

Flight Test Instrumentation Blade Clearance Optical Measurement Method and Optimization in Scope of T625 GÖKBEY Helicopter

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Abstract

Blade clearance is a fundamental safety parameter in rotary-wing aircraft, governing the allowable distance between main rotor blades and nearby structures throughout the flight envelope. In helicopters, reduced clearance margins caused by pilot unintentional command inputs, structural deformation, rotor dynamics or installation tolerances may result severe safety problems. Blade clearance measurement and optimization studied within the scope of T625 GÖKBEY Helicopter. Distance measurement methods are evaluated according to measurement interface requirements of T625 especially, required sampling rate calculation which is based on time interval of rotary blade passing over tail cone. Optical principal sensor is selected according to requirements and adjustment flexibility of the sensor.

To ensure measurement integrity, a stepwise verification and calibration strategy was applied. Initially, the sensor was evaluated in laboratory condition which is based on averaging optimization of sensor for measurement constrains. The second stage is static measurement tests conducted on helicopter in hangar condition. The test is performed to evaluate effect of helicopter environment and color optimization of target due to the wavelength of sensor for measurement accuracy improvement. After optimization, specific flight test campaign performed to obtain blade clearance margin which will be evaluated and verified with rotorcraft dynamic analyses team by rotor motion dataset of T625.

As next vision, the collected flight test data will be used to develop an artificial intelligent model in FTI Digital Twin Project to evaluate blade–structure interaction, enabling the estimation of tail cone contact probability through machine-learning techniques and supporting predictive safety assessments for extended flight envelopes.

Key words: Optical Distance Measurement, Blade Clearance, Optimization, Verification, Flight Test Campaign

Introduction

Blade clearance is the deflection between main rotor blade tip and the rotorcraft structure which is one of the most critical constrain that can cause catastrophic failures for rotorcraft platforms. There are many reasons that can affect blade clearance margin, which can be structural deformation on rotary part with tail cone structure, rotor dynamic, installation tolerances or undesired pilot input commands.

In design phase, analyses are performed according to critical maneuvers to see the response of the blade but analyses are not enough to see real world effects, so the blade clearance must be proved that the blade does not clash with any structure of the rotorcraft in specified control margin of helicopter. So, a sensor instrumentation and verification are required to be implemented on tail cone for blade clearance measurement on T625 GOKBEY platform.

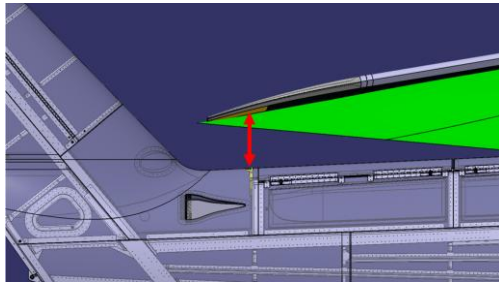


Fig. 1. Tail Cone Blade Clearance Illustration

In this motivation, traditional method which is balsa wood instrumentation is configured to see if any clash occurred during flight conditions and specified test points. Part of the balsa wood cut off by blade clash and can be noticed by real time as a level information which is provided by a circuit implementation on balsa wood as shown in the below figure.

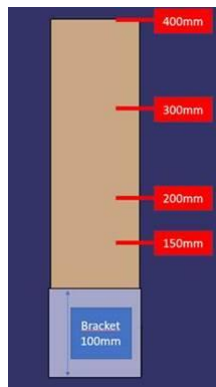


Fig. 2. Balsa Wood Instrumentation Levels

The thin wire implementation applied on balsa wood surface, when the blade tip cut one of the thin wire level, short circuit will trigger binary indicator data which is tracked by real-time in-flight test scenarios. But this solution is not enough to provide exact distance between blade tip and the top of tail cone structure.

As stated, balsa wood is not providing exact solution, so a new method of instrumentation must be integrated to gather blade clearance data. In this paper, the main objective is to explain optical method blade clearance measurement selection criteria, integration and hangar condition optimization on helicopter platform according to measurement principle. The hangar condition tests are performed to develop measurement quality in scope of accuracy and precision by adjusting sensor settings and target color and wavelength optimization.[1]

In the flight test, the sensor needs a verification step to confirm data to use in further certification phase of the helicopter projects. To do that with the support of dynamic rotor analyses team, main rotor motion data set,

Movepal sensor configuration which includes a set of string potentiometer to measure rotor motions on the designated main rotor blade stations, is used to build a correlation method to verify optic principal tail cone blade clearance sensor data.

The future work will be developing an AI model to implement in FTI digital twin project by using machine learning and deep learning algorithm which is using flight test data to estimate the distance between tail cone and main rotor blade tip and the possibility of clash in specified maneuver.

Sensor Selection Criteria of Blade Clearance

The blade clearance measurement is requested by rotor dynamic analyses team for T625 GOKBEY Platform to verify their analyses in flight test conditions with specified maneuver margins. The requested measurement zone is specified with its critical measurement values as shown in the below figure.

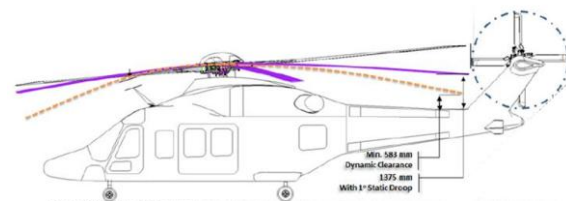


Fig. 3. Tail Cone Blade Clearance Measurement Request

As shown in the instrumentation zone, the measurement request comes with constrains by nature of rotary platform of helicopter. The first step is to understand constrains to select the method of measurement for blade clearance on tail cone structure. When the constrains are categorized by the challenges of measurement the below table can lead the constrains as follows.

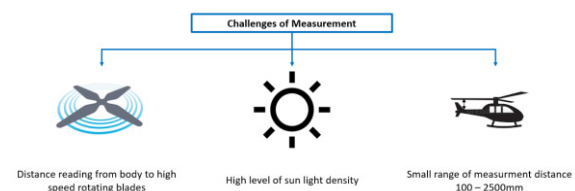


Fig. 4. Measurement Challenges

According to the stated challenges the sensor selection criteria are designated. The first impression is shaped to use optical measurement methods due to there is a scanning requirement on the rotary surface for distance measuring. Each challenge comes

with some outputs to define measurement sensor type for the aimed measurement.

Scanning High Speed Rotary Blades

The first challenge of measurement is arriving from distance measurement from the rotary target surface. According to the requested vertical distance measurement from tail cone, one of the points is fixed which is tail cone structure and the other part is rotary which is main rotor blade tip. To define measurement target, first check point is the determination of time interval during the rotor blade tip passes over the tail cone structure. So, operational rotating speed is required to calculate linear speed of the blade tip. The main rotor operational angular velocity of T625 GOKBEY is shared as below table.

Tab. 1: Main Rotor Rotational Speed Chart

MAIN ROTOR	Power-On (RPM)		Power-Off (RPM)*	
Operational Minimum	313.66	100%	282	90%
Normal Operation	313.66	100%	313.6	100%
Operational Maximum	313.66	100%	345	110%

According to the rotational speed of MR, calculations performed to determine time interval of blade tip passes over the tail cone. The formulas which are used for calculations are described in the below.

$$v_{Tip} = w_{Blade} * r_{Blade} \quad (1)$$

$$w_{Blade} = \frac{2 * \pi * n_{Blade}}{60} \quad (2)$$

$$t_{Tip_Pass} = \frac{x_{Blade_Width}}{v_{Tip}} \quad (3)$$

$$f_{measurement} = \frac{1}{t_{Tip_Pass}} \quad (4)$$

Eq (1) is basically converting rotational speed value to linear speed by blade length and by the Eq. (3) and Eq. (4), the speed value the passing time interval can be calculated theoretically by Newton's law of motion. In the equations, some input parameters are required for calculations these are MR rotational speed, Main Rotor Blade Length and the width of blade tip.

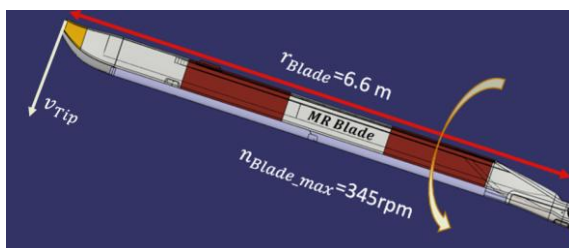


Fig. 5. Main Rotor Blade

The measurement zone is designated according to rotor motion limits, due to the blade tip shape, the width of tip is in between 0.2 to 0.35m as shown in the shaded area which is in below figure.

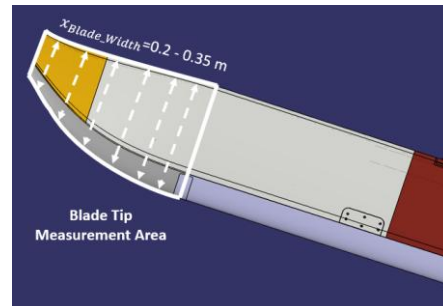


Fig. 6. Main Rotor Blade Tip Zone

The next step is to calculate the required frequency band with stated blade parameters; to determine blade tip passing time over tail cone structure, the frequency parameter will define sampling rate requirement which will be one of the selection criteria of measurement method. Due to the tip width is variable due to its shape and rotor dynamic motion, which means when the blade gets angle of attack the projection of width will be decreased.

The table below shows that the scanning rate of the blade tip with respect to variable parameters which are blade rotational speed and width of blade tip.

Tab. 2: Required Measurement Frequency Chart

rotor blade width (m)	Rotor Blade speed (rpm)	blade tip velocity (m/s)	measurement time (sec)	Blade Tip Scanning Rate (Hz)
0.2	345	238.4468824	0.000838761	1192.234412
0.25	345	238.4468824	0.001048452	953.7875296
0.3	345	238.4468824	0.001258142	794.8279414
0.2	313	216.3300701	0.000924513	1081.650351
0.25	313	216.3300701	0.001155641	865.3202895
0.3	313	216.3300701	0.00138677	721.1002338
0.35	345	238.4468824	0.001467832	681.2768069
0.35	313	216.3300701	0.001617898	618.0859146
0.35	282	194.9044082	0.001795752	556.8697378

The scanning rate will be a constrain to determine measurement frequency, so optical and vision-based sensors are focused to measure distance by scanning the blade tip zone with the defined measurement frequency range. The required sampling rate must be at least 566Hz. The requirement of rotary blades shows us the method of measurement will be shaped according to contactless methods [2].

Sun Light Density

The measurement request requires outside environment due to the request vertical distance is in between blade tip and tail cone structure. So, sun light effect in the environment considered as a possible challenge which the

sun light affect measurement during flight test. There is an interference of sun light to optical measurement methods due to the spectrum of sun light consist large scale of light radiation. A know fact is optical methods are sensitive to the sun light interference as stated in the literature [2]. So, a method to reduce effect of sun light will be considered during application phase.

Blade Clearance Distance Range

The required distance range of measurement method is built according to analyses output pf T625 GOKBEY blade clearance, the stated maximum distance is around 1.5 meter between the blade tip and tail cone structure which means the measurement scale is in short distance range for many optical sensor suppliers, the measurement range is also limits the possible method to focus on blade clearance measurement.

Blade Clearance Sensor Initializing and Optimization

According to measurement constrains stated in previous chapter, sensor selection performed as a contactless ToF principle infrared distance measurement sensor which is Astech LDS70A. The sensor has unique features which is capable to measure the distance range of 0-270 meter with up to 40kHz sampling rate. The details of sensor and the selection reasons will be discussed in further.

In the first stage the sensor initialized to scale measurement performance. The sensor has internal processor which is adjustable by admin setting parameters. In the next stage, by adjusting setting parameters measurement capability is tested and an optimization phase performed for sensor accuracy and precision under laboratory conditions. The third part is integration and verification of sensor on aircraft in hangar conditions. The details of each phase will be discussed in this chapter.

Blade Clearance Optical Sensor Specifications

The selected blade clearance sensor model is Astech LDS70A which is emitting and receiving laser light and processing the distance between target and sensor with respect to speed of light which means sensor measuring distance by principle of Time of Flight (ToF). The sensor measures high range of distance up to 270 meters with high sampling rate up to 40kHz.

The selected sensor is compatible with helicopter DC power source which is make the integration of helicopter much smoother. The sensor has internal chipset which is calculating distance by averaging user defined number of samples to increase accuracy and precision of the measurement. The coefficient of sensor can be adjusted by computer-based GUI software LDMTTool, which is provided by supplier. The sensor settings will be defined according to measurement requirements and coefficients will be optimized to achieve best precision and accuracy for blade clearance measurement.

As stated, sensor is adjustable by internal parameters to optimize quality and interface of measurement. In the application of blade clearance There are some parameters will be tuned by controlled test setup. The setting descriptions which will be adjusted while tune measurement are used to tune sensor

Measurement optimization will be held on according to adjustment iterations of stated parameters.

Blade Clearance Sensor Initialization

The sensor has multiple output option in itself it is also adjustable in GUI. According to required frequency range of measurement RS422 serial bus output is selected due to high message capacity of protocol. The sensor data is captured via CW KAM500 based data acquisition system which is operating in T625 GOKBEY for flight test data acquisition. The length of message and data parsing process held by interface control document of sensor. By considering the scanning rate constrain of measurement ASCII based RS422 data protocol is selected due to compatibility of data acquisition interface and high baud rate bandwidth.

The sensor can provide decimal output data with RS422 and can be adjusted by receiving terminals of RS422 protocol. To communicate sensor with GUI software to adjust sensor settings in optimization phase, a converter required to provide RS-422 to USB data conversion. The transmit terminals of serial bus are multiplexed to gather distance data while adjusting settings of sensor by LDMTTool in iterations of test so, directed to data acquisition channel and computer interface. According to the ICD, the payload of serial bus is 10 bytes which will be parsed as ASCII format to make it meaningful.

LDS70A User Manual Parameter setup and measurement

Table 8: Decimal output - Maximum measurement frequency (MF_{max})

Output values	Distance	Distance + signal quality	Distance + temperature	Distance + signal quality + temperature
Output data format	SD 0 0	SD 0 1	SD 0 2	SD 0 3
Length of output data	11	16	17	22
Baud rate	Maximum output frequency = MF _{max} with SA 1			
9600	80	50	48	40
19200	160	100	90	75
115200	1000	700	660	480
230400	2000	1400	1300	980
460800	4100	2750	2500	1850
921600	7300	4750	4350	3300
2000000	12200	7850	6480	5000

Fig. 7. Measurement Frequency with Respect to Baud Rate

The selected output data format contains distance data with 10 bytes the selection reason is the baud rate limitation of RS422 to USB converter device is compatible up to 921600 baud rate. The result of selection will limit the data transmission rate up to 7300Hz. The sampling rate optimization will be performed according to this boundary.[3]

The next step is to parse data to obtain data in engineering unit to work on accuracy and precision optimization processes. There are 10 bytes of data, the data parsing method is evaluated by a third-party serial bus monitoring software. According to ICD, the data type of decimal output is 7-bit ASCII. In the monitoring of ASCII format, there are 4 bytes can be used as header due to they are constant value for measurement application. The illustrated of ASCII format.

The initialization of sensor is done by parsing the serial bus data package.

Blade Clearance Sensor Optimization Processes

The further chapter is optimization of distance measurement performance of the sensor by adjusting sensor internal parameters to achieve good accuracy and precision combination. Before optimization phase, the sensor measurement performance will be determined to evaluate initial accuracy and precision values in the measurement request under controlled laboratory conditions.

The test conditions and requirements are defined according to blade clearance measurement requirements, the range and measurement frequency are the main constraints which effect the sensor internal parameter tuning in the laboratory improvement test processes.

The test environment is a linear rail calibration test bench which is used to measure distance by unit under test with precise mechanical distance control of calibration stand ability. The test setup configuration and data acquisition

method are based on LDMTTool software to track measurement while configure different setting configurations for sensor internal parameters.

Sensor installed on the moving rail part of the stand. The target is fixed and is not moving during measurement so reference frame is the target for the test scenario in the laboratory. The test setup is picturized as shown in the following figure.

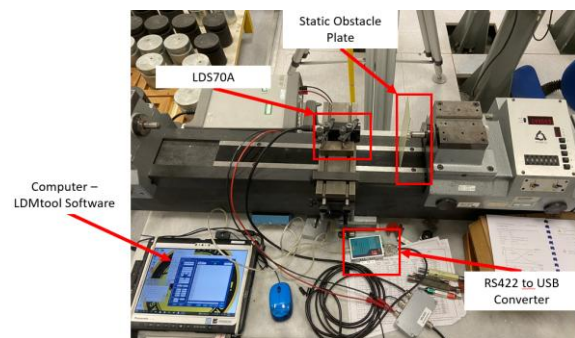


Fig. 7. Laboratory Optimization Test Setup

The sensor tested in the linear rail stand so due to the length limitation of the stand the distance of 100 to 1500mm can be measured and tested during laboratory study. In the test stand, iterative tests are performed for each set of internal sensor parameters which are briefly explained in the below table.

Tab. 3: Internal Parameter Descriptions

Parameter	Description	Value Range
MF	Measurement Frequency	1 ... 40000, resolution 1
SA	Mean average	32 bit integer, resolution 1
MW	Measurement Window	32 bit integer, resolution 1
OF	Offset Value	32 bit integer, resolution 1
TC	Time for calibration	0 (no calibration), 1 ... 3660 s
GN	Gain Setup	-1, 0, 1, 2, 3
SD	Serial data format	0 decimal 1 not available 2 binary
ST	Select Target	0 (first target) or 1 (last target)

The test is performed between 100 to 1500mm by 100mm increments to determine general linearity response for each test configuration to focus on best linearity curve. According to the best linearity curve settings, number of measurements will be increased to see precision performance of sensor in selected sensor settings.

The setting configurations for each test are shared as below table.

Tab. 4: Setting Configurations for Optimization

Iterations	Parameters								
	MF	SA	MW	OF	TC	GN	SD	AS	ST
1st Test	40 kHz	20	0 - 2	0	1	0	0 0	DT	0
2nd Test	40 kHz	50	0 - 2	0	1	0	0 0	DT	0
3rd Test	40 kHz	50	0 - 2	-0.02	1	0	0 0	DT	0
4th Test	40 kHz	40	0 - 2	0	1	-1	0 0	DT	0
5th Test	40 kHz	40	0 - 2	0	1	1	0 0	DT	0
6th Test	40 kHz	40	0 - 2	0	1	2	0 0	DT	0
7th Test	40 kHz	40	0 - 2	0	1	2	0 0	DT	1
8th Test	40 kHz	40	0 - 2	-0.04	1	1	0 0	DT	0

In the test configurations, measurement frequency defined as 40kHz due to it's the maximum possible sampling rate which means high number of sample equals to much higher precision. There are some configurations tried to change gain setting and the offset value to see the response of linearity of measurement with respect to linear rail calibration bench measurement. The measured values are taken and a graph has been built with those 9 iterations of data which is illustrated in the below figure.

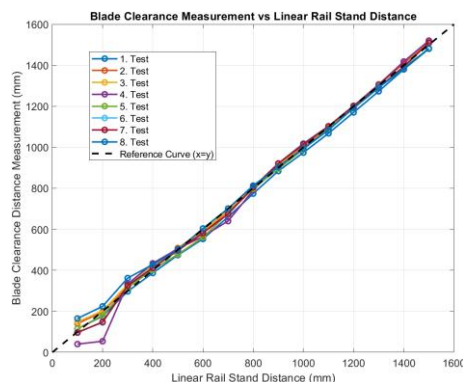


Fig. 8. Performed Test Results According to Linearity Behavior

As it can be examined from the graph, the best configuration is using the combination of SA 40 and MF as 40kHz so the result of output data sampling rate will be around 1kHz which is suitable according to calculations to define rotor blade across on the tail cone structure. The best tuning to define 1024Hz due to the data acquisition architecture of GOKBEY FTI is based on sampling rate with multiples of 2. So, the final configuration settings determined as below.

Tab. 4: Selected Internal Parameter Configuration

	Parameters								
	MF	SA	MW	OF	TC	GN	SD	AS	ST
Final Config	39936	39	0-2	0	1	0	00	DT	0

According to final configuration, the tested curve fitting to the reference distance curve is illustrated as below.

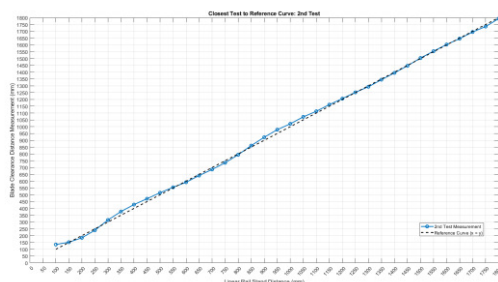


Fig. 9. Curve Fitting of Final Laboratory Test Result

In the final configuration, the accuracy and precision optimized by internal coefficient set of sensor by considering data acquisition system constraints.

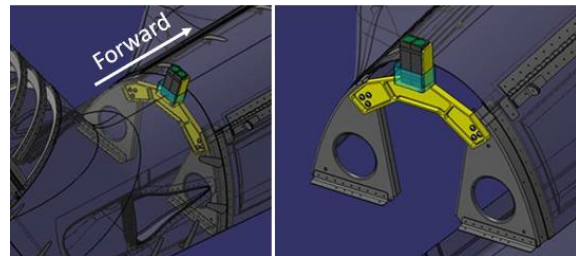
Blade Clearance Platform Integration, Hangar Test and Environmental Optimization

The sensor integration on helicopter has been performed after measurement optimization on laboratory conditions to make sense the delta difference of measurement on helicopter installed sensor measurement configuration. The hangar level sensor tests are performed to compare sensor healthy and measurement performance in operational scenario. According to accomplished tests, the environmental factors which affect measurement quality are focused to improve measurement quality in terms of accuracy and precision.

Integration of Blade Clearance Sensor

In the helicopter initializing phase, the sensor integration worked on swap volume constrain of main rotor blade movement and measurement requirement of blade tip. the installation location and interface determined according to conical scanning area of blade to track blade tip in rotor input command limitations.

Fig. 10. Sensor Installation on Tail Cone Structure



Helicopter Blade Clearance Static Hangar Test and Environmental Optimization

The blade clearance sensor installed on the helicopter configuration to track blade tip in calculated sampling rate. The next step is to testing sensor performance on the helicopter platform by considering external environmental effects. With regards to this motivation, a test scenario is modified to test sensor measurement capacity under blade angle of attack motion in static condition. The test scope is illustrated as below.

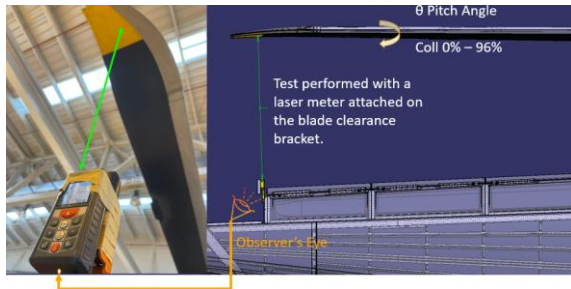


Fig. 11. Environmental Optimization Test Setup on Aircraft

As seen in the figure, test is performed with a calibrated laser meter device which is capable of measuring with $\pm 1.5\text{mm}$ distance accuracy. Additionally, the reference sensor is verified by a measuring tape. The scenario of test, is measuring distance between blade tip and tail cone by considering Angle of Attack of blade as independent variable both with reference sensor and blade clearance sensor by controlling collective input to change Angle of Attack of blade as independent variable. There are two main concerns to test in this scenario the first one is to see the response when the blade is rotated with an angle relative to the tail cone axis. The second is that identification of environmental factors potentially degrading measurement accuracy and precision in static condition. There are two sections of edges to be tested. The trailing and leading edges, these edges are boundaries for measurement zone. So, they are considered as testing zones which are illustrated in the below figure.

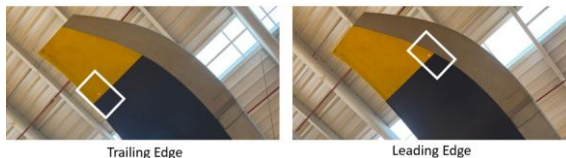


Fig. 12. Measurement Targets

In both trailing edge and leading edge, the blade clearance sensor measurement tested by adjusting collective input by each five percent to measure clearance with unit under test and reference sensor, the results show that the precision is getting lower and data oscillates around 500mm in the trailing edge zone, when collective input higher than sixty percent.



Fig. 13. Blade Clearance Behavior According to Collective Input

Color Optimization and Verification Applications

This issue is investigated in literature and test scope to match with a reason. As stated previously sensor working principle based on optical infrared laser tracking, the color spectrum of target gets importance as seen in the literature. According to the ASTM E903 [3], the target surface color reflectance is different for each color spectrum as stated in the below figure.

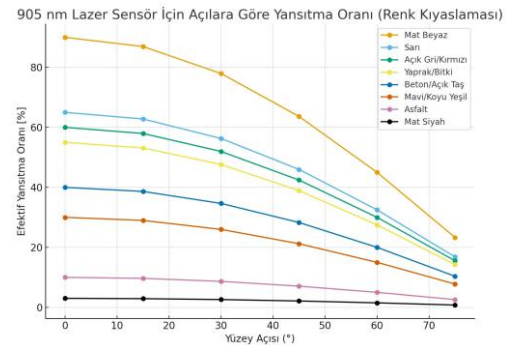


Fig. 14. Reflectance Ratio of Visible Colors According to Surface Angle

Also, if the target rotates and not perpendicular with the source the reflectance performance decreases according to Lambert Law. In this scope, the blade tip colors are observed as shown below.

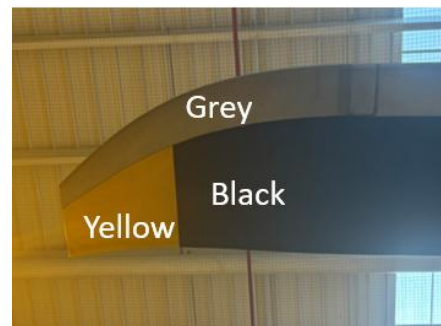


Fig. 15. Blade Tip Color Distribution

There are three different colors on tip, so as expected from literature the measurement performance getting worst in the case of laser hits to the black zone and it happens when the collective above sixty percent in trailing edge of blade tip. To verify the color affects on measurement quality the test is re-performed by applying standard paper under the blade tip zone to reach perfect reflectance according to stated literature. The reflectance for both perpendicular case and surface angle the best option is the matte white and the color can be demostarted with standard A4 paper. Performed test shows that the difference value between unit under test and reference sensor is getting better when the tip part coated with

matte white, the precision of measurement improved and also there is no oscillation occurred during the collective input iterations. There are 16 points of measurement performed with different collective percentages and for each test step the difference values and the average of test victims are illustrated in the below figure.

Tab. 5: Comparison of Raw and Coated Blade Measurement Performance

Test Point	Collective %	Without Coating (Grey-Black-Yellow)		With Coating (Matte White)	
		Trailing Edge Test "Difference" Values (mm)	Leading Edge Test "Difference" Values (mm)	Trailing Edge Test "Difference" Values (mm)	Leading Edge Test "Difference" Values (mm)
1	0	39	33	18	25
2	5	39	24	18	25
3	10	34	23	19	22
4	15	35	24	20	22
5	20	35	27	22	19
6	25	32	30	21	19
7	30	31	29	21	20
8	35	29	28	20	20
9	40	33	21	18	23
10	45	30	20	20	24
11	50	32	18	22	26
12	60	-	28	18	25
13	70	-	28	18	24
14	80	-	25	18	25
15	90	-	-	17	25
16	96	-	-	22	24
Average -->		33	26	19	23

As shown in the figure, the response of coated configuration improved in terms of precision and accuracy, so the color optimization required to increase sensor measurement healthy. As a result of performed test, with the support of Gökbey Product team and Blade Design team, the under of blade tip colorized with airborne matte white color to track blade clearance value with improve accuracy and precision. The final test for the environmental optimization part is performed with matte white colored blade tip to evaluate the response of measurement. The results of colored blade tip have the best difference response according to reference sensor measurement and this issue shows that the color optimization in the dynamic measurement applications.

Tab. 5: Final Comparison Table of Measurement Performance

Test Point	Collective %	Trailing Edge Test "Difference" Values (mm)		
		Without Coating (Grey-Black-Yellow)	With Coating (A4 Paper White)	Colored Plate (White)
1	0	39	18	15
2	5	39	18	17
3	10	34	19	16
4	15	35	20	18
5	20	35	22	17
6	25	32	21	17
7	30	31	21	17
8	35	29	20	18
9	40	33	18	21
10	45	30	20	18
11	50	32	22	16
12	60	-	18	17
13	70	-	18	9
14	80	-	18	20
15	90	-	17	16
16	96	-	22	13
Average -->		33	19	17

The response of each test scenario for trailing edge is observed due to high oscillation issue occurred in the un-coated blade configuration,

as shared in the below table best accuracy and precision in terms of color optimization observed in colored blade tip configuration.

Correlation with Rotor Motion Data Set and Future Work of Blade Clearance Measurement

Blade Angle Measurement System Architecture

The T625 helicopter utilizes a Main Rotor Motion Verification (MOVE) system to determine main rotor blade angles (lag, flap, and pitch) using potentiometers as illustrated in Figure 16. While the system typically employs potentiometers for all three angles, the lag angle is measured exclusively by a damper potentiometer due to its superior accuracy compared to the dedicated potentiometer.

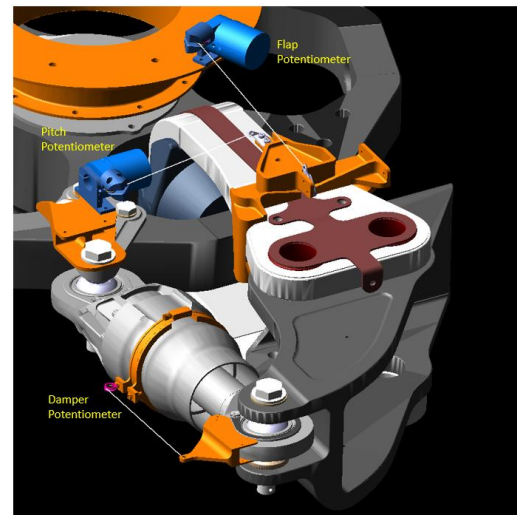


Fig. 16. Blade Angle Measurement System

The MOVE potentiometer is a specialized string potentiometer with three degrees of freedom: cable length, roundabout angle, and unroll angle. It functions by allowing a string to extend and retract linearly, guided by two identical pulleys. These pulleys rotate around a central roundabout axis, ensuring the string remains aligned with the pulley wrapping. Understanding the mathematical modeling of these three degrees of freedom is crucial for developing a proper kinematic model of the MOVE system.

The flap and pitch potentiometers are mounted on the hub, and the strings are anchored to fittings on the tension link.

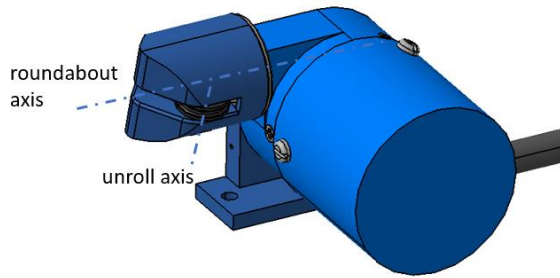


Fig. 17. Flap and Pitch Potentiometers

Damper potentiometer is mounted on damper casing and attached to bracket on the pitch control lever. It acts like a linear transducer in this configuration to measure the damper stroke.



Fig. 18. Damper Potentiometer

Mathematical model is based on vector summation over potentiometer readings. An illustration of pulley schematic is given in Figure 19. This diagram visually depicts the planar motion of the potentiometer string, with the y-axis representing the roundabout axis. The roundabout rotation is calculated using a Rodriguez transformation.

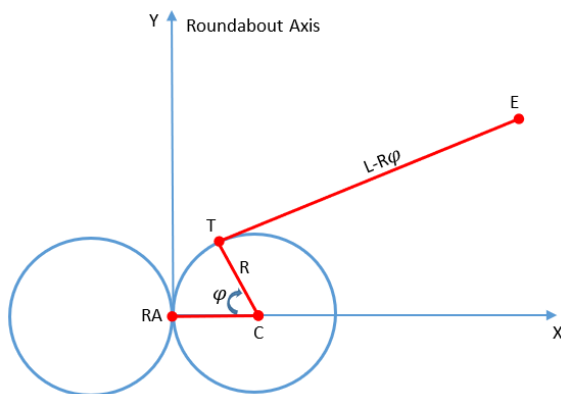


Fig. 19. Pitch and Flap Potentiometers Vector Model

Point E signifies the anchor point on the blade tension link, while point RA represents the anchor point on the pulley for the MOVE potentiometer cable. The following equation determine the position of point RA relative to point E. 'L' denotes the total length of the string between RA and E, 'R' represents the radius of

the pulleys, and 'φ' signifies the unroll angle of the pulley. The 'P' notation in the equations indicates a point definition.

$$\vec{P}_{RA} - \vec{P}_E = \begin{bmatrix} -R \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} R \cos \varphi \\ -R \sin \varphi \\ 0 \end{bmatrix} + \begin{bmatrix} -(L - R\varphi) \sin \varphi \\ -(L - R\varphi) \cos \varphi \\ 0 \end{bmatrix}$$

By including the roundabout rotations and blade angle rotations in 6 equations can be written for flap and pitch potentiometers. 1 equation can be written for damper length.

There are 7 equations; there are 7 unknowns; (ξ: lag angle, β: flap angle, θ: pitch angle, φ_β: flap pulley unroll angle, φ_θ: pitch pulley unroll angle, ψ_β: flap pulley round about angle, ψ_θ: pitch pulley round about angled). Flap angle, pitch angle, lag angle can be calculated when cable lengths are known depending on the transducer readings. Nonlinear equation set is iteratively solved in Matlab via "fsolve" algorithm which gives rotor blade angles for measured potentiometer data. Detailed formulation, calibration of sensors and post processing of sensor data will be presented in another paper.

Blade Clearance Correlation Theory with Rotor Motion Data Set

Configuration in Figure 1, implemented on three blades, records data during flight tests, which is subsequently processed via a MATLAB code based on the potentiometers' kinematic model to calculate the blade angles. Blade clearance measurements are compared with calculated distances from flap angles measured through motion verification blade instrumentation.

Conclusion and Discussion

In conclusion, the blade clearance fast scanning optical measurement method is an alternative solution to measure distance between fixed frame to rotary blades to track and observe warning and critical zones of blade clearance in the allowable maneuver spectrum of helicopter which increase the trust of aircraft in the certification and development phases.

The sensor has internal parameter tuning capability so, a modification and optimization required to set the internal coefficient of sensor by the laboratory test in Turkish Aerospace Calibration. In the phase of initialization and hangar level static tests, there is an additional optimization born about environmental effects. Sensor tests are performed to optimize the color of target to increase the accuracy and precision of measurement. As a result of

performed test the blade tips are colorized for blade clearance measurement.

The verification part of blade clearance data is planned to performed via rotor move dataset which is a special instrumentation on main rotor to calculate blade motion parameters by raw parameters of sensor instrumentation. The move dataset results the pitch and flap angle of blade motion. The correlation of blade clearance will be held on calculated flap angle and blade radius length.

The vision of the study will be evolved to machine learning model designing in the FTI Digital Twin architecture to predict the distance between blade tip and tail cone structure according to input parameters of planned flight test to observe safety of flight before flight test and predict the clash scenario according to given user parameters.

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