Virtual-Flipped-Physical Teaching for Planetary Gear Fault Diagnosis with Model-Experiment Verification

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Abstract. Condition monitoring and fault diagnosis (CMFD) is difficult to teach because students must connect mechanical dynamics, signal processing, sensing, and diagnostic reasoning with real rotating machinery. This paper presents a Virtual-Flipped-Physical (VFP) teaching case for sun-gear broken-tooth diagnosis in a planetary gearbox. Students first use a simplified dynamic model to calculate characteristic frequencies and observe simulated mesh-frequency sidebands. They then explain the modulation mechanism and common calculation errors in a flipped classroom before verifying the expected features on a two-stage planetary gear test rig. The paper emphasizes model-experiment comparison as a teaching task: the simulation provides a clean dynamic-transmission-error response, whereas the experiment measures casing acceleration under different speed and transmission-path conditions. By comparing the two, students learn to separate kinematic prediction, dynamic modulation, and measurement-path effects. The case offers a compact, reproducible teaching design that links virtual preparation, classroom reasoning, and physical verification.

Keywords: Virtual-Flipped-Physical, planetary gear, broken-tooth fault, condition monitoring and fault diagnosis, engineering education.

1 Introduction

Planetary gear systems are widely used in wind turbines, helicopter transmissions, vehicles, and other compact mechanical power systems. Their vibration signatures are complex because the mesh source, rotating carrier, and transmission path are coupled. Fault information is often reflected in modulation sidebands and resonance-region features rather than in a single isolated peak [1-3]. This makes planetary gear diagnosis a suitable but challenging case for CMFD teaching.

CMFD teaching requires students to integrate machine dynamics, signal processing, experimental operation, and diagnostic reasoning. Lecture-only teaching can introduce mesh frequency and sidebands, but students may still fail to connect formulas with

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measured vibration signals. Flipped-classroom and engineering-education studies suggest that pre-class preparation and in-class problem solving can improve engagement and interpretation when the activities are carefully aligned [4, 5].

This paper proposes a VFP teaching model that combines virtual dynamic simulation before class, flipped classroom reasoning during class, and physical test-rig verification in the laboratory. The contribution is threefold: it organizes a planetary gear broken-tooth case into a reproducible teaching sequence, aligns each phase with assessment evidence, and uses model-experiment differences and common student mistakes as targeted teaching checkpoints.

2 Course Context, Test Platform, and Dynamic Model

Course context. The target course is Equipment Condition Monitoring and Fault Diagnosis, a 54-hour, 3-credit graduate mechanical engineering course. The VFP unit is inserted into the gear-fault diagnosis module and uses laboratory time more deliberately by requiring students to prepare with simulation before entering the test room.

Test platform. The laboratory system consists of a driving motor, a bevel gear pair, a two-stage planetary gear set, a two-stage spur gearbox, and a load motor, as shown in Fig. 1. Corresponding parameters are listed in Table 1. The bevel gear pair before the first-stage planetary gear set has a 2:1 reduction ratio; therefore, at a motor speed of 1200 r/min, the first-stage sun gear input is 600 r/min. Accelerometers mounted on the casing acquire vibration signals, and broken-tooth faults can be implanted on the sun, planet, or ring gear. The model, simulation results, and experimental signals are adapted from the authors' previous study [6].

Table 1. Key parameters of the planetary gear test rig.

Parameter	**First-stage planetary gear set**	**Second-stage planetary gear set**
Number of planet gears	3	4
Sun gear teeth	32	28
Planet gear teeth	40	34
Ring gear teeth	112	96
Simulatable faults	Sun/planet/ring broken tooth	Sun/planet/ring broken tooth

Teaching-oriented dynamic model. The virtual part provides a compact bridge from gear damage to time-varying mesh stiffness, dynamic response, and spectral interpretation. It helps students predict the main diagnostic frequencies while keeping the modeling logic transparent enough for classroom use.

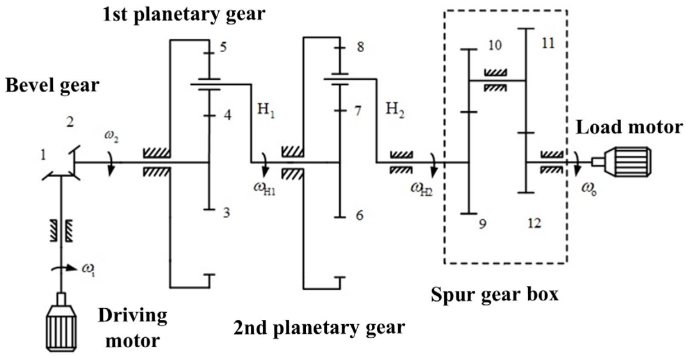

Fig. 1. Schematic diagram of the planetary gear test rig.

Broken-tooth representation. The broken tooth is represented by a partial cut defined by the broken width w_p and broken height s_p, as illustrated in Fig. 2. Following the potential-energy principle, the equivalent mesh stiffness is described through the series combination of Hertzian contact, bending, shear, axial compressive, and fillet-foundation stiffness components.

In the damaged region, the effective tooth width, cross-sectional area, and second moment of area are corrected according to the local broken width. This simplified description is sufficient for teaching because students can see how a local physical defect enters the model through stiffness variation.

The broken region reduces local bending stiffness and introduces a periodic disturbance in time-varying mesh stiffness. This disturbance is the mechanical source of the simulated impacts and mesh-frequency sidebands used later in the teaching case.

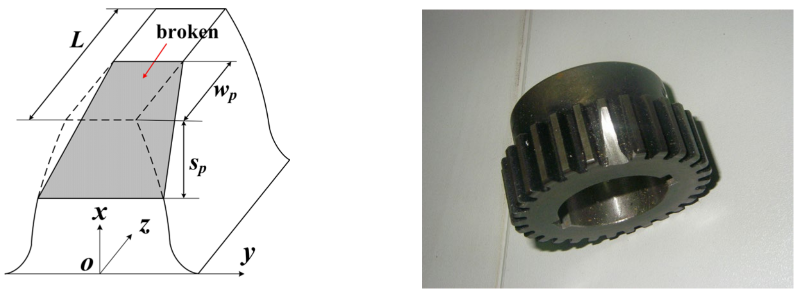

Fig. 2. Broken-tooth fault model and physical sun-gear specimen: (a) geometric model and (b) photograph of the sun gear with a broken-tooth fault.

Translational-torsional model. A translational-torsional lumped-mass model is used for the planetary gear set [7]. The sun gear, planet gears, ring gear, and carrier are represented by translational and torsional coordinates, and the response is solved numerically with the Newmark-beta method.

$$M\ddot{q} + C\dot{q} + K(t)q = F(t) \quad (1)$$

In Eq. (1), M, C, $K(t)$, q, and $F(t)$ denote the mass matrix, damping matrix, time-varying stiffness matrix, generalized displacement vector, and excitation vector, respectively. The time-varying stiffness matrix contains the sun-planet and ring-planet mesh stiffness terms $k_{spi}(t)$ and $k_{rpi}(t)$.

3 VFP Teaching Design and Case Implementation

Teaching sequence. The VFP model follows a progressive learning structure. In the Virtual phase, students receive model-based scaffolding before class; in the Flipped phase, they explain spectra and design the laboratory plan; in the Physical phase, they operate the test rig and compare model expectations with measured signals. This sequence follows scaffolding and constructive-alignment principles [8, 9], as shown in Table 2.

Table 2. VFP teaching flow.

Phase	Timing	Student task	Instructor role	Output
Virtual	Pre-class, 1-2 h	Run MATLAB simulation; identify mesh frequency and sidebands	Provide model, guide questions, and short quiz	Time response and FFT notes
Flipped	In class, 2-3 h	Present findings; explain spectra; propose experiment plan	Clarify concepts and connect modulation with broken-tooth impacts	Group explanation and lab plan
Physical	Laboratory, 2-3 h	Install fault gear; collect vibration; perform FFT	Supervise safety and ask diagnostic questions	Laboratory report and reflection

Misconception-oriented design. The teaching design is organized around common diagnostic misconceptions rather than around software operation alone. The Virtual phase checks speed-chain and unit-conversion errors; the Flipped phase checks confusion among sun speed, carrier speed, relative sun rotational frequency, and mesh frequency; and the Physical phase checks whether students can separate fault-related sidebands from carrier-related transmission-path sidebands. Typical diagnostic mistakes and targeted teaching interventions are listed in Table 3.

This table is used as a teaching checklist, not as statistical evidence of student performance. During implementation, each mistake is tied to a specific deliverable: the pre-class calculation sheet, the annotated spectrum, the group explanation, or the laboratory reflection.

Table 3. Typical diagnostic mistakes and targeted teaching interventions.

Typical mistake	Diagnostic consequence	Targeted intervention
Using the motor speed directly after the bevel gear reduction is introduced.	The physical-stage frequency target is shifted, and the expected mesh-frequency location becomes wrong.	Students complete a speed-chain worksheet from motor speed to first-stage sun-gear input before inspecting any spectrum.
Treating the planetary set as an ordinary fixed-axis gear pair.	Carrier motion and relative rotation are ignored, leading to incorrect sideband spacing.	Students derive the sun, carrier, relative, and mesh frequencies step by step and attach a physical meaning to each term.
Interpreting every sideband as a broken-tooth feature.	Carrier-related transmission-path sidebands in the healthy case may be misread as fault evidence.	Healthy and faulty spectra are compared in pairs; students must identify newly strengthened or fault-consistent sidebands rather than list all peaks.
Memorizing the sideband rule without explaining modulation.	The diagnosis becomes peak matching and does not show why stiffness disturbance produces periodic impacts.	Groups draw the causal chain from broken tooth to stiffness loss, impact, amplitude modulation, and mesh-frequency sidebands.
Expecting the simulation and experiment to have identical spectra.	Additional peaks in casing acceleration are interpreted as model failure instead of measurement-path effects.	The laboratory report includes a short difference explanation covering operating condition, measured variable, and transmission path.

Virtual phase. Before class, students run the MATLAB program for the first-stage sun-gear broken-tooth case. For the virtual case, the sun gear speed is 1500 r/min. Students calculate the relevant frequencies before inspecting the spectrum, so the simulation becomes a prediction task rather than a peak-matching exercise.

Flipped phase. Class time is used for reasoning rather than one-way lecturing. Student groups explain why a broken tooth causes periodic stiffness disturbance, why the disturbance produces impacts, and why sidebands occur at intervals related to the relative rotational frequency. The instructor then corrects misconceptions about absolute shaft speed, carrier speed, and relative motion in planetary transmissions.

Physical phase and assessment. In the laboratory, the broken sun gear is installed in the first-stage planetary gear set. The motor speed is 1200 r/min, but the 2:1 bevel gear reduction makes the first-stage sun gear input 600 r/min. Under this condition, f_{mp1} = 248.89 Hz, f_{rs1} = 7.78 Hz, and f_{c1} = 2.22 Hz. Assessment includes a preparation quiz and annotated virtual spectrum, a flipped-classroom explanation, a laboratory report, and a final case-based diagnostic question.

Frequency-calculation task. For the first-stage planetary gear set with a fixed ring gear, students first derive the characteristic frequencies from gear teeth and speed before they inspect any spectrum.

$$f_s = n_s / 60 \tag{2}$$

$$f_c = N_s f_s / (N_s + N_r),\ \ f_{rs} = f_s - f_c \tag{3}$$

$$f_m = N_s f_{rs} \tag{4}$$

For the virtual case, N_s = 32, N_r = 112, and n_s = 1500 r/min, so f_s = 25 Hz, f_c = 5.56 Hz, f_{rs} = 19.44 Hz, and f_m = 622.22 Hz. For the physical case, the first-stage sun input is 600 r/min after bevel-gear reduction, so f_s = 10 Hz, f_c = 2.22 Hz, f_{rs1} = 7.78 Hz, and f_{mp1} = 248.89 Hz. This step exposes typical errors: using motor speed directly, forgetting rpm-to-Hz conversion, using carrier frequency as sideband spacing, or treating the planetary gear set as a fixed-axis gear pair.

Virtual observation. Figure 3 shows the simulated dynamic transmission error. In the healthy condition, the spectrum is dominated by the mesh frequency and its harmonics. In the broken-tooth condition, periodic impacts appear in the time response, and their interval is approximately 0.0514 s, close to $1/f_{rs}$. The spectrum shows sidebands around the mesh-frequency components, helping students connect local stiffness reduction with amplitude modulation.

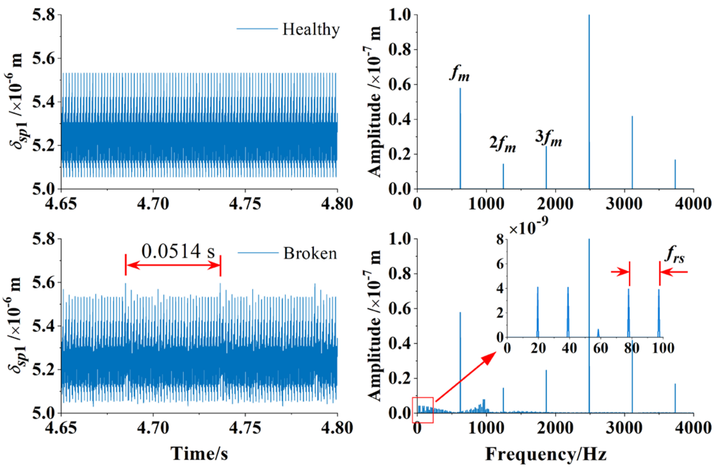

Fig. 3. Virtual simulation result for the sun-gear broken-tooth case.

Flipped interpretation. After the virtual observation, students enter the Flipped phase with annotated spectra and preliminary frequency calculations. Each group explains the causal chain from broken tooth, stiffness reduction, periodic impact, modulation, and sideband generation. The group output is a short laboratory plan specifying expected frequency components, measurement direction, and a strategy for distinguishing fault-related sidebands from carrier-related transmission-path sidebands.

Physical verification. During the Physical phase, Fig. 4 shows the measured vibration signals. In the healthy case, the spectrum contains f_{mp1} and carrier-related sidebands, which is consistent with planetary transmission-path modulation. In the broken-tooth case, additional sidebands at $f_{mp1} + f_{rs1}$ and $f_{mp1} + 2f_{rs1}$ are identified. Students therefore compare healthy and faulty spectra by focusing on newly strengthened fault-related sidebands rather than treating every sideband as a fault indicator.

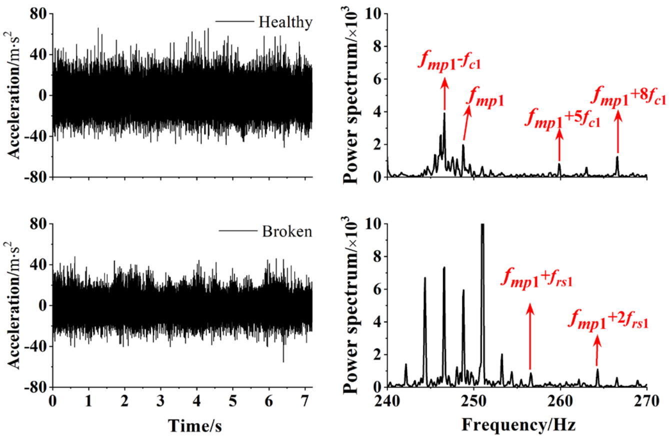

Fig. 4. Experimental vibration result under healthy and broken-tooth conditions.

4 Model-Experiment Comparison and Teaching Implications

Complementary evidence. The virtual and physical phases serve different teaching functions. The virtual phase uses a 1500 r/min sun-gear input and dynamic transmission error, whereas the physical phase uses casing acceleration at the reduced first-stage sun-gear input speed of 600 r/min. Thus, students compare diagnostic mechanisms and side-band patterns, not one-to-one numerical peak equality.

Model-experiment comparison. The simulation and experiment are compared at the level of diagnostic mechanism. The first difference is operating condition: the virtual case uses 1500 r/min at the sun gear, whereas the physical case uses 600 r/min at the first-stage sun gear after the bevel reduction. Therefore, the simulated mesh frequency of 622.22 Hz and the experimental mesh frequency of 248.89 Hz should not be expected to coincide numerically.

Measured-variable difference. The model outputs dynamic transmission error, while the experiment measures casing acceleration after vibration passes through shafts, bearings, the gearbox casing, and the accelerometer mounting path. The simulated spectrum is therefore cleaner, whereas the measured spectrum contains structural response, background excitation, and noise.

Transmission-path modulation. Because the mesh source moves with the carrier but the accelerometer is fixed on the casing, carrier-related sidebands can appear even in the healthy condition. This is an important teaching point: students must distinguish sidebands caused by transmission-path modulation from sidebands strengthened by the broken tooth.

Model simplification. The teaching model emphasizes time-varying mesh stiffness and broken-tooth excitation, whereas the real test rig also includes casing flexibility, bearing and assembly effects, load fluctuation, downstream gearbox excitation, and actual damping conditions. These factors explain why the experimental spectrum is more complicated without implying that the model is pedagogically invalid.

For this reason, students are instructed not to expect one-to-one peak coincidence between Fig. 3 and Fig. 4. The model is first used to predict the mechanism: a local broken tooth changes mesh stiffness periodically and produces modulation around the mesh-frequency components. The experiment is then used to test whether a consistent diagnostic pattern can still be recognized after the signal has passed through the real transmission path. The comparison task therefore asks whether the sideband spacing and fault-related strengthening are physically explainable, rather than whether every spectral line in the two figures is identical.

Targeted teaching strategies. For frequency-calculation errors, the instructor requires a speed-chain worksheet before spectrum interpretation. For modulation errors, students must explain the physical meaning of f_s, f_c, f_{rs}, and f_m before identifying sidebands. For over-diagnosis of sidebands, healthy and faulty spectra are compared side by side so that students focus on newly appearing or strengthened fault-related components. For model-experiment mismatch, students write a reflection separating kinematic prediction, dynamic modulation, and measurement-path effects.

The final laboratory report requires students to separate three layers of reasoning: kinematic prediction, dynamic modulation, and measurement-path influence. A correct answer must first compute the relevant frequency targets, then explain why broken-tooth excitation gives rise to sidebands, and finally justify why the experimental spectrum contains additional components. This assessment rule makes the model-experiment difference an explicit learning outcome rather than an incidental observation.

To make the comparison operational, the report template asks students to complete three short evidence boxes. The first box records the calculated frequency targets and the speed-reduction path used to obtain them. The second box identifies the sideband spacing observed in the simulated or measured spectrum and explains whether it is related to relative rotation or carrier-related transmission-path modulation. The third box explains why additional experimental components may appear even when the model predicts the main diagnostic mechanism correctly. This structure prevents the comparison from becoming a loose visual description and turns it into a repeatable diagnostic argument.

The instructor also uses two follow-up prompts during the flipped discussion. First, students are asked whether a sideband would still be considered fault-related if it appears in the healthy spectrum; this prompt guides them to compare healthy and broken-tooth conditions before assigning diagnostic meaning. Second, students are asked why the simulated mesh-frequency component and the measured component have different numerical values; this prompt checks whether they have noticed the different input speeds and measured variables. These prompts are intentionally narrow because they target the exact misunderstandings that otherwise lead to wrong frequency calculation, over-diagnosis of sidebands, and unrealistic expectations of model-experiment agreement. The answers are discussed publicly so that calculation errors and interpretation errors are corrected before students operate the test rig.

5 Conclusion

This paper presented a VFP teaching case for planetary gear broken-tooth diagnosis. The case links dynamic modeling, characteristic-frequency calculation, flipped classroom explanation, and physical verification. By comparing simulated dynamic transmission error with measured casing acceleration, students learn to distinguish kinematic prediction, dynamic modulation, and measurement-path effects while avoiding common errors in speed conversion and sideband interpretation.

Future work may extend the case to planet gear, ring gear, and compound faults, and may add a small-scale cohort study when student-performance data become available.

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