# A Unique Tidal Frequency to the Damage Induced Vibration of Planetary Gear System

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***Abstract*—Structures and dynamics of planetary gears are very different from fixed axis gears. Special attentions to fault diagnostics of planetary gear system need to be carefully studied. In this paper, a distinctive nature of damage induced vibration of planetary gear box, namely tidal frequency, considering fault transmission paths of planetary gear system is discussed and proposed. Artificial planetary sun gear fault is introduced to an experimental test rig, the proposed tidal frequency to planetary sun gear faults are demonstrated and it may be a promising feature for planetary gear system condition monitoring.**

***Keywords-planetary gear system; fault diagnostic; tidal frequency***

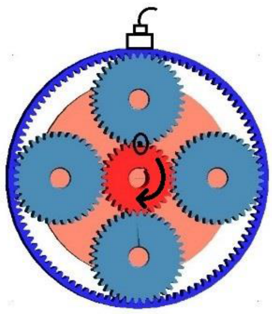
## I. INTRODUCTION

Planetary gearboxes are widely used in transmission systems, such as helicopter, wind turbine transmission system and etc.. The complicated physical structures and its sun gear and planet gear motion behaviors make it more difficult in fault diagnosis and condition monitoring. Lei[1] summarized features of planetary gear system from various worldwide researchers' works. He mentioned that due to multiple and time-varying vibration transmission paths, torques or loads applied to the planetary gearbox system, the fault characteristic vibrations will be hidden in complicated vibration signals [2,3]and various frequency contents will distract attentions to the decisions of fault diagnostics. Vibration monitoring planetary gear system becomes a challenge job. And there is a great need to find unique features for planetary gear system fault diagnostics.

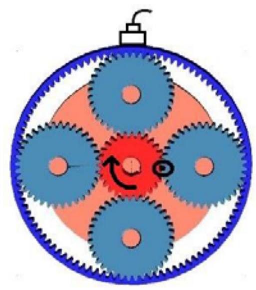
In this paper, a damage induced vibration feature in terms of vibration transmission path is explored. A characteristic dynamic feature of sun gear local fault, namely tidal frequency, is proposed. The proposed feature is further demonstrated in sun gear local fault diagnostics.

## II. TIDAL FREQUENCY

Planetary gear system consists of a ring gear, a sun gear and several planet gears that mesh together with ring gear and sun gear simultaneously. Damage induced vibration at the meshing location has three possible vibration transmission paths from its origin to the sensor through solid mechanical components and their contacts, this was stated in the reference [4, 5]. Among three transmission paths, one path contains more information of faulty gear and without vibration signal attenuation through bearings. It is recognized as a more direct transmission path to reveal gear meshing conditions than the other two paths. However it is suffered from time-varying vibration propagating distance when the planet carrier and sun gear rotate. To illustrate this varying path, a typical planetary gear system with four planet gears and stationary ring gear is considered and depicted in Figure 1.



a.



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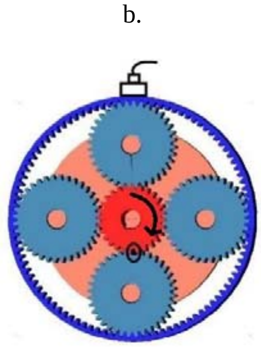


c.

FIGURE I. TYPICAL PLANETARY GEAR SYSTEM WITH POSSIBLE VARYING DAMAGED INDUCED VIBRATION TRANSMISSION PATHS

In Figure 1, an illustrative accelerometer is placed on top of the ring gear to represent a frequently used measurement position. A sun gear local fault is marked with a black circle at meshing location. It can be seen that damaged induced vibration from local fault gear meshing position may transmit through all possible mechanical contacts to the sensor on the top. And it should notice that the vibration propagating routes are multiple and time varying, as example positions in Figure 1(a), (b) and (c) in which three possible damaged gear meshing positions are shown. With the local fault gear meshing position changes, the induced damaged vibrations propagating routes are also varying with respect to the relative motion of sun gear and planet gears. The amplitude and frequency modulation to damage induced vibration perceived at sensor consequently will be resulted in. Thus, it is reasonable to investigate in details of this time varying process and find its nature.

TABLE I. TIDAL FREQUENCY FOR LOCAL SUN GEAR FAULT

| | Local fault of Sun gear | Any planet gear on planet carrier on top of sun gear in line with sensor |
|---|---|---|
| Repeat in revolutions | 1 | $\frac{N}{R}$ |
| Tidal cycle in revolutions | $Least\ \ Common\ \ Multiple\left(1, \frac{N}{R}\right)$ | |
| Thus tidal frequency : $f_t = \dfrac{Z}{Least\ \ Common\ \ Multiple\ \left(1, \frac{N}{R}\right)}$ | | |
| $f_t$ :tidal frequency, $Z$ :Sun gear rotational frequency | | |

In Figure 1, when system rotating and consider three possible positions as is shown in Figure 1, the local fault on sun gear will shift its meshing positions with different planet gears from (a) to (b) to (c) and eventually return to (a) and repeat this rotating process. Distances and routes of transmission paths from local fault to sensor are time varying. While, due to this repetition motion, it is reasonable to predict that there should be a periodic nature in that the fault meshing positions is periodic with close to and away from sensor.

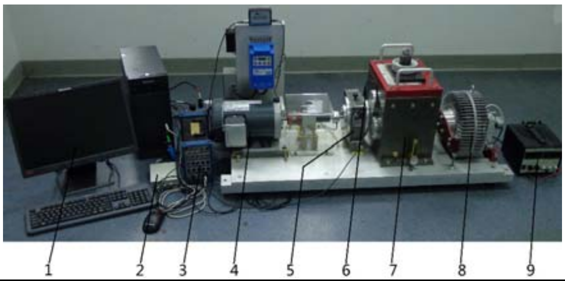
Examining Figure 1 carefully, it is not difficult to find that the sensor perceived damage induced vibration should reach a high amplitude when the transmission path distance is minimal shown in Figure 1(a). Other scenarios, such as Figure 1(b) with longer transmission path should have less vibration amplitude perceived at sensor due to the amplitude attenuation of a longer distance. And Figure 1(c) is the longest transmission which may render a comparatively lower vibration amplitude perceived at sensor. While the system rotating, the local fault sun gear meshing with a planet gear in line with the sensor in a closest distance will occur repeatedly. And this is a characteristic feature determined by the physical structure of a planetary gear system. Similarly, in natural world, the lunar tide, when the earth and the moon in the closest distance and the pull to the sea reaches maximum. This is very much similar to this planetary sun gear local fault dynamic motion phenomenon. Thus, it may be called this phenomenon as planetary gear local fault vibration tide. And calculating the frequency of planetary gear fault vibration tide gives a new indicator – tidal frequency.

The fundamentals to find period of tidal frequency is to find how many revolutions to damaged sun gear position mesh with a planet gear on planet carrier in line with sensor in a closest distance. The tidal frequency could be obtained by finding least common multiple between repeats of local fault on sun gear and any planet gear on planet carrier meshing on top of sun gear in line with the sensor. Bedsides, an important fact is that transmission ratio of a given planetary gear system is a fixed value, therefore, the period of tidal frequency is also a fixed value for a given planetary system. For a given planetary system with number of planet gears $N$ , number of teeth for sun, planet and ring gear with $Z_s$ , $Z_p$ , $Z_r$ and transmission ratio $R = \dfrac{Z_r + Z_s}{Z_s}$ . It may calculate the tidal frequency as is described in Table1.

## III. EXPERIMENTAL STUDIES

### A. *Experimental Set-up*

An experimental planetary gearbox at University of Electronic Science and Technology of China, Engineering Reliability and Prognostic and Health Management laboratory (ERPHM) is used for studies. The experimental set-up consists of a spur gearbox and a one stage planetary gearbox driven by a 2.24 kW three phase electrical motor controlled by a motor speed controller. An accelerometer (with sensitivity of 100mV/g and frequency range 0-10kHz, see in Figure 2) is used for capturing vibration signals. The data are captured under 3000 RPM or 50Hz of electrical motor. The sampling frequency was set to be 7680Hz to accommodate all interested frequency contents of this test rig. The whole set-up arrangement is shown in Figure 2.




| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| computer | Encoder interface | Data acquisition set-up | Motor | Planetary gear box |
| 6 | 7 | 8 | 9 | |
| Accelerometer | Spur gearbox | Load | Load controller | |

FIGURE II. PLANETARY GEAR EXPERIMENTAL SET-UP

In the experimental process, sun gear under good and faulty conditions is considered to obtain damaged induced vibration signals. In fault scenarios, local sun gear defect is introduced artificially, see in Figure 3.

FIGURE III. SEEDED FAULT ON SUN GEAR

The physical parameters for planetary gear box are listed in Table 2 in which gear teeth, number of planet gear and transmission ratio are given and calculated. In the experimental set-up, the ring gear of planetary gear box is stationary and the sun gear is the input of the planetary gear box system. Another very important calculation to the planetary gearbox is its characteristics frequencies and listed in Table 3. Details readers may refer to [6].

TABLE II. PHYSICAL PARAMETER OF PLANETARY GEAR BOX

| Sun gear | Planet gear | Ring | No. of Planet gear | Transmission ratio |
|---|---|---|---|---|
| 28 teeth | 36 teeth | 100 teeth | 4 | 4.57 |

Then, the proposed tidal frequency is tested by experimental data. Since the tidal nature will modulate damage induced vibration amplitude, therefore, the data may first obtain its envelope. The Fourier analysis to the envelope signal is then performed to yield the periodic contents of the data, both good and faulty conditions are shown in Figure 4.

Figure 4(a) clearly tells that for good condition data at 50Hz, 100Hz which are due to the sun gear rotation ($f_n$) clearly show up and planet carrier frequency ($f_c$) is also clear at 10.93Hz. For the sun gear characteristic fault frequency and the proposed tidal frequency are all absent in the figure. This confirms that this data from the healthy gear data. Figure 4(b) is the case with local fault, again with the appearance of 50Hz, 100 Hz and 10.93Hz of planet carrier frequency. The sun gear fault characteristic frequency at $f_s$=156. 25Hz shows up in the frequency spectrum and this clearly refers to the sun gear fault. And more other frequency contents are also appeared in the spectrum, among those frequency peaks, the proposed tidal frequency is also found. If zoomed in to the frequency range from 0 to 50Hz, all the important frequency peaks may be revealed as is shown in Figure 5.

TABLE III. CHARACTERISTIC FREQUENCIES FOR SUN GEAR LOCAL FAULT

| | |
|---|---|
| $f_n$: Sun gear rotational frequency | 50Hz |
| $f_m$: Gear meshing frequency | 1093.75 Hz |
| $f_s$: Characteristic sun gear local fault frequency | 156.25Hz |
| $f_c$ : Planet carrier rotational frequency | 10.93Hz |
| $f_t$: Tidal frequency | $\frac{50}{8}=$ 6.25Hz |

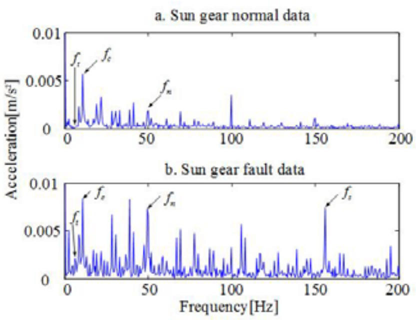



FIGURE IV. FOURIER ANALYSIS TO ENVELOPE DATA UNDER GOOD AND FAULTY CONDITIONS

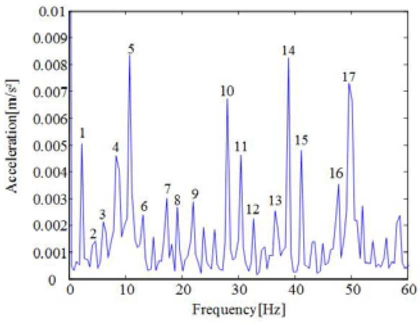



FIGURE V. ZOOMED IN PLOT OF FIGURE 4

In order to clarify the composition of vibration signal. The frequency peaks are numbered as is shown in Figure 5. The detailed order content explanation is listed in Table 4. From Figure 4, 5 and Table 4, it is not difficult to find that though numbers of frequency peaks are many, they are all due to interactions among $f_n$, $f_s$, $f_c$ and $f_t$. The damaged induced vibration from planet gear system are indeed very complicated and in here, the proposed tidal frequency plays an important role in the composition of the signal.

TABLE IV. FREQUENCY CONTENT FOR SUN GEAR LOCAL FAULT

| 1 | 2 | 3 |
|---|---|---|
| $\frac{1}{8}f_s - f_c - f_t$ | $f_c - f_t$ | $f_t$ |
| 4 | 5 | 6 |
| $\frac{1}{8}f_s - f_c$ | $f_c$ | $2f_t$ |
| 7 | 8 | 9 |
| $2(\frac{1}{8}f_s - f_c)$ | $\frac{1}{8}f_s$ | $2f_c$ |
| 10 | 11 | 12 |
| $f_t + 2f_c$ | $\frac{1}{8}f_s + f_c$ | $3f_c$ |
| 13 | 14 | 15 |
| $\frac{1}{8}f_s + f_t + f_c$ | $\frac{1}{4}f_s$ | $\frac{1}{8}f_s + 2f_c$ |
| 16 | 17 | |
| $\frac{1}{8}f_s + 2f_c + f_t$ | $f_n$ | |

The experimental studies demonstrate that the tidal frequency as a very important nature of planet gear system do exist. However, it should notice that the amplitude of tidal frequency is comparatively small and reason for that is because the tidal frequency is due to the phenomenon of amplitude modulation of damage induced vibration. The amplitude depends on the vibration severity of local fault and attenuation effect of transmission path, therefore it is reasonable to obtain a comparatively small amplitude but it is no doubt the tidal frequency gives an insightful evidence to planetary gear fault behavior.

## IV. CONCLUSION

In this paper, a distinct amplitude modulation nature to the sun gear local fault vibration of planetary gear system, namely tidal frequency, is discussed and proposed for understanding of local sun fault in planetary gearbox vibrations. A planetary gear system experimental data with local sun gear faults demonstrate the existence of the proposed tidal frequency and this frequency is unique to planetary gear system.

## ACKNOWLEDGMENT

This research is supported by National Natural Science Foundation of China (51305067 and 51375078).

## REFERENCES


[1] Y.G. Lei , J. Lin, M. J. Zuo and Z. J. He, Condition monitoring and fault diagnosis of planetary. Measurement, 48, 2014, pp.292-305.

[2] D.M. Blunt, J.A. Keller, Detection of a fatigue crack in a UH-60A planet gear carrier using vibration analysis, Mechanical Systems and Signal Processing, 20, 2006, pp.2095-2111.

[3] J.A. Hines, D.S. Muench, J.A. Keller, et al., Effects of time-synchronous averaging implementations on HUMS features for UH-60A planetary carrier cracking, American Helicopter Society 61st Annual Forum, Grapevine, TX, Jine 1-2, 2005.

[4] Z. P. Feng and M. J. Zuo, Vibration signal models for fault diagnosis of planetary gearboxes. Journal of Sound and Vibration, 331(22), 2012, pp.4919-4939.

[5] X. H. Liang, M. J. Zuo and M. R. Hoseini, Vibration signal modeling of a planetary gear set for tooth crack detection. Engineering Failure Analysis, 48, 2015, pp.185-200.

[6] Z. P. Feng, L. L. Zhao and F. L. Chu, Vibration Spectral Characteristics of Localized Gear Fault of Planetary Gearboxes. Proceedings of the CSEE, 33 (5), 2013, pp.119-127.