

Gear Teeth Parameter Identification in Helicopter Planetary Gearbox Using Tachometer and Vibration Signals

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ABSTRACT

Accurate identification of gear tooth counts in planetary gearboxes is essential for condition-based maintenance and health monitoring in gearbox systems. However, direct inspection of internal gear components—especially planet gears—is often infeasible due to the gearbox's enclosed structure and lack of documentation in aging or mixed fleets. This paper presents a methodology to estimate the number of gear teeth in bevel, sun, planet, and ring gears with fixed ring gear planetary gearboxes using vibration and tachometer signals. By applying Time Synchronous Averaging (TSA) and Fast Fourier Transform (FFT), we isolate gear mesh frequencies from noise and harmonics. Three case studies—UH60 Black Hawk, AS350, and Bell 407GX main gearboxes—demonstrate the application of the technique. For bevel gear estimation, TSA is performed using the input shaft rate, allowing dominant frequency peaks to reveal the gear mesh. In planetary gears, TSA is applied using the output shaft rate. Candidate mesh frequencies are identified, with harmonics and known gear interactions used to eliminate false positives. The most plausible planetary mesh frequency is used to estimate the ring gear tooth count, from which the sun gear tooth count is inferred using the total gear ratio.

1. INTRODUCTION

Gearboxes play a critical role in a wide range of industries, from wind turbines to aerospace applications, where they are essential for torque transmission and speed reduction. In helicopters, the main gearbox is a vital component that links the engines to the main rotor system, distributing power through a series of complex gear meshes. The planetary gearbox is particularly important in helicopters due to its compact design, high torque-to-weight ratio, and ability to support multiple power paths.

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Monitoring and evaluating gear health in a planetary gearbox is a challenging task. Vibration and tachometer signals have long been fundamental tools in Health and Usage Monitoring Systems (HUMS) for detecting mechanical faults. Early studies demonstrated their effectiveness in identifying bearing defects (McFadden & Smith, 1984) and gear fatigue cracks through demodulation techniques (McFadden, 1986). Subsequent research expanded their application to gear fault detection algorithms (Bechhoefer, 2019) and more recently to gearbox casing crack detection using both frequency- and time-domain vibration analysis (Cho & Bechhoefer, 2025). Collectively, these works underscore the critical role of vibration and tachometer-based diagnostics in ensuring rotorcraft gearbox reliability.

The enclosed design limits direct physical inspection, and the lack of precise knowledge about tooth counts can make the process even more difficult. Monitoring and evaluating gear health in a planetary gearbox is a challenging task. The enclosed design limits direct physical inspection, and the lack of precise knowledge about tooth counts can make the process even more difficult for operators. Furthermore, unless one is the original equipment manufacturer (OEM) or a certified maintenance, repair, and overhaul (MRO) organization, it is unlikely that operators or third-party analysts have access to detailed gearbox layout or internal gear specifications—particularly the number of teeth on components such as the planet gears. This lack of direct information complicates fault diagnosis, condition-based maintenance, and rotorcraft HUMS.

Sawalhi, N. and Randall, R. B. (2014) present a methodology for identifying unknown gear parameters, such as the number of gear teeth, through the analysis of vibration signals collected during gearbox operation, even in a variable speed condition. By applying signal processing techniques including order tracking, envelope analysis, and spectral averaging, authors were able to extract gear meshing frequencies and their harmonics from the noisy vibration environment of a wind turbine. These frequencies were then used to estimate gear tooth counts and validate gearbox configurations. The approach demonstrates the potential of

non-intrusive diagnostics in complex, inaccessible gear systems. This approach was successful for the two parallel stages; however, the estimated tooth numbers in the planetary section remain somewhat uncertain.

This paper focuses on a method for gear teeth number estimation and gear meshing frequency identification in helicopter planetary gearboxes using tachometer-synchronized vibration signals, which does not require new instrument to identify gear teeth. By utilizing tachometer signals from the input shaft and vibration data from accelerometers mounted on the gearbox housing, gear mesh frequencies can be identified and gear tooth counts estimated.

We apply this to three helicopter gearboxes:

- UH60 Black Hawk: Four blade, twin engine, medium-lift military utility helicopter developed by Sikorsky
- AS350 Écureuil: Three blade, light, single-engine helicopter with a compact gearbox developed by Eurocopter
- Bell 407GX: Four blade, single engine, Multi-role utility helicopter by Bell Helicopter

2. PLANETARY GEARBOX GEAR TEETH PARAMETER IDENTIFICATION

We estimate the number of teeth on the bevel gear (T_b), ring (T_r), sun (T_s), and planet (T_p) gears within a planetary gearbox with a fixed ring gear. Three case studies are presented to illustrate the algorithm's functionality and demonstrate its effectiveness in identifying gear tooth counts. The main gearboxes from the UH60 Black Hawk, AS350 and Bell 407GX helicopters are analyzed. For example, Fig. 1 shows the UH60 gearbox, which serves as a primary example for demonstrating the algorithm. Table 1 summarizes UH60 gearbox components by shaft rate, gear mesh frequency, and gear tooth count—including the lower bevel gear, sun, ring, and planet gears. The lower bevel gear operates at a shaft rate of 20.1 Hz, has 81 teeth, and a corresponding gear mesh frequency of 1629 Hz.

2.1. Vibration Sensor and Tachometer

Tachometer data is needed for calculating shaft speed, while vibration data is required to estimate the number of gear teeth. A vibration sensor is mounted on the side of the main gearbox, as shown in Fig. 2. The yellow sensor bracket has a natural frequency above 20 kHz, ensuring robust and accurate vibration measurements. An accelerometer sampling rate of 23,438 samples per second is used. Tachometer signals are obtained either from the aircraft's onboard variable reluctance (VR) sensor or an optical pickup. Both input and

output shaft rates are known, allowing the calculation of the overall gear ratio ($\text{ratio} = \omega_{\text{output}} / \omega_{\text{input}}$).

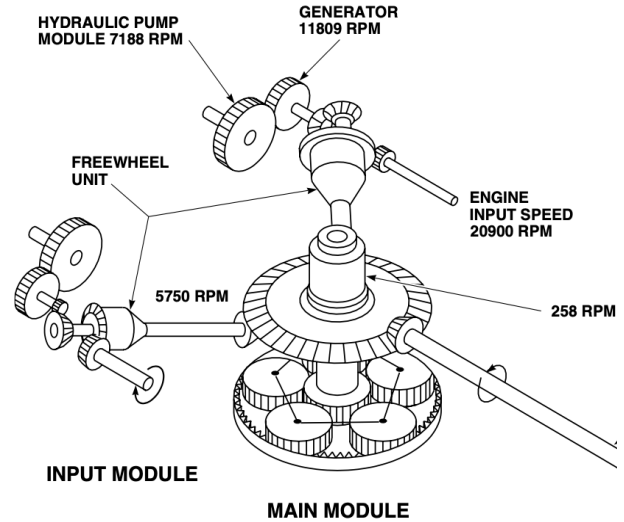


Figure 1 Schematic UH60 gearbox

Table 1. Number of teeth and associated gear mesh in UH60

Name	Shaft Rate	Gear Mesh	Teeth #
Lower Bevel	20.1 Hz	1629 Hz	81
Sun Gear	15.8 Hz	980 Hz	62
Ring Gear	4.3 Hz	980 Hz	228
Planet Gear	11.8 Hz	980 Hz	83

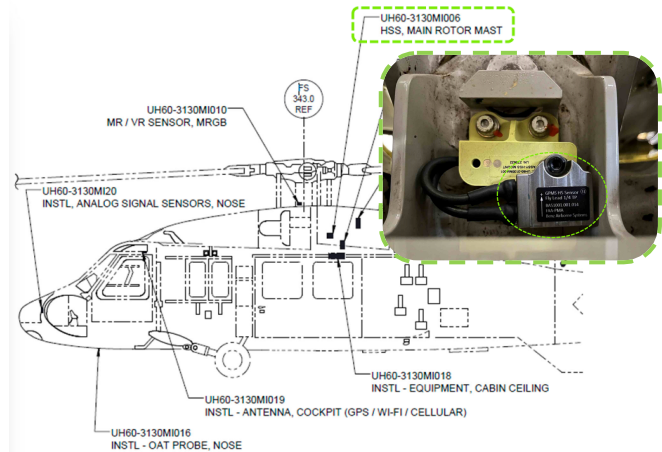


Figure 2 Vibration Sensor Position in UH60

2.2. Jitter Free Algorithm and TSA

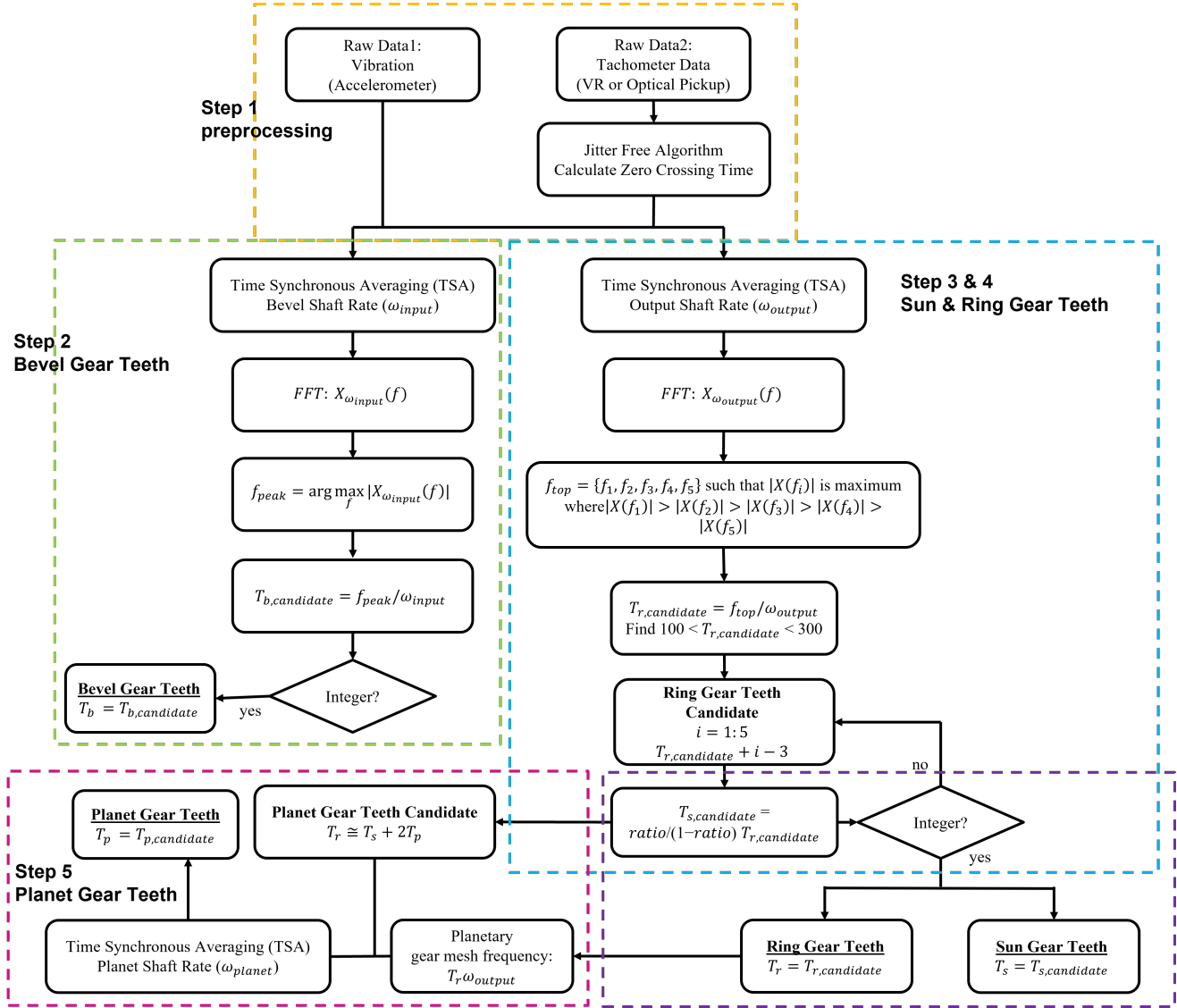


Figure 3 Gear Teeth Identification Algorithm

Figure 3 demonstrates algorithm to identify the number of teeth in the gearbox. Tachometer signals are often affected by jitter, introducing noise that can lead to inaccurate analysis. To address this, a jitter-free algorithm developed by Bechhoefer and He (2016) is applied to the raw VR or optical sensor signal in Step 1. Time Synchronous Averaging (TSA) is then used to suppress noise unrelated to the shaft harmonics and gear mesh frequencies with either input shaft rate (ω_{input}) or output shaft rate (ω_{output}) depending on which gear is targeted in Step 2, 3 and 4. While input shaft is used to identify bevel gear mesh in Step 2, the output shaft rate is used to find planetary gear mesh in Step 3, 4, and 5.

After TSA processing, a Fast Fourier Transform (FFT) is applied to convert the vibration signal into the frequency

domain. TSA length is chosen with radix-2 number for faster computation in Eq. (1).

$$TSA \text{ length} = 2^{\lceil \log_2 sps/freq \rceil} \quad (1)$$

In FFT, one would hypothesize gear mesh frequencies typically appear with higher amplitudes due to the periodic impacts between gear teeth. These dominant frequency peaks serve as strong candidates for identifying gear mesh frequencies. By dividing the gear mesh frequency by the known shaft rate (input or output), the number of gear teeth can be estimated. Constraint would be

- Number of gear teeth (T_b, T_r, T_s, T_p) should be integer
- Ring gear teeth: $80 < T_r < 320$
- $T_r \cong T_s + 2T_p$

In Step 4, reduction gear ratio can be calculated with

$$(T_r + T_s)\omega_c = T_r\omega_r + T_s\omega_s, \quad (2)$$

where ω_c , ω_r , and ω_s is shaft rate of carrier (mast), ring gear, and sun gear, respectively. ω_r is 0 when the ring gear is fixed. Rearranging Eq. (2), $T_s = \omega_c / (\omega_s - \omega_c) T_r$, which should be the integer.

In Step 5, ring and sun gear are identified, estimated planet gear teeth would be:

$$T_p \cong (T_r - T_s)/2 \quad (3)$$

3. RESULTS

3.1. UH60 Black Hawk

Figure 4 shows the raw accelerometer signal alongside the jitter-free angular speed measured on the hydraulic pump in the UH60. Using the known input and output shaft rates, TSA is applied to the vibration signal to extract gear mesh frequencies, including those of bevel and planetary gears. When TSA is performed using the input shaft rate, dominant frequency peaks emerge that are associated with bevel gear interactions. Dividing a prominent gear mesh frequency by the input shaft rate yields the number of bevel gear teeth—an integer value. The hydraulic pump speed—typically measured at 100% of nominal speed—can vary slightly over time, often within a narrow band such as $\pm 0.5\%$. These variations are caused by several dynamic and mechanical factors, even when the aircraft is operating in steady-state conditions. One major contributor is the torque ripple resulting from the advancing and retreating rotor blades during rotation. Due to asymmetrical lift generation—particularly in forward flight—the advancing blade encounters higher airspeeds than the retreating blade, creating a periodic fluctuation in torque transmitted through the drivetrain. This torque variation causes cyclic loading and unloading of the shaft system, slightly modulating the angular speed of the shaft driving the pump.

FFT is applied to TSA-processed signal (based on the input shaft rate) for the UH60 gearbox in Fig. 5. The dominant frequency peak appears at 1642 Hz, which is a strong candidate for the bevel gear mesh frequency. Dividing 1642 Hz by the input shaft rate ω_{input} gives 81 teeth, which confirms the bevel gear count in Table 1.

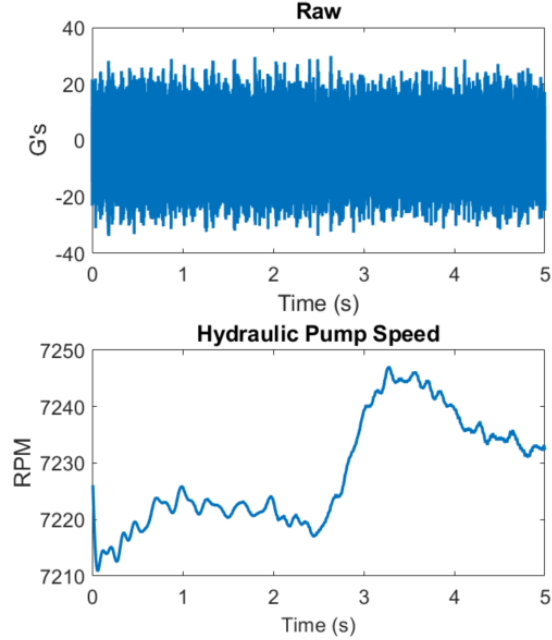


Figure 4 Acceleration raw data and hydraulic pump speed

Figure 6 shows planetary gear mesh frequency candidates derived from TSA using the output shaft rate. Three peaks are observed: 996.6 Hz, 1984 Hz, and 1642 Hz. The 1642 Hz peak is excluded since it corresponds to the bevel gear. While 1984 Hz could be a second harmonic, 996.6 Hz is selected as the likely planetary gear mesh frequency. Using this frequency and the output shaft rate, the estimated ring gear tooth count is 230. However, this may not represent the true mesh frequency due to signal asymmetry caused by the sensor's placement.

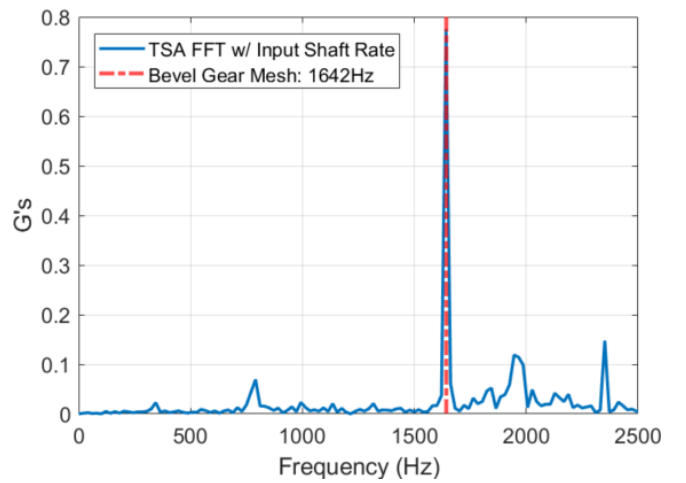


Figure 5 Estimated bevel gear mesh frequency in UH60

As McFadden (1985) noted, gear mesh frequencies may appear shifted by one or two teeth depending on sensor location and signal modulation. The total gear ratio is calculated from the input and output shaft rates. Using this ratio, the sun gear tooth count can be estimated with the following relationship:

Five ring gear tooth candidates (± 2) are evaluated by varying the ratio slightly around the measured value to refine the sun gear tooth estimate. By calculating $T_{s,candidate} = \omega_c / (\omega_s - \omega_c) T_{r,candidate}$, one would confirm by checking if $T_{s,candidate}$ is integer. When ring gear candidate is 228, Sun gear teeth is satisfied integer, which is 2 teeth off from the measured planetary gear mesh due to the asymmetric sensor location. So, the corrected planetary gear mesh is 987.9Hz (996.8Hz - 2teeth * 4.3Hz) where 4.3Hz is the mast rate.

The candidate number of planet gear teeth can be estimated by solving Eq. (3). Using the planetary carrier shaft rate, TSA followed by FFT is performed to identify the planetary gear mesh frequency, which becomes apparent once the ring gear tooth count has been determined. Due to its function as an idler gear, the planet gear does not produce a dominant gear mesh frequency on its own, making exact identification challenging. Several approaches have been taken including harmonic components up to the fifth order (UH60 contains five planet gears) in TSA FFT, and envelope analysis. However, no distinct or consistent relationship was observed, suggesting limited contribution of planetary gear harmonics to the overall signal.

Figure 7 compares the raw FFT with the TSA-processed FFT. When using the raw FFT to estimate gear teeth, it becomes challenging to accurately identify the true gear mesh frequency. If an incorrect shaft ratio, derived from a poor gear tooth estimate, is used in the TSA process, the resulting averaging can suppress the actual gear mesh signal. This may lead to inaccurate conclusions in gear fault diagnostics.

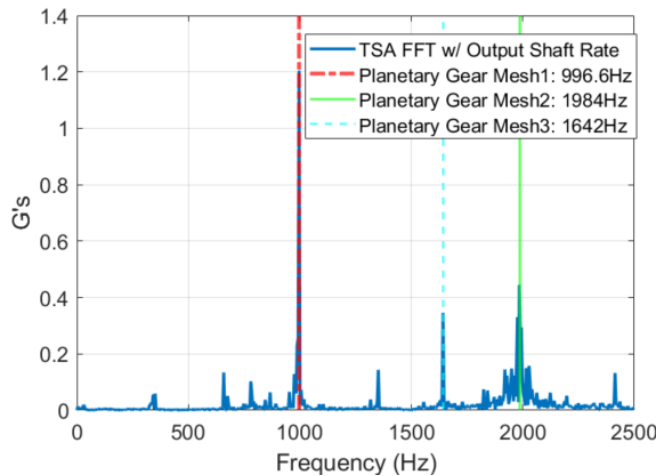


Figure 6 Estimated planetary gear mesh frequency in UH60

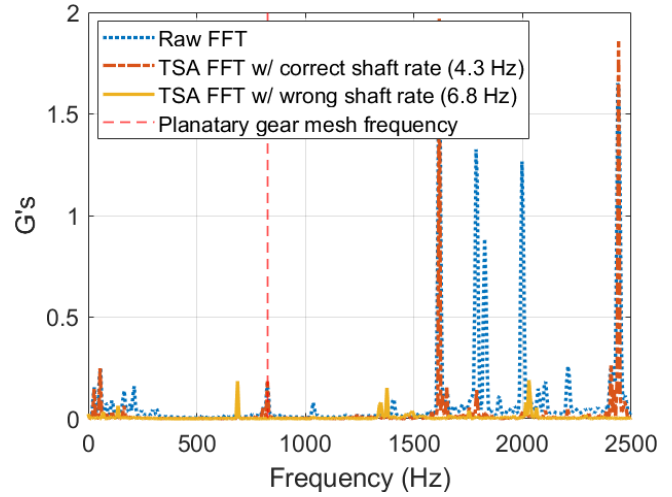


Figure 7 Raw FFT, TSA FFT with correct and wrong shaft rate in UH60

3.2. AS350 Écureuil

The AS350 features a compact gearbox that transmits lower vibratory energy compared to the UH60, presenting a greater challenge for vibration-based diagnostics. This example aims to evaluate whether the proposed algorithm and sensor setup are sensitive enough to detect the planetary gear mesh vibrations necessary for identifying gear tooth counts. As shown in Figure 8, an optical pickup sensor is used to capture the tachometer signal and determine the input and output shaft rates, while an accelerometer is mounted on the gearbox housing to collect vibration data. To validate estimated results, Table 2 shows the shaft rates, gear tooth counts, and gear mesh frequencies for the lower bevel (=61), sun (=30), ring (=100), and planet gears (=35).

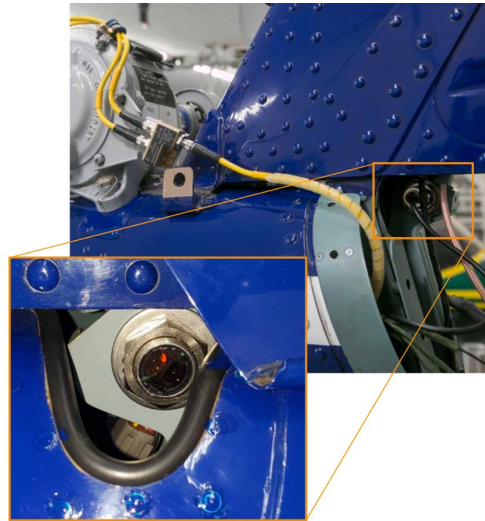


Figure 8 Optical pickup sensor in AS350

Table 2. Number of teeth and associated gear mesh in AS350

Name	Shaft Rate	Gear Mesh	Teeth #
Lower Bevel	27.82 Hz	1724 Hz	61
Sun Gear	21.4 Hz	642 Hz	30
Ring Gear	6.42 Hz	642 Hz	100
Planet Gear	18.35 Hz	642 Hz	35

TSA FFT based on input shaft rate for the AS350 gearbox is shown in Fig. 9. The dominant frequency peak appears at 1725 Hz, which is a good candidate for the bevel gear mesh frequency. Dividing 1725 Hz by the input shaft rate gives 61 teeth matching with true bevel teeth in Table 2.

Figure 10 shows planetary gear mesh frequency candidate derived from TSA using the output shaft rate and 652 Hz is chosen, the frequency with the highest amplitude as the likely planetary gear mesh frequency. Using this frequency and the output shaft rate (measured 6.52Hz), the estimated ring gear tooth count is 100. Planet gear teeth can be estimated by solving Eq. (3). Estimated teeth is verified with TSA FFT using the planetary carrier shaft rate.

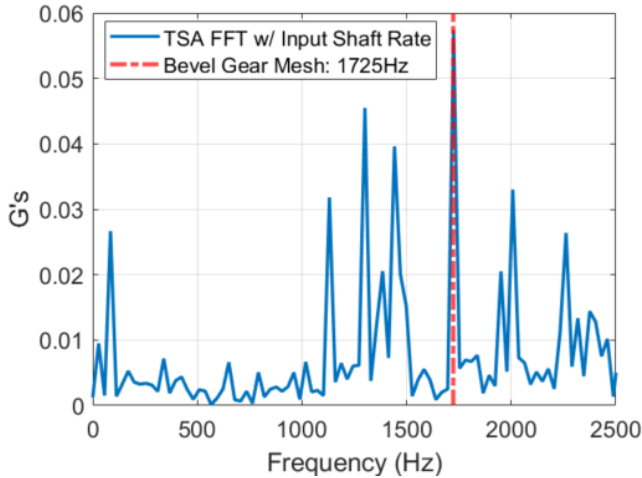


Figure 9 Estimated bevel gear mesh frequency in AS350

3.3. Bell 407GX

The Bell 407GX is a medium-sized, multi-role helicopter equipped with a four-bladed main rotor and a single engine. Table 3 presents key information related to its planetary gearbox, including shaft rates, gear tooth counts, and gear mesh frequencies for critical components. Specifically, the lower bevel gear has 62 teeth, the sun gear has 32, the ring gear has 118, and each planet gear has 41 teeth. The gear mesh frequencies for the bevel and planetary stages are approximately 2000 Hz and 812 Hz, respectively.

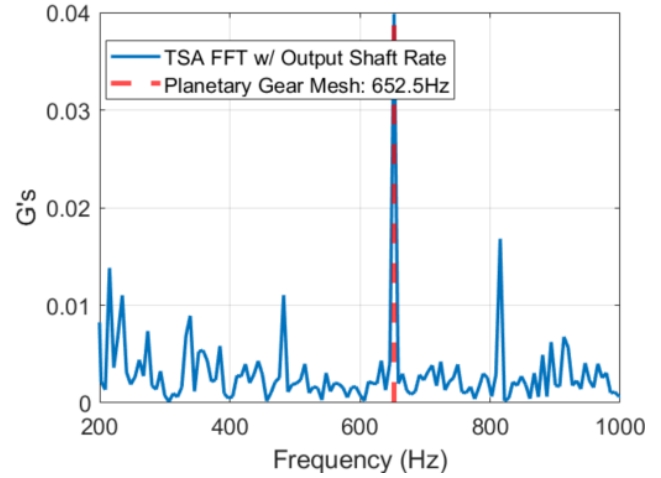


Figure 10 Estimated planetary gear mesh frequency in AS350

Table 3. Number of teeth and associated gear mesh in Bell407GX

Name	Shaft Rate	Gear Mesh	Teeth #
Lower Bevel	32.26 Hz	2000 Hz	62
Sun Gear	25.38 Hz	812 Hz	32
Ring Gear	6.88 Hz	812 Hz	118
Planet Gear	19.81 Hz	812 Hz	41

Figure 11 shows the TSA FFT of the Bell 407GX gearbox using the input shaft rate (~28 Hz). A dominant frequency peak appears at 1999 Hz, which corresponds well with the bevel gear mesh frequency. Dividing 1999 Hz by the input shaft rate yields 62 teeth, consistent with the known bevel gear specification listed in Table 3.

Figure 12 presents the planetary gear mesh frequency candidate derived from TSA using the output shaft rate (~6.9 Hz). The peak at 825.3 Hz is identified as the likely planetary gear mesh frequency. Dividing this by the output shaft rate yields a ring gear tooth estimate of 120. However, this value may be skewed due to signal asymmetry caused by sensor placement.

To compensate the sun gear tooth estimate, five candidate ring gear values (± 2 teeth) are evaluated. The sun gear tooth count is calculated using the relation: $T_{s,candidate} = \omega_c / (\omega_s - \omega_c) T_{r,candidate}$. An integer result is achieved when the ring gear tooth count is 118, suggesting the initial 825.3 Hz planetary mesh frequency was offset by 2 teeth. Correcting for this offset using the mast rate (6.8 Hz), the adjusted planetary gear mesh frequency becomes ~811 Hz.

Planet gear tooth count is estimated by solving Eq. (3) once the ring gear is identified. Although TSA-FFT was performed

using the carrier shaft rate, the planet gear—acting primarily as an idler—does not generate a dominant mesh frequency. Investigations into harmonic components up to the third order (Bell 407GXi uses three planet gears) and envelope analysis yielded no strong or consistent indicators, suggesting that planetary gear harmonics have minimal impact in this configuration.

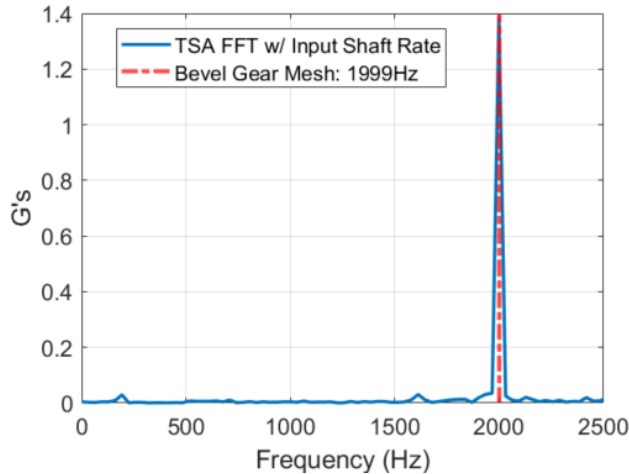


Figure 11 Estimated bevel gear mesh frequency in Bell407GXi

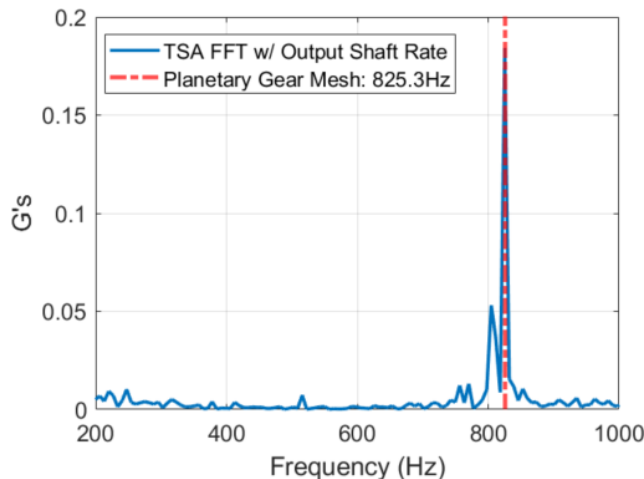


Figure 12 Estimated planetary gear mesh frequency in Bell407GXi

4. CONCLUSION

This study presents the approach for estimating gear tooth counts in planetary gearboxes using vibration data and tachometer signals. By applying TSA and spectral analysis, gear mesh frequencies corresponding to both bevel and planetary gear interactions can be extracted. These frequencies provide a pathway to infer the number of gear

teeth for each component without requiring physical inspection or detailed mechanical drawings—especially valuable in legacy or undocumented systems. Here is a summary of key lessons learned:

Bevel gear identification is robust across platforms

- In all three gearboxes, TSA applied with the input shaft rate consistently isolated the dominant bevel gear mesh frequency.
- Dividing the identified frequency by the input shaft rate yielded integer tooth counts that matched design specifications, validating the method for bevel gear characterization.

Planetary gear mesh frequencies require careful interpretation

- Planetary gear mesh frequencies were less straightforward to identify due to sensor placement asymmetry and signal modulation.
- In each case, candidate mesh frequencies initially led to tooth count offsets of ± 2 teeth, which required correction using the mast rate and integer checks on gear tooth relationships.
- This highlights the importance of validating results with multiple candidates and applying physical constraints (e.g., gear ratio relationships).

Planet gear detection remains inherently challenging

- Across all cases, planet gears contributed weakly to the vibration spectrum because they function as idler gears.
- Harmonic and envelope analysis (up to 5th order in the UH-60 and up to 3rd order in the Bell 407GXi) did not produce reliable indicators of planet gear counts.
- This suggests that current vibration-based methods have limited reproducibility for directly identifying planet gear teeth.

The case studies collectively show that gear tooth estimation in planetary gearboxes requires a multi-step validation process—robust for bevel gears but still limited for planet gears. Careful attention to sensor placement, shaft-rate alignment, and integer tooth checks is critical for reliable diagnostics across different helicopter platforms.

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BIOGRAPHIES

Changik Cho received his B.S. and M.S. degrees in Mechanical Engineering from Sungkyunkwan University in South Korea, and earned his Ph.D. in Mechanical Engineering from Pennsylvania State University, where his research focused on active vibration control for electrical vertically take-off and landing (eVTOL) aircraft. His work spans vibration control, rotor dynamics, and battery modeling, with contributions to both analytical methods and experimental validation. He has collaborated with industry partners such as Siemens on Li-ion battery optimization and with an eVTOL company on full-scale tiltrotor aircraft vibration analysis during his Ph.D. Dr. Cho is currently a Systems Engineer at GPMS, where he focuses on the development of Health and Usage Monitoring Systems (HUMS) for rotorcraft. He has published his work in leading venues including AIAA SciTech, the VFS Forum, ASME IDETC, and the AIAA Journal of Guidance, Control and Dynamics.

Eric Bechhoefer received his BS in Biology from the University of Michigan, his MS in Operations Research from the Naval Postgraduate School, and a Ph.D. in General Engineering from Kennedy Western University. He is a former Naval Aviator who has worked extensively on condition-based maintenance, rotor track and balance, vibration analysis of rotating machinery, and fault detection in electronic systems. Dr. Bechhoefer is a Fellow of the Prognostics Health Management Society, a Fellow of the Society for Machinery Fault Prevention Technology, and a senior member of the IEEE Reliability Society. Additionally, Dr Bechhoefer is also a member of the SAE committee covering Integrated Vehicle Health Management, and a member of the MSG-3, Rotorcraft Maintenance Programs Industry Group.