ENGINE VIBRATION SURVEY TESTING ACTIVITIES

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Abstract

T-625 helicopter, created by the Turkish Aerospace Helicopter Group, serves as a light utility multi role helicopter. It is powered by a pair of CTS800-4AT turboshaft engines, which were developed by the Light Helicopter Turbine Engine Company (LHTEC). This paper presents aspects of engine vibration characteristics in powerplant integration of the T-625 helicopter. The results of engine vibration flight test campaign, engineering activities to control engine vibration amplitudes to acceptable levels accordance to the certification requirements. The impact of the helicopter’s weight and center of gravity configuration on vibration levels are examined, with an evaluation of how specific configurations are affected depending on different kind of maneuvers. In this survey, the test points have been successfully completed by satisfying engine vibration certification regulations.

1. NOTATION

Acronyms:

ECU	Electronic Control Unit
ERF	European Rotorcraft Forum
HIGE	Hover In Ground Effect
LHTEC	Light Helicopter Turbine Engine Company
MGB	Main Gearbox
NR	Main Rotor Speed
FADEC	Full Authority Digital Engine Control
OEI	One Engine Inoperative
RAP	Resonance Assessment Profile
RTCA	Radio Technical Commission for Aeronautics
VFS	Vertical Flight Society
Vne	Never Exceed Velocity

2. INTRODUCTION

The T-625 Gökbey Helicopter Program a versatile dual-engine helicopter in the 6-ton class initiated in 2013. The first flight is made in 2018 and currently it is under certification process by Turkish Aerospace. It's designed to easily adapt to various mission profiles for civilian use, including passenger transport, VIP services, air ambulance, search and rescue, cargo transport, and offshore operations. The characteristics of the rotorcraft are given in Table 1.

Table 1 T-625 GÖKBEY Rotorcraft Characteristics

Characteristic	English	Metric
Engines	2 x LHTEC CTS800-4AT turboshaft	
Take-off Power	2 x 1,374 shp	2 x 1,025 kW
Capacity	2 pilots + 12 passengers	
Length	52.07 ft	15.87 m
Main Rotor Diameter	43.31 ft	13.2 m
Max Gross Weight	13,338 lb	6,050 kg
Service Ceiling	20,000 ft	6,096 m
Max Speed (Vne)**	165 kts	306 km/h

*Full fuel tank

**ISA, SL with MTOW

The T-625 helicopter is subject to certification according to CS-29 [1]. In order to comply with CS29.901 (b) (1) (i), the requirements imposed by the “Installation Design Manual” of the engine manufacturer will be verified through the flight test campaigns. The first campaign, which is engine control tuning tests [2], was completed on February 2023 and the second campaign, which is engine installed performance tests [3], was completed on January 2024. The other critical campaign, the engine vibration tests, will demonstrate the engine vibration environment does not exceed the specified limits with regarding to the followings:

- Engine vibration limit.
- Airframe excitation frequencies drivers and magnitude.
- Engine output shaft torsional vibration and torsional damping.

T625 Helicopter powerplant system consists of:

- Two-spool turboshaft LHTEC CTS800-4AT engines ,
- FADEC,
- Engine front and mid mounts,
- Engine output shaft assembly,
- Plenum type air inlet and screen protection,
- Engine exhaust system,
- Engine cowling,
- Firewalls

Figure 1 CTS800-4AT Turboshaft Engine

Each engine is attached to helicopter by means of three locking points; one front and two mid-mounts. The engine mount configuration is an “isostatic structure”; in the mid-mounts, all rods are connected to each other by means of spherical bearings to ensure allowance of axial and radial thermal expansion of the engine. At the forward mount location, a torque tube and a gimbal joint connect the engine to the main helicopter gearbox, which absorbs shear loads in three directions and torque in the engine longitudinal axis. Crosshead structure provides structural alignment between the engine and MGB.

Dynamic connection between engine and gearbox is provided by engine output shaft assembly. It contains two main parts, which are engine drive shaft and tufflex coupling. The shaft, which is connected to the engine, has an axially floating type spline that is lubricated by the engine lubrication system. This design helps the system to compensate the axial location errors caused by both tolerances and thermal growth. The tufflex coupling and the spline, which has crowned teeth, allow angular misalignment.

Proper engine installation with respect to the gearbox and rotorcraft structure in terms of dynamic stability is checked with engine vibration survey. In order to check engine vibration levels against the limits specified by the engine manufacturer, piezoelectric type accelerometers are installed at the front mount interface, compressor and power turbine sections of each engine. The frequency range of the accelerometers is very large since they need to measure the vibration levels at all helicopter excitation frequencies. Possible sources of helicopter excitation are main rotor blade passing frequency at 1/rev and 2/rev at all potential steady-state rotor speeds. Tail rotor frequencies are also evaluated, however tail rotor frequencies do not traditionally cause excitation to enough magnitude to be a concern for the engines. Vibration from the engine output shaft (coincident with 1/rev frequency of the engine power turbine shaft (1/rev Np)) can cause high radial loads at the engine bearings, due to higher unbalance of the shaft assembly.

Each engine includes FADEC system, which features dual channel electronic control in the form of two aircraft-mounted ECUs. They are mounted onto the base plate in the avionics bay section. Despite the fact that each ECU mount interface incorporates a vibration isolator, vibration levels of ECUs have to be checked and monitored through the accelerometers that installed to each ECU. The vibration limits of the unit is determined based on the environmental qualification tests conducted in accordance with RTCA/DO-160G standards and these limits were followed during the flight test.

In this paper, the execution of predetermined test points at both ground and flight, the evaluation of the gathered data and the troubleshooting activities in case of limit exceedances are presented. These stages are described in the following sections in details.

3. MODAL TESTS

During the design phase, special care has been taken to prevent the natural frequencies of the engine integrated parts and engine mounts from clashing with the operating frequencies of the engine. After the engine installation on the rotorcraft, resonance assessment profile (RAP) testing with hammer was performed on each attachment and it is verified that there is enough margin for all parts. During these tests, the brackets used to attach the accelerometers to the engine were also evaluated with the instrumentation shown in Figure 2. Different configurations for the brackets in terms of shape, material and installation method were evaluated and the best solution, which will not add extra amplitudes to the vibration levels of the engines, was chosen.

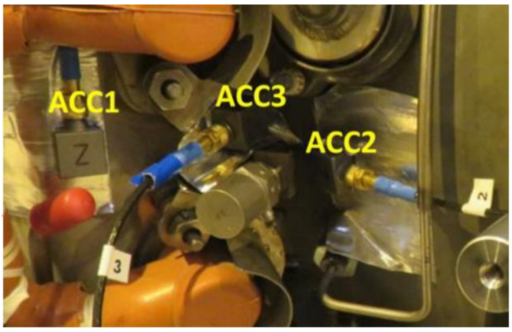


Figure 2 Modal Testing Accelerometer Bracket on the Engine

Two types bracket configuration and material was selected for modal test. The aim was to find the optimum bracket design by checking natural frequencies of the bracket whether they are as far away as possible from operating frequencies of the engine. Initially, long and steel bracket configuration was used for modal test yet it is observed in Figure 3 below spikes are filling the operation regime frequency envelope so that another configuration was tested.

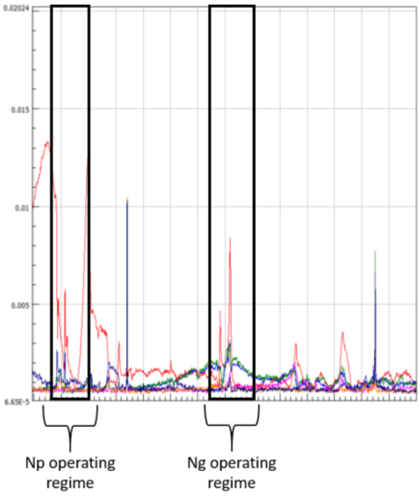


Figure 3 Modal Test Results for Long and Steel Sensor Bracket

Secondly, material of the bracket was changed to steel to inconel and the same test repeated again. Yet according to the results remarkable decrease was not observed.

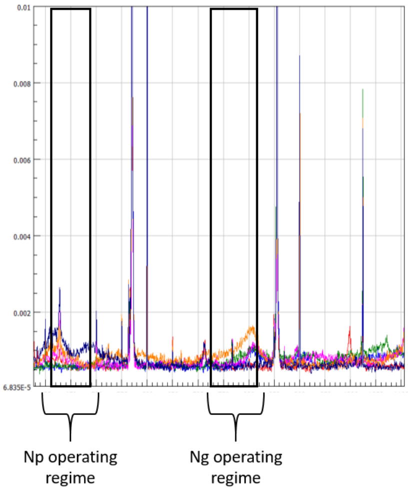


Figure 4 Modal Test Results for Long and Inconel Sensor Bracket

Finally, shorter bracket configuration was chosen with inconel material for modal test. Special care was taken to shorten the bracket by a certain amount to ensure that the harnesses attached to the sensors located in hot zone of the engine would not burn. The results of modal test done to show that the sensor bracket has no any neutral frequency in the operating speed regime of the engine power and gas generator turbines are shown in Figure 5. No significant peaks were observed within the operating frequencies when the impact is applied at the different locations of the engines. Each color in Figure 5 represents the different impact location.

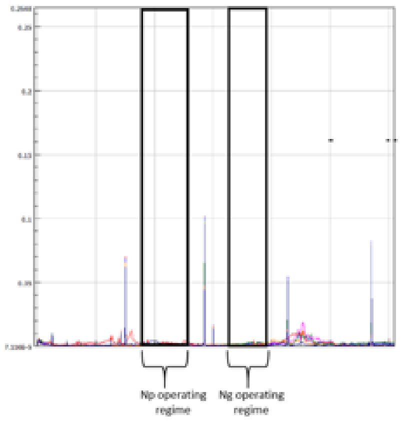


Figure 5 Modal Test Results of Short and Inconel Sensor Bracket

4. GROUND TESTS

Prior to the ground tests, vibration levels of the accelerometers installed at the front mount of the engine were checked with a reference run. According to the results limit exceedance was anticipated for further high torque required ground test steps, shaft balance procedure was performed to decrease vibration levels. For the numbered locations on flexible coupling in Figure 6 below, additional standard washers were installed to specified red marked locations (1,2,3) and vibration levels were measured again. Based on the results, washers were installed to at the white marked locations (4,5,6) of the flexible coupling until vibration levels show a trend that will not exceed the limits during high torque required steps. During the procedures, vibration levels were recorded by running each engine independently to IDLE and FLT mode to prevent damage and fatigue engines due to excessive vibration. Difference of the vibration levels can be observed from the Figure 7 and Figure 8 below:

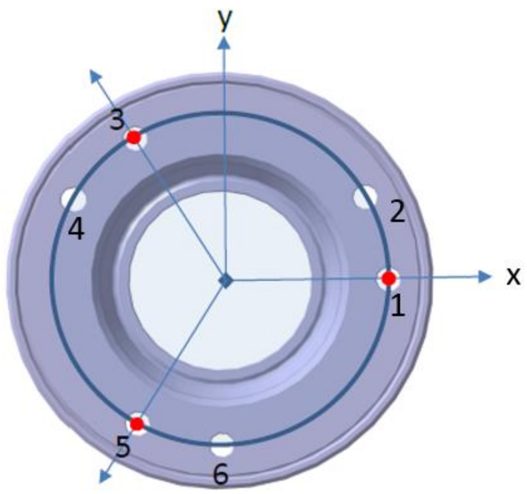


Figure 6 Balancing Plane Marking Sequence

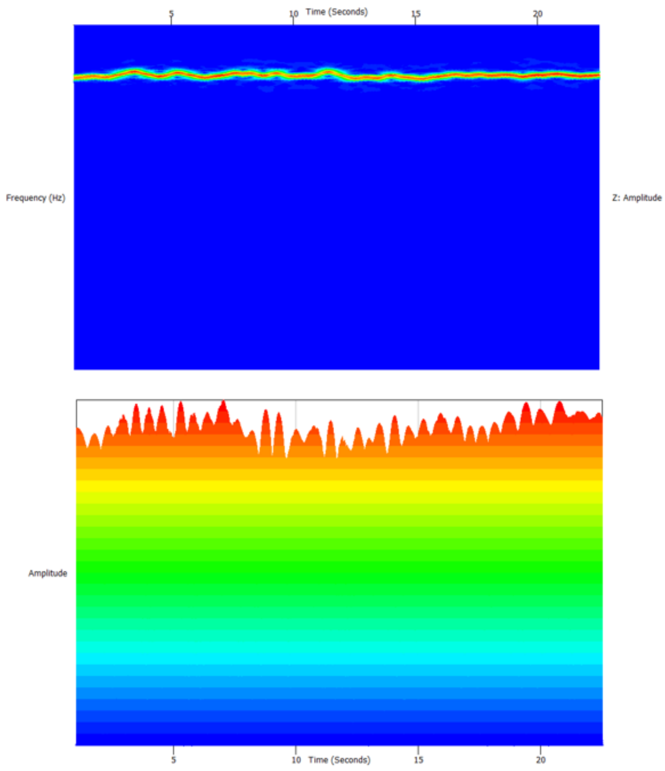


Figure 7 Vibration Levels of Rear Mount Accelerometer Before Engine Shaft Balance

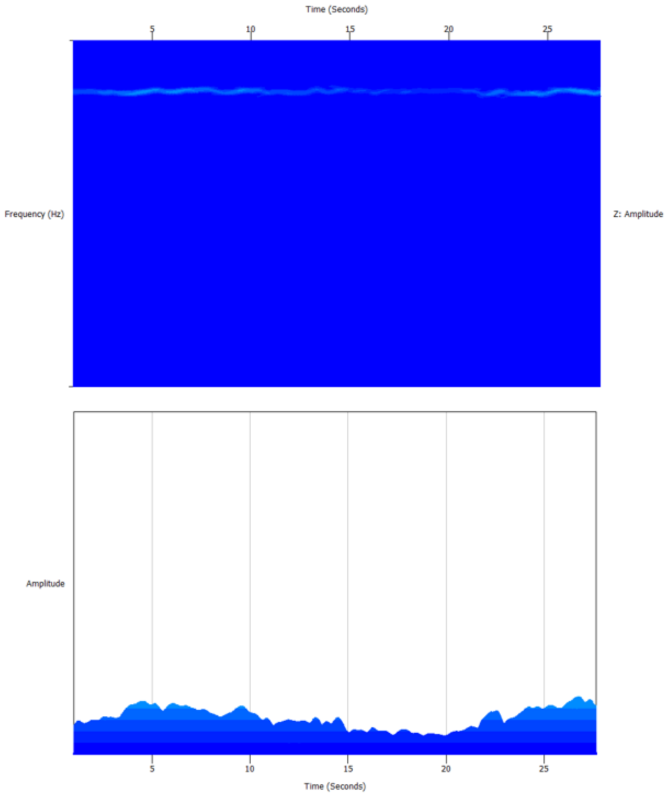


Figure 8 Vibration Levels of Rear Mount Accelerometer After Engine Shaft Balance

Performing ground tests on the prototype was crucial stage prior to performing engine vibration tests during flight. The ground tests include power sweeps from ground idle to 30 seconds OEI (one engine inoperative) limits in order to check the engine vibration amplitudes up to maximum achievable rotorcraft torque levels and engine gas generator turbine speeds. For these tests, the helicopter was tied down to the ground at the special test facility (Figure 9). Throughout these tests, the vibration levels were controlled against the unbalance of the output shaft and rotor blades, the misalignment between the engines and gearbox and the natural frequencies of the engine-integrated parts such as exhaust nozzle, air intake and ventilation ducts.

Figure 9 T625 in Ground Test Facility

In the ground tests, it was shown that the engine vibration levels are under the limits with a large safety of margin at every sensor location. The critical speed of the output shaft is far away from the 1/rev Np frequency range as estimated with the rotordynamics analysis and the dynamic balance of the shaft is at acceptable levels such that it will not impose high radial loads on the engine's No. 1 bearing. Additionally, there was no resonance case in any of the engine mounts, engine integrated parts and brackets for attaching the sensors. The vibration levels against the limits in front and rear of the engine during engine acceleration are shown in Figure 10 and Figure 11.

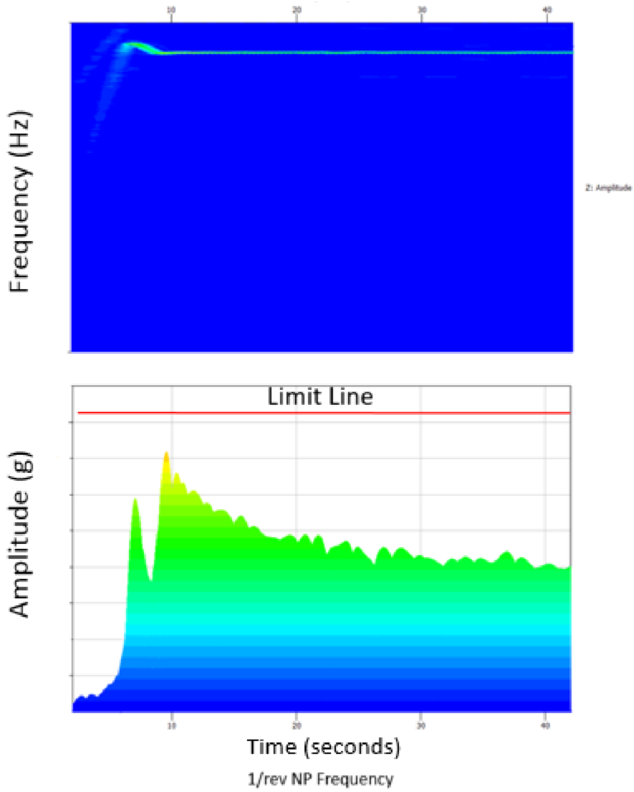


Figure 10 Vibration Levels in Front of the Engine During Acceleration

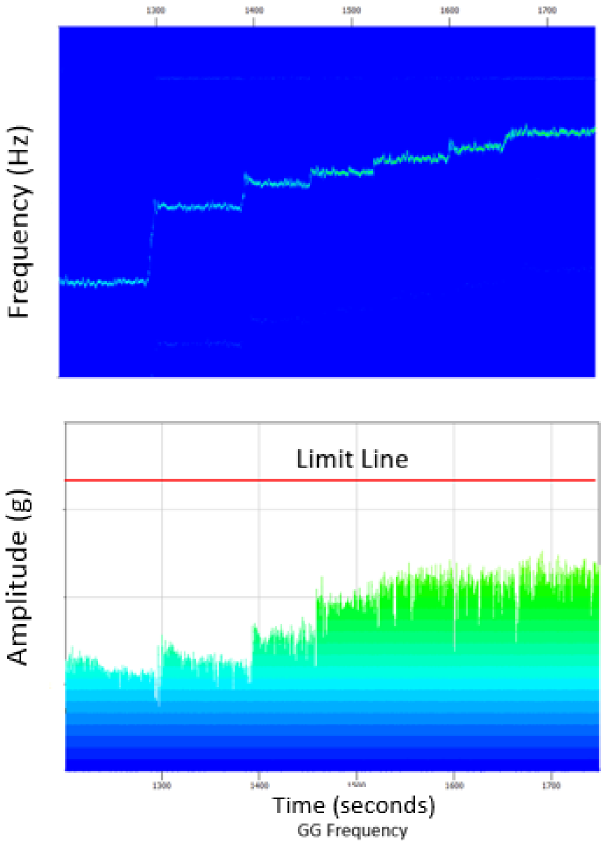
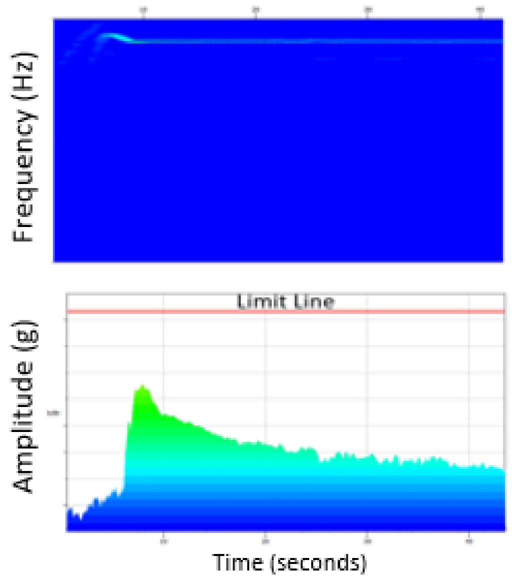
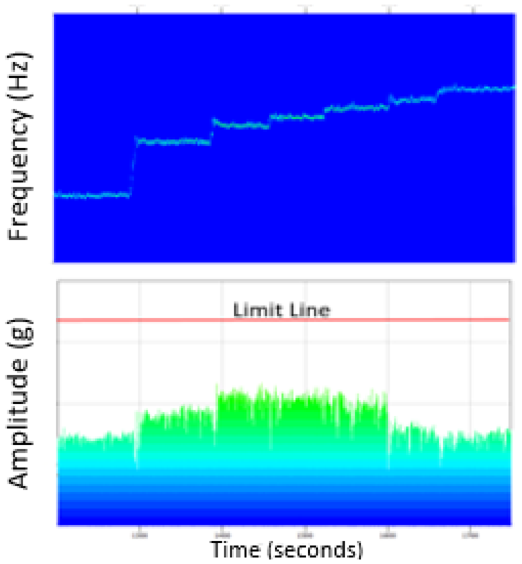


Figure 11 Vibration Levels Rear of the Engine During Acceleration



1/rev Np Frequency



GG Frequency

After completion of the ground runs, flight tests were planned according to the test requirements provided by the engine manufacturer and rotorcraft certification regulations [1]. In order to observe the vibration levels in air, the following harsh helicopter maneuvers were conducted at sea level and maximum service ceiling.

5. FLIGHT TESTS

After completion of the ground runs, flight tests were planned according to the test requirements provided by the engine manufacturer and rotorcraft certification regulations [1]. In order to observe the vibration levels in air, the following harsh helicopter maneuvers were conducted at sea level and maximum service ceiling.

- Dive maneuvers up to 1.1 Vne speeds of the rotorcraft
- Left and right turns under maximum g loads
- Stabilized autorotation at different main rotor (Nr) speeds and helicopter air velocities
- Sudden deceleration from Vne to level flight with minimum air speed
- Climb with maximum continuous power and take-off power
- Hover in ground condition (HIGE) with one engine inoperative

Initial plan was to collect engine vibration data at each of the maneuver at the all helicopter configurations, which are at maximum helicopter weight & aft center of gravity (c.g.), maximum weight & forward c.g. and minimum weight & aft c.g. However, at the beginning of the testing, it was shown that the center of gravity does not have significant impact on the engine vibration levels and the levels do not vary remarkably as the helicopter burns fuel and its weight decreases. Therefore, all the remaining maneuvers were performed at one helicopter configuration as agreed with the engine manufacturer. Since the results were similar for both engines only result of one of them is given. Graphs showing the vibration levels at ground run test points according to c.g and weight are provided in Figure 12, Figure 13, Figure 14 and Figure 15 below:

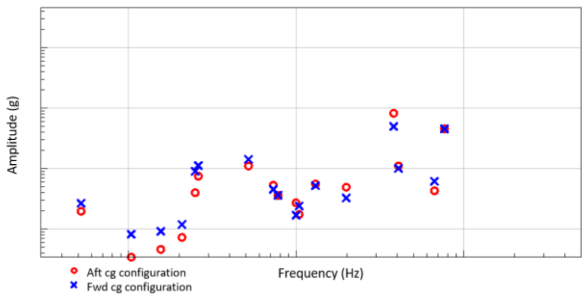


Figure 12 Vibration Levels Comparison of Rear for Aft and Fwd Cg Configuration

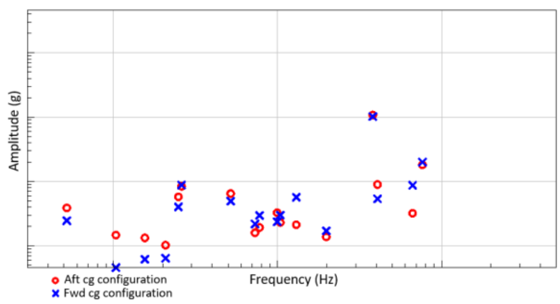


Figure 13 Vibration Levels Comparison of Front for Aft and Fwd Cg Configuration

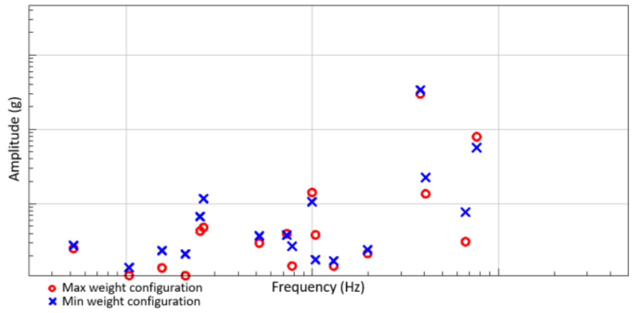


Figure 14 Vibration Levels Comparison of Aft for Max and Min Weight Configuration

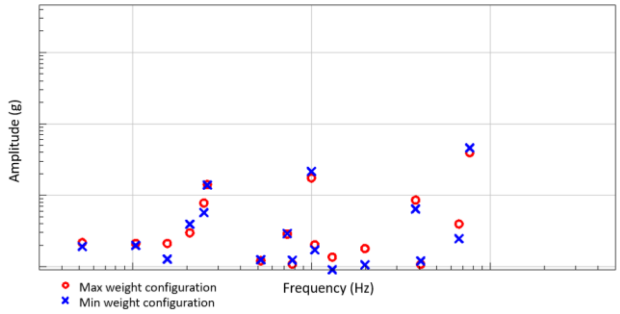


Figure 15 Vibration Levels Comparison of Front for Max and Min Weight Configuration

With guidance of these results, remaining maneuvers were performed with single configuration as indicated above. As requested by AC 29 [4], in order to fully verify vibration levels of the engine the helicopter has to be critically challenged in terms of structurally and controllability by performing extreme maneuvers such as 1.1 Vne Dive, HIGE with OEI condition, climb with MCP and so on.

All of these indicated challenging maneuvers were performed and limit exceedance did not occur for both engines and ECUs. Engine and ECU Vibration levels during 1.1 Vne maneuver are shown in Figure 16, Figure 17and Figure 18 below:

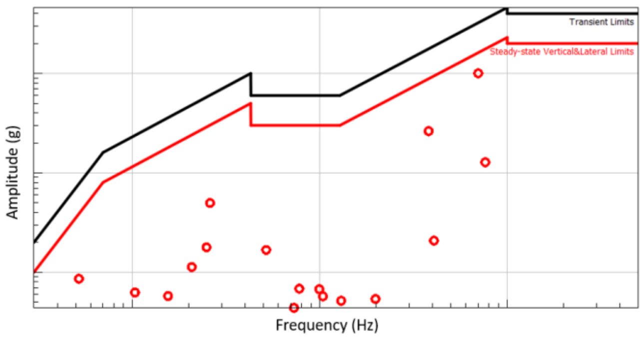


Figure 16 Vibration Levels in Rear of the Engine During Dive 1.1 Vne

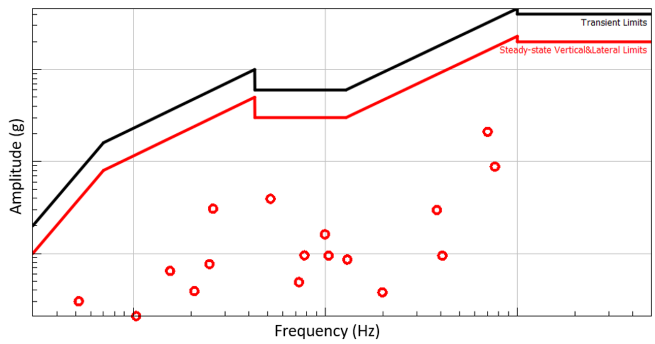


Figure 17 Vibration Levels of Front of the Engine During Dive 1.1 Vne

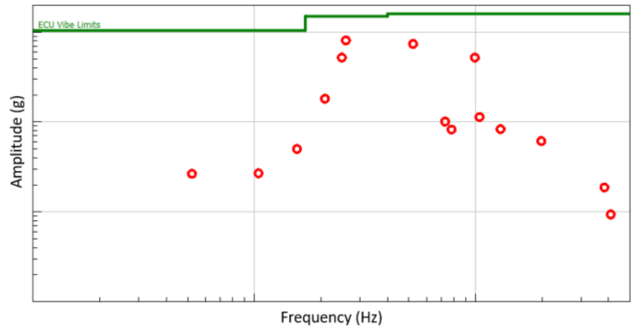


Figure 18 Vibration Levels in ECU During Dive 1.1 Vne

The results are indicated above were performed for AEO conditions. Yet, in case of losing one engine during the operation vibration levels of the remaining engine must be lower than the defined limits during the 1.1 Vne maneuver as well. These maneuvers were performed satisfactorily and limit exceedance was not observed. Results are given in figures below:

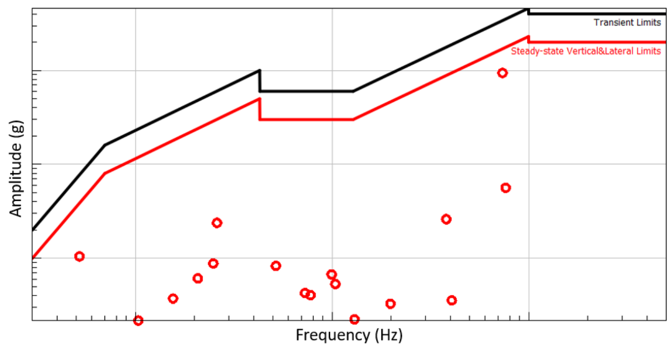


Figure 19 Vibration Levels of Front of the Left Engine During OEI Dive 1.1 Vne

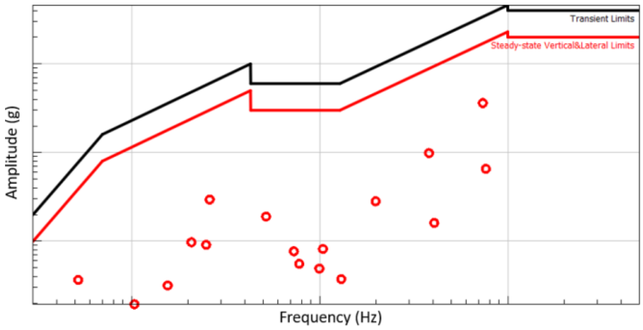


Figure 20 Vibration Levels of Rear of the Left Engine During OEI Dive 1.1 Vne

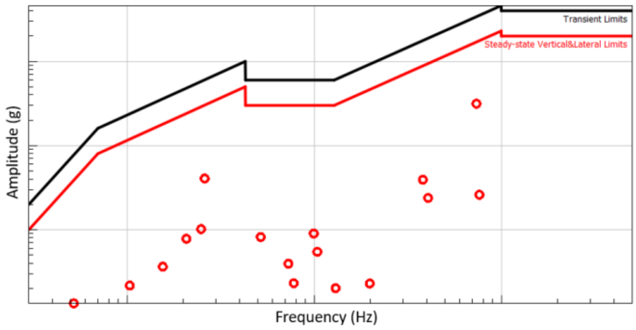


Figure 21 Vibration Levels of the Front Right Engine During OEI Dive 1.1 Vne

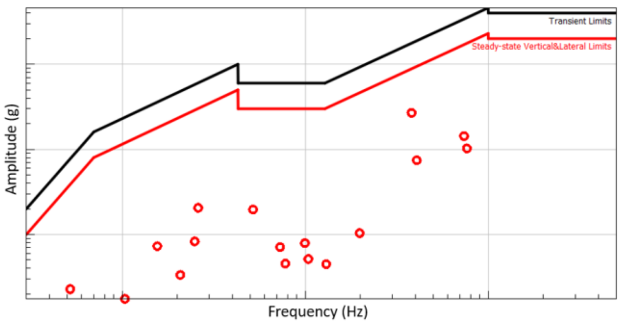


Figure 22 Vibration Levels of the Rear Right Engine During OEI Dive 1.1 Vne

For high power demanding maneuvers such as speed flight and take-off, NR target speed is allowed to be maintained at 102% NR. Therefore natural frequencies of main rotor shifts proportional to this value in the helicopter. In this case, engine vibration levels have to be checked to ensure that shifted natural modes of the rotor frequencies will not cause engine vibration level exceedance. During the HIGE maneuver NR was set to 102% and vibration levels were obtained below in Figure *1*Figure 23 and Figure 24 below:

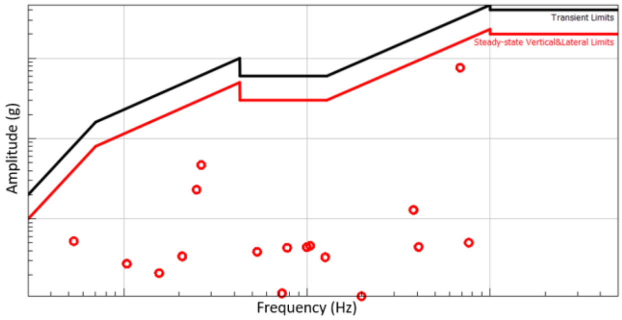


Figure 23 Vibration Levels of Front of the Engine During HIGE 102%NR

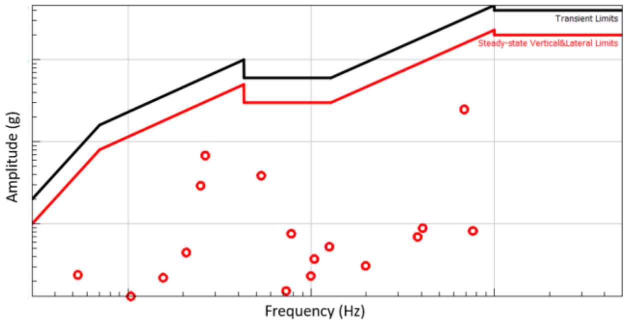


Figure 24 Vibration Levels of the Rear Right Engine During HIGE 102%NR

Since the helicopter is certified up to 20k feet, it is mandatory to verify engine vibration levels for this altitude as well. Even though it was hard to perform flight test at 20k feet due to harsh ambient conditions, Climb-TOP maneuver was performed at this altitude satisfactorily and engine vibration limit exceedance was not observed. The levels are shown in Figure 25, Figure 26 Figure *26* and Figure 27.

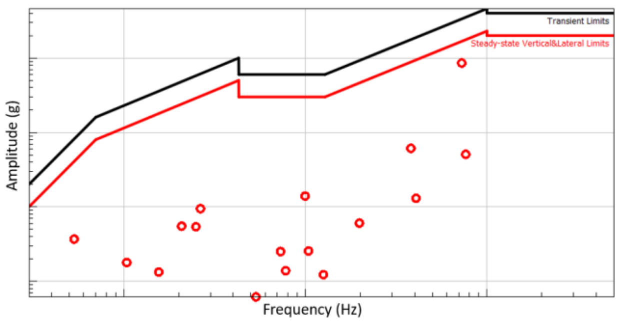


Figure 25 Vibration Levels of the Front Engine During MCP TOP

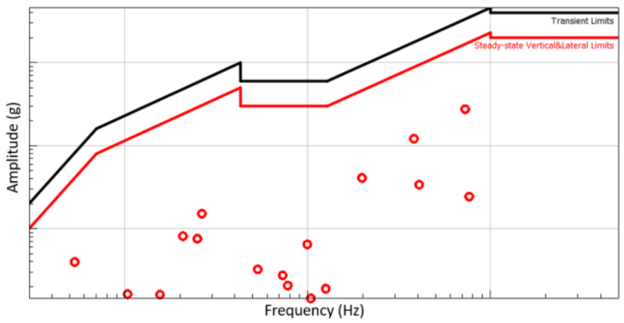


Figure 26 Vibration Levels of the Front Engine During MCP TOP

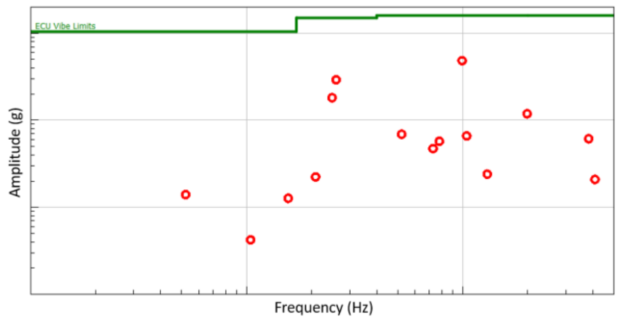


Figure 27 Vibration Levels of the ECU During MCP TOP

6. CONCLUSION

In this survey, according to CS-29 engine vibration regulations and the engine manufacturer's requirements, the engine vibration survey test points were successfully completed. In addition to meeting the specified criteria, several effective methods for reducing engine vibration levels were discovered to provide benefits for future engine integration activities.

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3. A. Mayda, E. Sancar, A.B. Daldal, L. Okatan, T. Çakıroğlu, A. Bayat, A.A. Ezertaş, *"Engine Installed Performance Testing Activities*," in 80th Vertical Flight Society Forum, Montreal, 2024

4. AC 29-2C, Advisory Circular