Effective Identification of Cyclic Excitation and Resonance in Non-stationary Gearbox Vibration Monitoring

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Abstract. Since as a rotating machinery, the gearbox is an important source of vibration, the identification of signals and parameters of the component content of the gearbox is necessary for the monitoring of the system. Within the mechanism, the rotation of elements with periodic discrete geometries (bearings, gears, turbines, ...) is the origin for potential excitations which are commonly cyclic. These excitations are therefore characterized by frequencies that evolve with rotation speed that reconstructing them, is equivalent to an inverse problem or an identification problem. The main problem is to find the right external excitation conditions particularly in torque to reveal behaviors that are either resonances (a well-known linear problem and treated by identification) or internal excitations (less known and less well-treated). The difficulty here lies effectively in non-stationary operating conditions for a good exploitation of time and angular Fourier Transform framework.

Introduction

The global dynamic behavior of the system is influenced by rotating velocity, the superposition of its eigenmodes, and the internal exciting frequencies. This behavior also varies as the angular speed changes. When the frequencies of angle-periodic phenomena correspond to the frequency values of one or more eigenmodes, the cyclic behavior becomes more pronounced and their magnitude amplifies. To address this, it is important to distinguish the time-periodic phenomenon associated with the system's modal response from the angle-periodic behavior generated by components like gears and bearings. The primary objective of analyzing the non-stationary operating conditions is to facilitate the distinct separation of both time-related and angle-related phenomena present within the signals.

To achieve this separation, using the angular approach and angle Fourier transform, the magnitude of the time-dependent phenomenon in the angular spectrum can be reduced as the energy is distributed across a bandwidth of angular frequencies. This bandwidth is guessed by the range of operating speed. Previous studies [1] have shown that a time-dependent artifact appears in the spectrum when the angular speed does not vary significantly. Therefore, it is necessary to have a wide swept frequency range to adequately disperse the energy associated with the modal responses. Additionally, the length of the time history signal is a crucial parameter that should be sufficiently long to effectively mitigate time-related effects within the angular spectrum.

Under non-steady operating conditions, as the rotating speed changes, higher frequencies are induced in the signals, especially if this evolution takes place along longer time history signals. However, using an excessively large swept frequency interval relative to the system's resonance frequencies can spread the energy over an extremely wide frequency range, making it challenging to identify the eigenmodes and Frequency Response Function (FRF). Similarly, speaking of the length of temporal signals, the increased length leads to higher frequency resolution, requiring a smaller sampling step. This, in turn, results in a loss of accuracy in the identification process too.

Hence, to find the right external excitation conditions, the key challenge lies in finding the right balance between the length of the temporal signal and the rate at which the rotational speed increases. This trade-off is necessary to achieve both fine angular resampling and effective mitigation of time-dependent phenomena within the angular spectrum, while also ensuring accurate estimation of the FRF and the identification procedure for resonances.

The system of study, illustrated in Figure 1, is a single-stage gear transmission system. There are two degrees of freedom, translation x_i and rotation θ_i associated with each gear (i is the gear number) with mass and inertia, respectively M_i, and I_i . The first gear inertia i.e., I_1 is subjected to a driving torque T_M , and the second one i.e., I_2, is exposed to a load torque T_R .

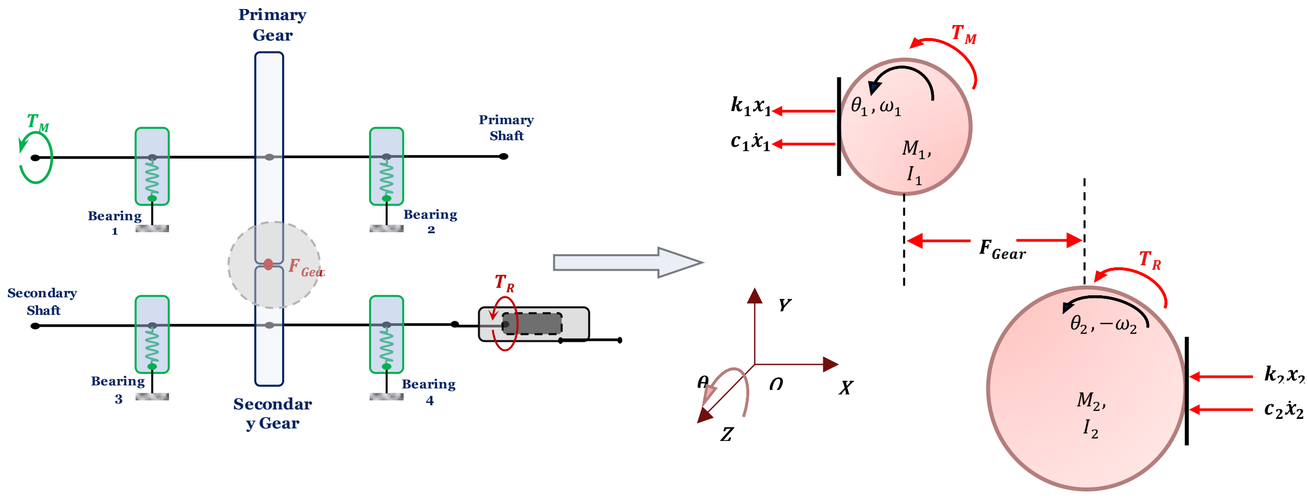


Figure 1. The schema and free body diagram of a gear coupling

Where F_{Gear} is the gear transmission force.

As is depicted by Figure 2., the presence of the cyclic internal excitation associated to the gear transmission introduces a non-linear coupling which is characterized by the angular position of the reference shaft, denoted by θ_1 :

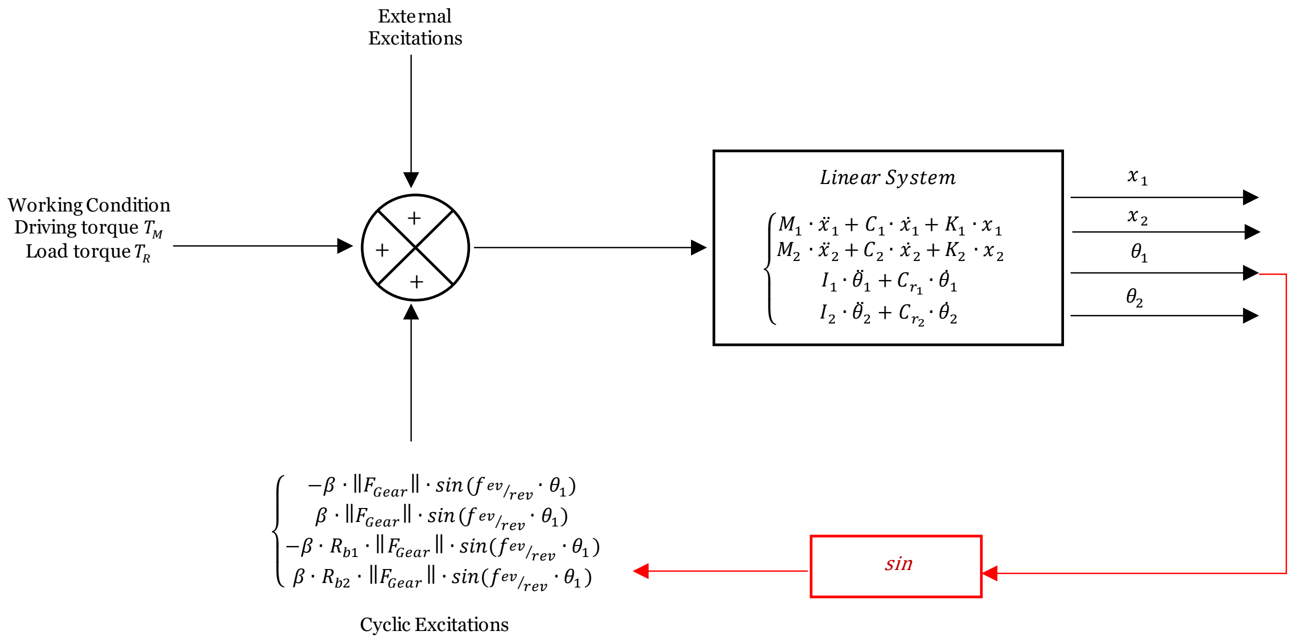


Figure 2. Block diagram of the system under consideration

Where $f^{ev}/_{rev}$ is the mesh harmonic component in the load.

In order to evoke the most informative reaction from the system and ensure that the frequency of the stimulation covers a specific range of interest, the concept of sine-sweep excitation can be employed. According to the definition [eq 1.], for a linear sweep rate, the frequency variation of the actual output signal $y(t)$ corresponds with the instantaneous frequency $f(t)$, which is determined by the time derivative of the phase $\psi(t)$.

$$\begin{cases} y(t) = sin(\psi(t) + \phi_0) \\ f(t) = \frac{1}{2\pi} \cdot \frac{d\psi(t)}{dt} \end{cases} \tag{1}$$

Using eq 1., and from analogy, once we can rewrite $y(t)$, ($\phi_0 = 0$), to have the nonlinear internal cyclic excitation, depending on the angular position of the shaft $\theta_1(t)$:

$$\begin{cases} y(t) = sin\left(f^{ev}/_{rev} \cdot \theta_1(t)\right) \\ f(t) = \frac{f^{ev}/_{rev}}{2\pi} \cdot \frac{d\theta_1(t)}{dt} = \frac{f^{ev}/_{rev}}{2\pi} \cdot \dot{\theta}_1(t) \end{cases} \tag{2}$$

Hence, to achieve a frequency sweep across a specific range, it is necessary for the system to operate under non-stationary conditions, resulting in significant variations in the instantaneous angular speed (IAS) of the shaft over time. Consequently, the signal we are looking as the response of the system during this analysis is the IAS signal of each shaft. To induce an increase in the angular speed, the system is stimulated by a ramp-like external driving torque. The parameters of the excitations, whether internal (e.g., $f^{ev}/_{rev}$) or external (e.g., ramp rate), are adjusted based on the physical properties and characteristics of the system.

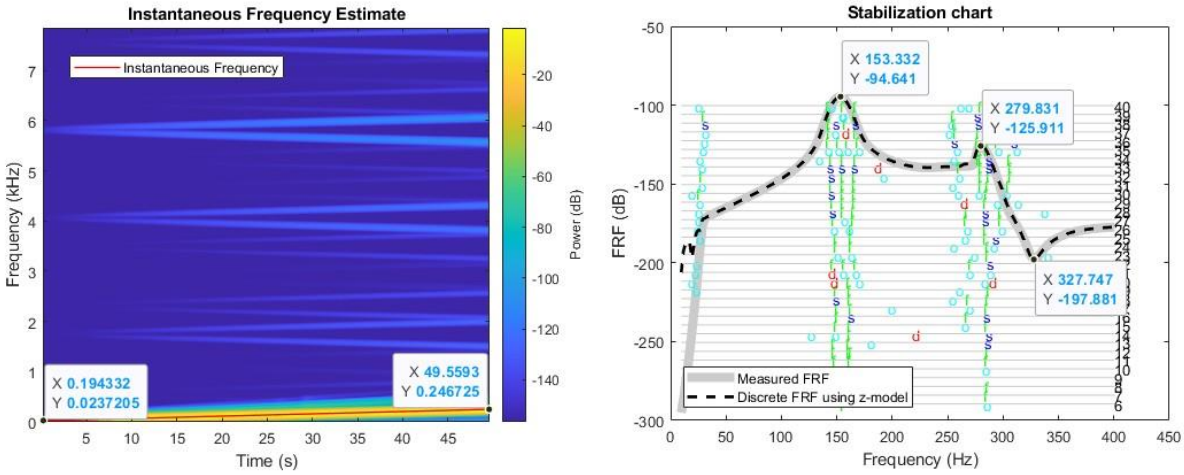
A frequency-domain technique utilizing the Least-Squares Complex Frequency (LSCF) estimator and its Poly-reference implementation ([2]) has been employed to detect temporal events. The key benefit of utilizing the LSCF estimator is its ability to generate "fast-stabilizing" stabilization chart.

Results and Discussion

According to eq 2., the angular speed is equivalent to the instantaneous frequency of the present cyclic excitation, and under non-stationary operating conditions, the rate at which it ramps up, induces frequency sweep over an interval of time. Hence, in order to have a correct separation of time-related phenomena from cyclic ones and improved signal identification it is crucial to find proper working conditions.

Figure 2. a, presents a meticulously induced swept frequency signal, by adding a moderated ramp in the rotational speed through a torque. The two correct resonances of the system are located at frequencies $152.55\,Hz$ and $275.98\,Hz$. Although the induced instantaneous frequency by angular speed (cyclic excitation) covers the interval of $[23 \;\; 248]\,Hz$, which is lower than the system's second resonance, the superposition of the transient response with the forced response ensures precise identification of temporal phenomena during varying working conditions which is depicted in Figure 2. b.

Furthermore, the length of the temporal signal was also chosen accordingly to make a balance between a time-phenomena identification and angular post-processing analysis. As a result, imposing a suitable operating condition, regarding the characteristic of the system makes it possible to perform a correct identification of resonances and reducing the effect of temporal phenomena on the angular spectrum to identify the cyclic harmonic components within the signals.



a) *b)*

*Figure 2. a) Instantaneous Angular Frequency of the response. b) Stabilization Chart, displaying the estimated FRF by **LSCF** and comparing with the measured one.*

Conclusion

In conclusion, the accurate identification of signals and parameters in a gearbox is essential for system monitoring due to its significant role as a source of vibration. The cyclic excitations generated by rotating elements with periodic discrete geometries pose a challenge in reconstructing their frequencies, as they vary with rotation speed but are definitely valuable excitations for FRF identification of structural parts. The presence of resonances and internal excitations further complicates the identification process, particularly under non-stationary operating conditions. To address this, a careful balance needs to be struck between the length of the temporal signal and the rate at which the rotational speed increases. This ensures effective separation of time-related and angle-related phenomena within the signals, facilitating accurate estimation of the Frequency Response Function (FRF) and resonance identification. Then by utilizing a meticulously induced swept frequency and appropriate working conditions, it becomes possible to mitigate temporal phenomena and achieve precise identification of cyclic phenomena.

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