7. Conclusions

This paper investigates the nonlinear dynamic behavior of a planetary gear system with equally spaced planets. The effect of mesh frequency is evaluated and the system behavior at different rotational velocities is examined; this may helps designers to understand how velocity can affect dynamic response of a planetary gear system. The main results are summarized below.

Modes corresponding to multiples of mesh frequency can be excited due to: i) the presence of higher harmonics of mesh stiffness variation; ii) nonlinear superharmonic resonance. Moreover, the resonance peaks lean-to the left, implying softening nonlinearity induced by teeth separation.

Comparing the presents results with those of the work of Ambarisha and Parker Ref.[2] shows that there are additional resonance peaks below 1600 Hz, ≅1800 Hz (the first distinct mode) and ≅8000 Hz. These peaks are the due to a combination of effects: i) the parametric instability from higher harmonics of mesh stiffness; ii) nonlinear subharmonic and superharmonic resonances of the first and second distinct modes.

Reducing the translational bearing stiffnesses generally cause decreasing the natural frequency as we expect from elementary considerations. Moreover, changing the bearing stiffness can influence the ratios between modes and, for certain values, produce additional internal resonances; this is reflected in a higher modal interaction in nonlinear regimes.

Different nonlinear phenomena such as nonlinear jumps, chaotic motions, and period-doubling bifurcations occur when the mesh frequency or any of its higher harmonics are near a natural frequency of the system. The nonlinearity is due to teeth separation that take place when the amplitude of vibration generates inertia forces exceeding the static preload.

The occurrence of a parametric instability is found when the rotational speed is twice the resonance of a rotational mode; this phenomenon is typical of almost all gearboxes.

In presence of internal resonances remarkable changes is observed; in particular, the variation of the bearing stiffness can greatly influence and enrich the dynamic scenario.

One of the most interesting disclosures of this work is related to the chaos-induced-imbalance; i.e. due to the symmetry of the system there is a perfect force balance, this means that the sun bearings are subjected to negligible forces (theoretically zero), this is true in principle both in linear and nonlinear regular vibrations. However, when the vibration is chaotic, the system experiences a symmetry breaking, a well known phenomenon in chaotic dynamics. This symmetry breaking in the response has an important counterpart in the mechanical behavior of the system, i.e. it generates unexpected and undesirable loads on the sun supports. This aspect of the system dynamics cannot be accounted for using the classical design tools, leading to possibility of new failure modes.

8. Acknowledgment

The authors would like to thank the Lab INTERMECH-More (HIMECH District, Emilia Romagna Region) for supporting the research.

References

[1] V.K. Ambarisha, R.G. Parker, Nonlinear dynamics of planetary gears using analytical and finite element models, Journal of Sound and Vibration, 302, 577–595 (2007).

[2] C.J. Bahk, R.G. Parker, Analytical Solution for the Nonlinear Dynamics of Planetary Gears, Journal of Computational and Nonlinear Dynamics, 6(2), 1-15 (2011).

[3] M. Amabili, A. Rivola, Dynamic analysis of spur gear pairs: steady-state responde and stability of the SDOF model with time-varying meshing damping, Mechanical Systems and Signal Processing, 11(3), 375-390 (1997).

[4] Y. Wang, H.M.E. Cheung, W.J. Zhang, 3D Dynamic Modelling of Spatial Geared Systems, Nonlinear Dynamics, 26(4), 371-391 (2001).

[5] M. Faggioni, K. Avramov, F. Pellicano, S.N. Reshetnikova, Nonlinear oscillations and stability of gear pair, Journal of Mechanical Engineering (Ukraine), 4, 40-45 (2005).

[6] G. Bonori, F. Pellicano, Non-smooth Dynamics of Spur Gears with Manufacturing Errors, Journal of Sound and Vibration, 306, 271–283 (2007).

[7] G. Liu, R.G. Parker, Nonlinear dynamics of idler gear systems, Nonlinear Dynamics, 53(4), 345-367 (2008).

[8] F. Cunliffe, J.D. Smith, D.B. Welbourn, Dynamic tooth loads in epicyclic gears, Journal of Manufacturing Science and Engineering, 96(2), 578-584 (1974).

[9] M. Botman, Epicyclic gear vibrations, Journal of Manufacturing Science and Engineering, 98(3), 811-815 (1976).

[10] A. Kahraman, Planetary gear train dynamics, Journal of Mechanical Design, 116(3), 713–720 (1994).

[11] A. Kahraman, Natural-modes of planetary gear trains, Journal of Sound and Vibration, 173(1), 125–130 (1994).

[12] A. Kahraman, Load sharing characteristics of planetary transmissions, Mechanism and Machine Theory, 29(8), 1151–1165 (1994).

[13] P. Velex, L. Flamand, Dynamic Response of Planetary Trains to Mesh Parametric Excitations, Journal of Mechanical Design, 118, 7–14 (1996).

[14] J. Lin, R.G. Parker, Analytical Characterization of the Unique Properties of Planetary Gear Free Vibration, Journal of Vibration and Acoustics, 121, 316–321 (1999).

[15] J. Lin, R.G. Parker, Structured vibration characteristics of planetary gears with unequally spaced planets, Journal of Sound and Vibration, 233, 921– 928 (2000).

[16] M. Faggioni, F.S. Samani, G. Bertacchi, F. Pellicano, Dynamic optimization of spur gears, Mechanism and Machine Theory, 46, 544–557 (2011).

[17] G. Bonori, M. Barbieri, F. Pellicano, Optimum profile modifications of spur gears by means of genetic algorithms, Journal of Sound and Vibration, 313(3–5), 603-616 (2008).

[18] L. Walha, T. Fakhfakh, M. Haddar, Nonlinear dynamics of a two-stage gear system with mesh stiffness fluctuation, bearing flexibility and backlash, Mechanism and Machine Theory, 44, 1058–1069 (2009).

[19] R.G. Parker, J. Lin, Mesh Phasing Relationships in Planetary and Epicyclic Gears, Journal of Mechanical Design, 126, 365-370 (2004).

[20] J. Lin, R.G. Parker, Planetary Gear Parametric Instability Caused by Mesh Stiffness Variation, Journal of Sound and Vibration, 249(1), 129-145 (2002).

[21] R.G. Parker, A physical explanation for the effectiveness of planet phasing to suppress planetary gear vibration, Journal of Sound and Vibration, 236(4), 561–573 (2000).

[22] V.K. Ambarisha, R.G. Parker, Suppression of planet mode response in planetary gear dynamics through mesh phasing, Journal of Vibration and Acoustics, 128, 133–142 (2006).

[23] X. Wu, R.G. Parker, Modal Properties of Planetary Gears With an Elastic Continuum Ring Gear, Journal of Applied Mechanics, 75(3), 031014 (2008).

[24] D.R. Kiracofe, R.G. Parker, Structured vibration modes of general compound planetary gear systems, Journal of Vibration and Acoustics, 129, 1–16 (2007).

[25] Y. Guo, R.G. Parker, Purely rotational model and vibration modes of compound planetary gears, Mechanism and Machine Theory, 45(3), 365-377 (2010).

[26] Y. Guo, R.G. Parker, Analytical determination of mesh phase relations in general compound planetary gears, Mechanism and Machine Theory, 46(12), 1869-1887 (2011).

[27] A. Al-shyyab, A. Kahraman, A non-linear dynamic model for planetary gear sets, Journal of Multi-body Dynamics, 221(4), 567-576 (2007).

[28] Y. Guo, R.G. Parker, Dynamic modeling and analysis of a spur planetary gear involving tooth wedging and bearing clearance nonlinearity, European Journal of Mechanics - A/Solids, 29, 1022-1033 (2010).

[29] T. Sun, H.Y. Hu, Nonlinear dynamics of a planetary gear system with multiple clearances, Mechanism and Machine Theory, 38(12), 1371-1390 (2003).

[30] F. Chaari, T. Fakhfakh, M. Haddar, Dynamic analysis of a planetary gear failure caused by tooth pitting and cracking, Journal of Failure Analysis and Prevention, 2, 73-78 (2006).

[31] C. Zhe, H. Niaoqing, G. Fengshou, Q. Guojun, Pitting damage levels estimation for planetary gear sets based on model simulation and grey relational analysis, Transactions of the Canadian Society for Mechanical Engineering, 35(3), 403-417 (2011).

[32] Z. Chen, Y. Shao, Dynamic simulation of planetary gear with tooth root crack in ring gear, Engineering Failure Analysis, 31, 8–18 (2013).

[33] R. August, R. Kasuba, J.L. Frater, A. Pintz, Dynamics of planetary gear trains, NASA Contractor Report 3793, Lewis Research Center (1984).

[34] X. Gu, P. Velex, A dynamic model to study the influence of planet position errors in planetary gears, Journal of Sound and Vibration, 331(20), 4554-4574 (2012).

[35] X. Gu, P. Velex, On the dynamic simulation of eccentricity errors in planetary gears, Mechanism and Machine Theory, 61, 14-29 (2013).

[36] S. Li, Q. Wu, Z. Zhang, Bifurcation and chaos analysis of multistage planetary gear train, Nonlinear Dynamics, 75(1-2), 217-233 (2014).

[37] F. Pellicano, F. Vestroni, Complex Dynamics of High-Speed Axially Moving Systems, Journal of Sound and Vibration, 258(1), 31–34 (2002).

[38] M. Barbieri, A. Zippo, F. Pellicano, Adaptive grid-size finite element modeling of helical gear pairs, Mechanism and Machine Theory, 82, 17-32 (2014).