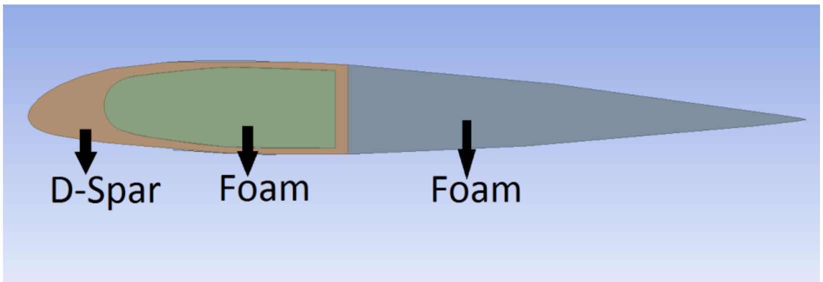

Figure 5: Cross-section of the helicopter rotor blade.

Piezocomposites

Piezocomposite is a polymer material with embedded piezoelectric material. Piezocomposites as find a fundamental type of smart materials, it`s inexpensive and easy manufacture way than other smart materials. That's why, many research still in progress. Piezocomposite actuators can easily integrated into the composite structure on blade as active plies which are oriented at ±45^0 angle to reduce shear stresses resulting due to twisting deformation. MFC (macro fiber composite), AFC (active fiber composites), PFC (Piezoelectric Fiber Composites) and single crystal piezoelectric fiber composites are type of the piezoelectric. They display different behaviour on active twist rotor systems when applying voltage.

Active-Fiber Composites (AFC)

Active Fiber Composite was developed at MIT to overcome drawbacks of monolithic piezoceramics which has an application problem due to brittle nature. AFC consists of piezoceramics fibers and soft polymer matrix to provide the load transfer mechanism as seen in Figure 5. Although, brittle ceramic fibers provide the actuation characteristic with high stiffness, piezoceramic fibers which shows low strain behavior are inclined to crack. Polymer matrix applied around the fiber improved the strength properties of AFC and occurs a path around the fiber to improve load transfer mechanism. [Jones, R. M, Mechanics of Composite Materials, Taylor & Francis, 1999]. Therefore, actuator can withstand higher strains than individual fibers. Polyimide film which has a conductive pattern to enable for applying the driving electrical field sandwich the fibers which are located in epoxy matrix. Interdigitated electrode pattern is used to excitation of the actuator which means an in-plane mechanical deformation in the direction of the fibers.

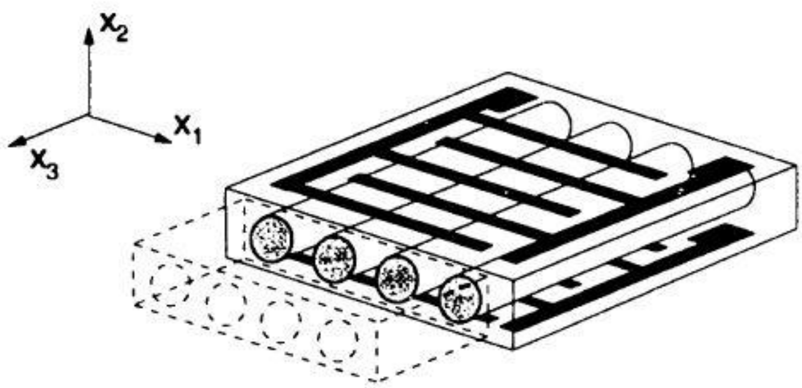

Figure 5: General arrangement of an active fiber composite (AFC) and active situation illustration. [Bent A. A, 1997]

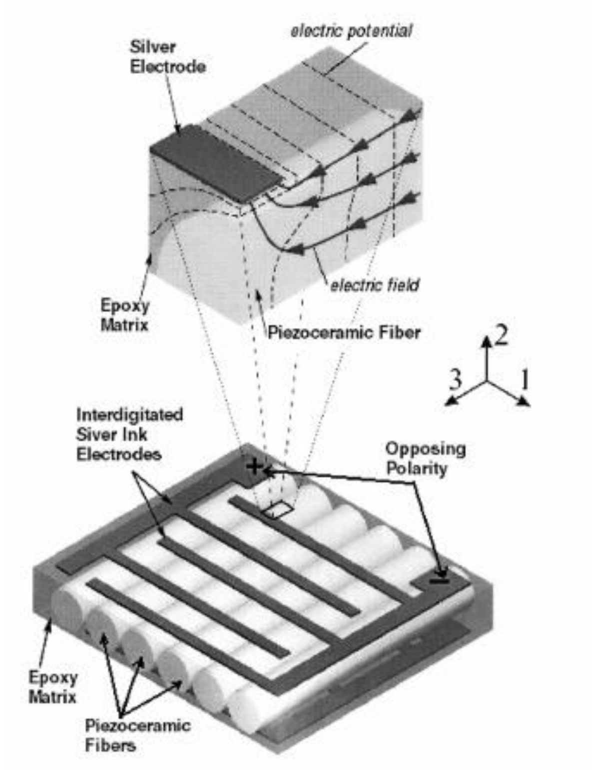

Figure 6: Detailed Illustration of Active Fiber Composite (AFC) [Hagood N. W., Bent A. A.,1993]

Macro-Fiber Composite (MFC)

Macro-Fiber Composite (MFC) which has the rectangular cross section consists of piezoceramic fiber and sandwiched between polyamide films that have attached interdigitated electrode patterns. MFC actuator developed at NASA's Langley Research Center in 1996 is used as smart material.[Proc 34th AIAA Structures, Structural Dynamics and Materials Conference, La Jolla, CA, Part 6. 1993] Unlike the AFC, rectangular cross section of piezoceramic increases the maximum contact area between the piezoceramic fibers and the interdigitated electrodes.It can be operate between 500 V and +1500 V by helping of particular electrode design. They produce strain-induced twisting motions of the blade when using electrical voltage. The proposed actuation concepts are based on piezoelectric actuation with focus on d33-mode. MFC has piezoelectric actuators between a two thin epoxy matrix and it can be producing 2-3 inch plates nowadays (Figure 7).

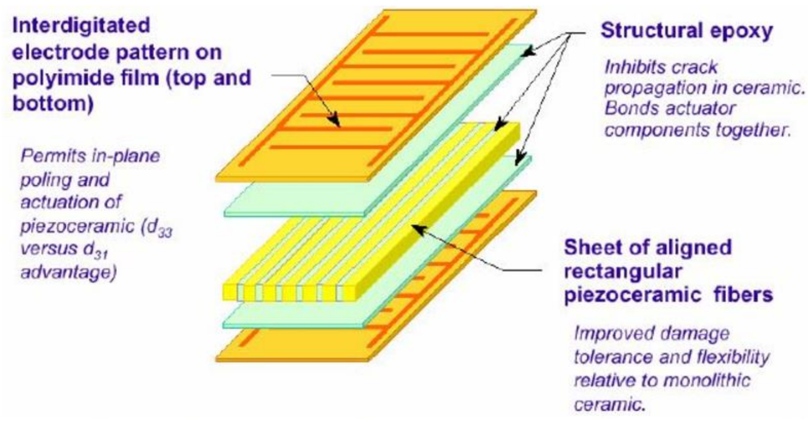

Figure 7: NASA-ARL Macro-Fiber Composite actuator. [8 Keats W., Matthew L., Wilbur, and Wilkie, 2004]

The difference between AFC (active fiber composite) and MFC (macro fiber composite) is in the manufacturing process of the fiber. While the AFC fibers are developed using standard sol-gel technique, the MFC fibers are essentially chopped from PZT blocks. The MFC fibers are rectangular in cross-section and hence it offers better electrical contact between the fibers.

Single Crystal Macro Fiber Composite

High performance single-crystal piezoelectric materials can give greater stress and strain output by using interdigitated piezocomposites. [Park, S.-E. and Shrout, T. 1997- H. and Harmer, M. 1999] Single-crystal piezoelectrics illustrate much higher coupling, energy density and maximum strain outputs compare with their polycrystalline counterparts. ‘Single-crystal piezoelectrics exhibit maximum strains of up to 1% and piezoelectric coupling of up to 90%, compared to maximum strains of 0.1% and piezoelectric coupling of 75% for comparable polycrystalline piezoelectric materials.’[Park, S.-E. and Shrout, T. 1997] Single-crystal strain energy densities demonstrate five times the strain energy densities of polycrystalline piezoelectric material.

Mechanic properties of rotor blade component with different piezocomposites used to active twist method can be seen as follow:

Table 1: Properties of materials used in the cross-section.

	Glas Fiber Reinforced Polymer (GFRP)	Foam	Active-Fiber Composites (AFC)	Single Crystal Macro Fiber Composite	Macro-Fiber Composite (MFC)
E_X	45.166 GPa	0.035 GPa	16.11 GPa	6.23 GPa	15.5 GPa
E_Y	11.981 GPa	0.035 GPa	16.11 GPa	6.23 GPa	15.5 GPa
E_Z	11.981 GPa	0.035 GPa	30.54 GPa	11.08 GPa	30.0 GPa
Gxz	4.583 GPa	0.014 GPa			5.7 GPa,
Gyz	1.289 GPa	0.014 GPa	5.5 GPa	2.01 GPa	10.7 GPa,
Gxy	1.289 GPa	0.014 GPa	5.5 GPa	2.01 GPa	10.7 GPa
υyz	0.325	0.25			0.35
υxz	0.238	0.25	0.36	0.229	0.4
υxy	0.238	0.25	0.36	0.229	0.4
ρ	2008 kg/m3	52 kg/m3		5338.3	4700 kg/m3

Table 2: Thermal Expansion Coefficient of MFC and Single Crystal MFC. [Park, J.S., Kim, J.H., 2006]

Thermal Expantion Coefficient	AFC	Standard MFC	Single Crystal MFC
α_1 (x $10^{-6}/^oC$)	0.95	4.81	18.86
α_2 (x $10^{-6}/^oC$)	2.256	14.76	18.86

METHOD

To decrease the amplitude in the resonance frequency range, piezoelectric actuators are set on both top and bottom of the blade. The results were obtained by using different type of piezoelectric materials individually. These arrangements and analyses performed using ANSYS® mechanical (workbench) program. Analyses are performed using a method called Fluid Structure Interaction (FSI). FSI provides a coupled solution to the fluid and structure dynamics. Electric field is modelled by using a thermal analogy and the relationship between the piezoelectric strain and thermal strain is calculated by formulas.

ANSYS® Fluent tool is used to represent the aerodynamic loads. Harmonic and modal analyses are conducted after structural, thermal and fluent analyses are performed. All aerodynamic forces are directly transferred to harmonic and modal analysis. The real twist effect of piezoelectric chips on blade after applying voltage can be shown.

Mesh structure for skin and inner side of the rotor includes foam and D spar can be seen in figure 8.

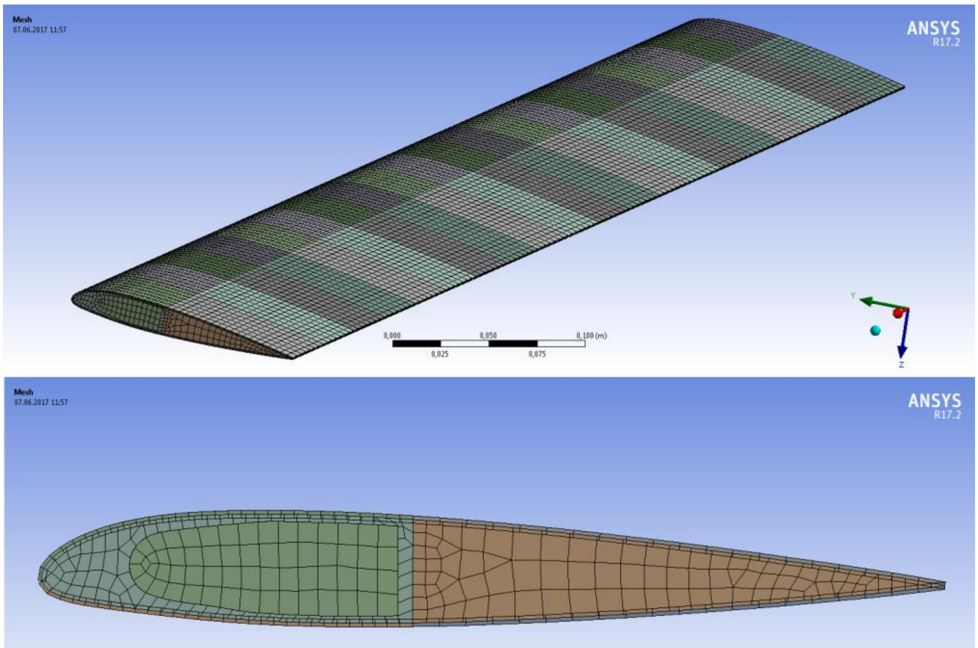

Figure 8: Finite Element Model of Rotor Blade

Also, figure 9 indicates the boundary of air around the rotor blade in forward flight. There are two different fluid region to consider CPU and GPU limitations. First fluid region is constitute with near blade region by using fine mesh. The other one is cover remote region of blade with coarser mesh.

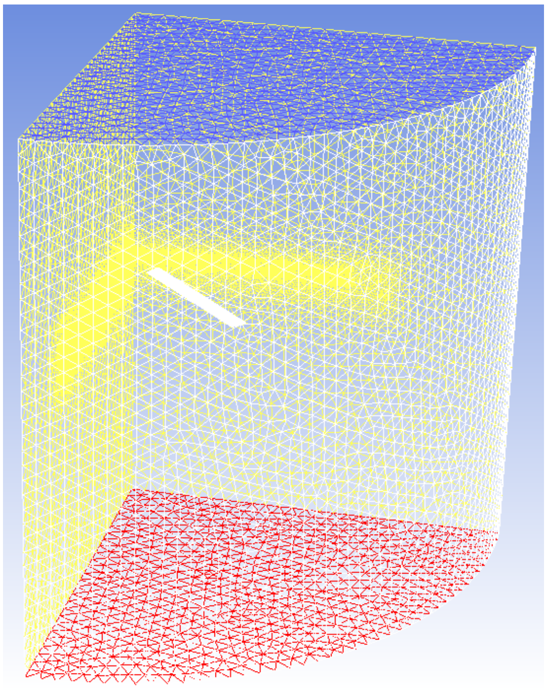

Figure 9: Fluent Model of Rotor Blade

According to modal analysıs results, torsion mode is used to determine the optimum placement of piezoelectric actuators. Figure 10 shows the mode shape of torsion mode which is fifth mode when looking to modal analysis and also application points of piezoelectric actuators.

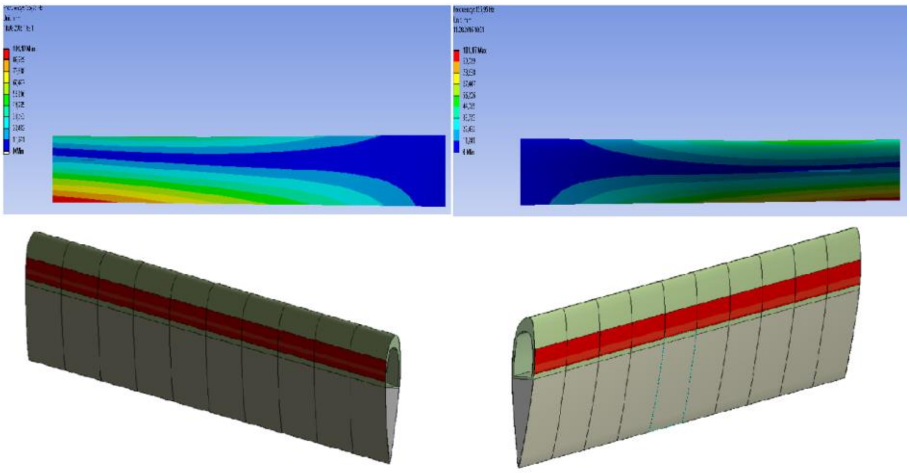

Figure 10: Application of Piezoelectric Actuators

"*To observe the voltage effect on piezoelectric actuator in Ansys, thermal analogy method is used. According to this analogy, the strain caused by the voltage difference is modelled analogous to strain as a result of temperature difference so voltage effect on model can be simulate with thermal effect without using piezoelectric modelling. Thermal expansion coefficients are used to input to represent piezoelectric strain effect. The relationship between piezoelectric strains and thermal strains is obtained as following*" [Sicim, S. , Unlüsoy, L. , 2017]

$$\propto_{ij} = \frac{d_{ij}}{t}$$

Voltage difference assume same with the temperature difference. Therefore, during analysis, voltage effect is simulated by application of temperature. Shape change of due to smart materials can be observed on thermal analysis.

RESULTS and DISCUSSION

In this paper, effects of different smart material on vibration reduction by using active twist rotor blade method is investigated. MFC (Macro Fiber Composite), AFC (Active Fiber Composite) and single crystal piezoelectric fiber composite are used as a smart material to obtain twist motion by helping of voltage effect. At the beginning of the analysis, patch are added to 3D blade model. Therefore, change in weight doesn't affect the modal and harmonic analysis results. Table 3 shows first ten natural frequencies of blade. Twist mode shapes related to fifth mode of the model can be shown as Figure 11.

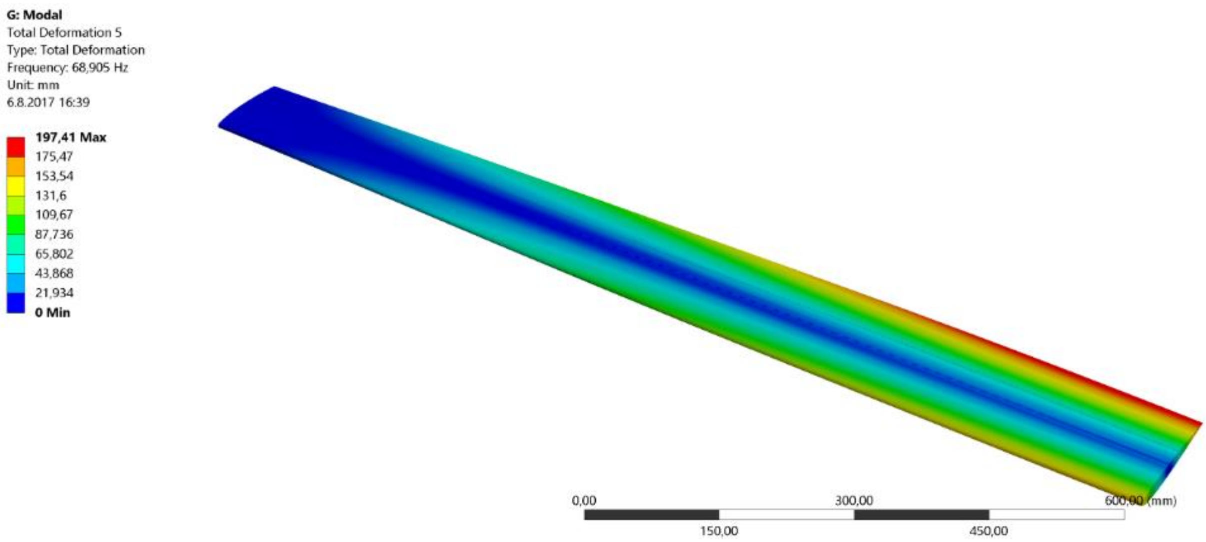

Figure 11: Twist mode shape of rotor blade without application of smart material

Table 3: Natural Frequency of Rotor Blade without smart material application

Mode Number	Frequecny [Hz]
1,	3,6423
2,	20,567
3,	23,38
4,	56,161
5,	68,905
6,	108,22
7,	138,4
8,	174,8
9,	178,86
10,	256,72

Application of different smart materials by application of +1500 V is conducted. Decreasing of amplitudes at critical tortion mode frequency is compared for each smart material application according to without smart material condition. In addition, change in tortion mode frequency is investigated. Formula given as below is used to calculate rate of vibration reduction.

$$R = \left(1 - \frac{A}{A_0}\right) * 100\%$$

where A_0 is amplitude when V=0 and A equals to amplitude when V≠0.

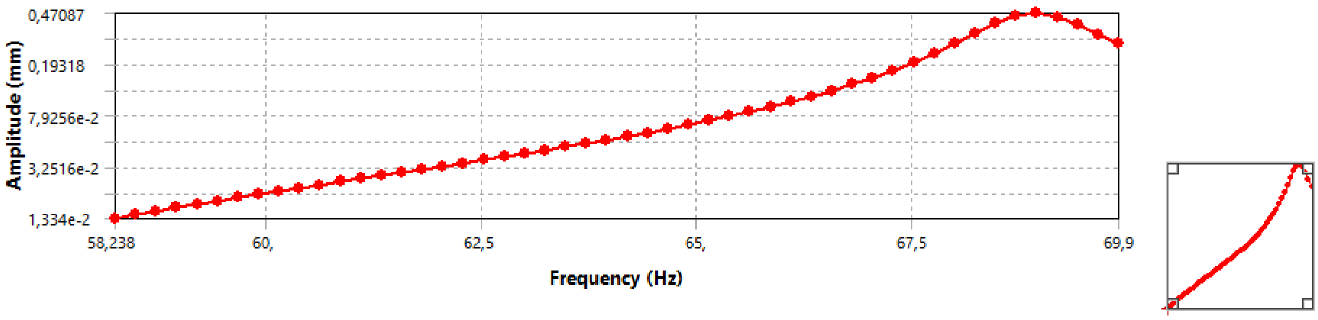

Figure 12: Amplitude vs Frequency without smart material application

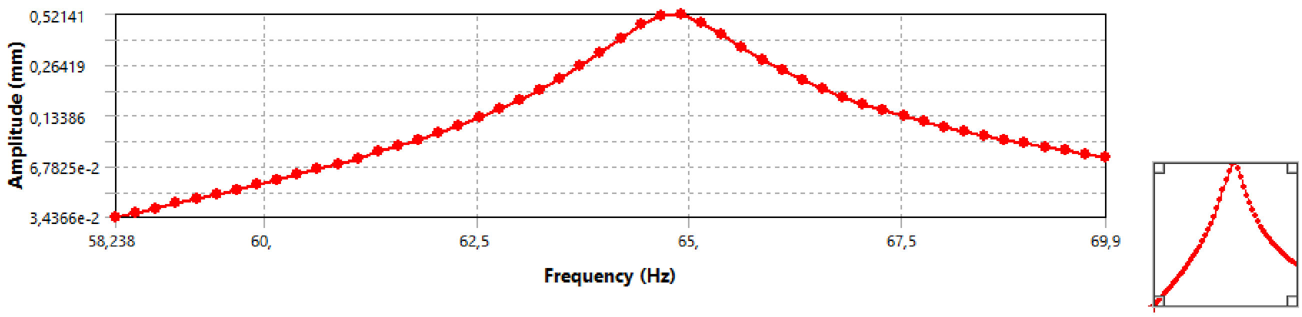

Figure 13: Amplitude vs Frequency with AFC

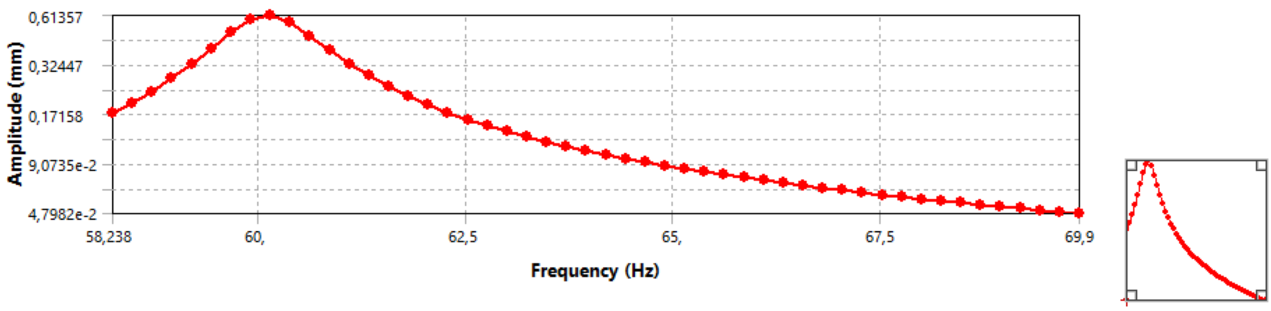

Figure 14: Amplitude vs Frequency with MFC

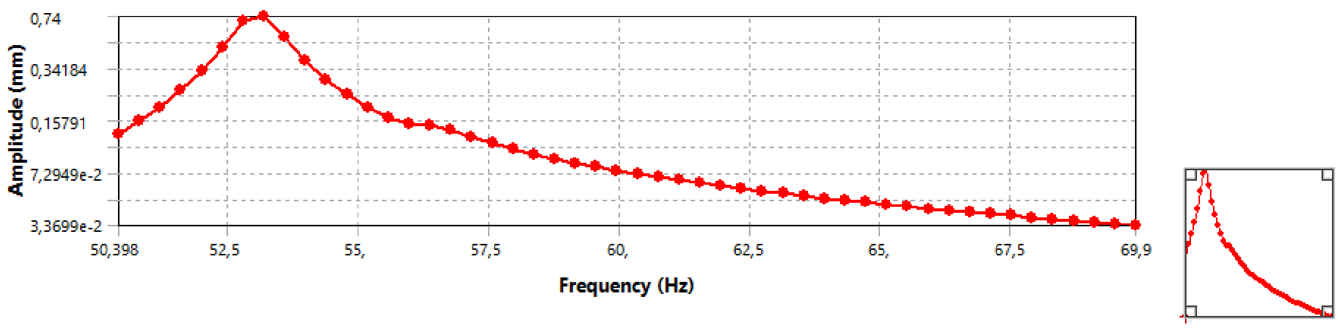

Figure 15: Amplitude vs Frequency with Single Crystal MFC

Table 4: Rate of reduction according to used smart materials

Patch Input	Amplitude [mm]	Decrease in %
No MFC	0,47087	0,0%
AFC	7,1119e-002	19,57%
MFC	5,2387e-002	88,87%
Single Crystal MFC	3,6111e-002	92,33%

Table 5: Decrease in critical tortion mode frequency

Patch Input	Tortion mode frequency (Hz)
No MFC	68,9
AFC	64,789
MFC	60,094
Single	53,034

CONCLUTION

Vibration reduction on helicopter rotor blade by using different piezocomposite material. Active twist rotor blade method is selected to vibration reduction methodology. The results are obtained by using AFC, MFC and Single Crystal MFC. Results are obtained by ANSYS packages. Thermal analogy is used instead of voltage applied. The study shows that all of the material which are used in analysis are highly efficient to reduce vibration on rotor. Tortion mode decreases 68.9 Hz to 53.0 Hz by using active materials. Moreover, by helping Single Crystal MFC, %92.33 vibration reduction rate is obtained while vibration reduction rate for MFC material application equals to %88.87. According to study, Single Crystal MFC is more effective solution to reduce vibration on rotor blade. At this point, density of the single crystal MFC is very high compare the density of AFC and MFC. Therefore, optimum case must be selected to actuate structure effectively.

References

Bent A. A., “Active fiber composites for structural actuation”, PhD Dissertation, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, (1997).

Barkanov E., Gluhihs S., Kovalovs A., (2007). NUMERICAL OPTIMIZATION OF HELICOPTER ROTOR BLADE DESIGN FOR ACTIVE TWIST CONTROL, Aviation

Chattopadhyay A., Liu Q., Nam C.,(1999). Rotor vibratory response analysis using smart materials and aero elastic control / AIAA-99-1504.

CHEN, P., CHOPRA, I., (1996). Induced strain actuation of composite beams and rotor blades with embedded piezoceramic elements. Smart Material Structures., vol. 5, p. 35–48.

CHEN, P., CHOPRA, I., (1997).Hover testing of smart rotor with induced-strain actuation of blade twist. AIAA proc. (1997), vol. 35, p. 6–16.

Centolanza L.R., Munsky B.,Smith E.C., (2002). Induced-shear piezoelectric actuators for rotor blade trailing edge flap// Smart Mater. Struct. – Vol. 11. – P. 24–35.

Choi K., Lee J., Lee I. and Kim J., (2012)*DETERMINATION OF EXTERIOR ORIENTATION PARAMETERS THROUGH DIRECT GEO-REFERENCING IN A REAL-TIME AERIAL MONITORING SYSTEM,* International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XXXIX-B1, (2012) XXII ISPRS Congress

Dong X., Meng G., (2005), Dynamic analysis of structures with piezoelectric actuators based on thermal analogy method, International Journal of Advanced Manufacturing Technology. 27: 841–844.

Hagood N. W., Bent A. A., “Development of piezoelectrical fiber composites for structural actuation”, In: Proc 34th AIAA Structures, Structural Dynamics and Materials Conference, La Jolla, CA, Part 6. 1993. pp. 3625–38.

Keats W., Matthew L., Wilbur, and Wilkie, (2004) *ACTIVE-TWIST ROTOR CONTROL APPLICATIONS FOR UAV,* U.S. Army Research Laboratory Vehicle Technology Directorate Hampton, VA 23681

Khan, A., Meschke, F., Li, T., Scotch, A., Chan, H. and Harmer, M. (1999). ‘‘Growth of Pb(Mg1/3Nb2/3)O3-35 mol% PbTiO3 Single Crystals from (111) Substrates by Seeded Polycrystal Conversion,’’ Journal of the American Ceramics Society, 82(11).

Kumar D., (2013). Design and Analysis of Composite Rotor Blades for Active/Passive Vibration Reduction, Doctor of Philosophy (Aerospace Engineering) vin The University of Michigan

Monner, H., Opitz, S., Riemenschneider J., and Schulz M., (2011). “Development of active twist rotors at the German Aerospace Center (DLR), ” 52nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference
 19th 4 - 7 April (2011), Denver, Colorado

Matthew L. Wilbur and W. Wilkie K., (2004) Active-Twist Rotor Control Applications For UAVs, U.S. Army Research Laboratory Vehicle Technology Directorate Hampton, VA 23681

Park, J.S., Kim, J.H., (2006). “Coefficients of thermal expansion for single crystal piezoelectric fiber composites,” Composites Part B Engineering

Park, J.S., Kim, J.H., (2007). “Design and aeroelastic analysis of active twist rotor blades incorporating single crystal macro fiber composite actuators,” Composites Part B: Enginnering

Park, S.-E. and Shrout, T. (1997). ‘‘Ultrahigh Strain and Piezoelectric Behavior in Relaxor Based Ferroelectric Single Crystals,’’ Journal of Applied Physics, 82(4).

Sicim, S. , Unlüsoy, L. (2017). “ Vibration Reduction in a Helicopter Using Active Twist Rotor Blade Method,” 7TH EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS)

Sekula, M. K. , Yeager W. T. and Wilbur, M. L., (2004). “Aerodynamic design study of an advanced active twist rotor,” in: Proc. Amer. Helicopter Soc. 4th Decennial Specialist’s Conf. Aeromech.

Johnson W., (1994), Helicopter Teory, Page 339.

Jones, R. M, Mechanics of Composite Materials, Taylor & Francis, (1999).

Wood, E. R., Powers, R. W., Hammond, C. E., and Cline, J. H., “On Developing and Flight Testing A Higher Harmonic Control System,” Journal of the American Helicopter Society, Vol. 30, (1), January 1985, pp. 3-20.

Wilkie W., High, J., Mirick, P., Fox, R., Little, B.,Bryant, R. Piezocomposite Actuator for Structural Control Applications,” Proceedings, SPIE’s 7th International Symposium on Smart Structures and Materials, Newport Beach, California, March 5-9, (2000).

Wilkie, W., Inman, D., and Lloyd, J., “Anisotropic piezocomposite actuator incorporating machined PMN-PT single crystal fibers,” Proceedings, AIAA/ASME/AHS/ASC Structures, Structural Dynamics and Materials Conference, Palm Springs, California, April 19-22, (2004)