12th Research/Expert Conference with International Participation
"QUALITY 2021", Neum, B&H, June 17-19, 2021

PROCEDURES FOR MEASUREMENT AND ANALYSIS OF TORSION VIBRATIONS

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SUMMARY
This paper presents the occurrence of torsional vibrations of mechanical systems and instruments for measuring and analyzing natural frequencies and modal forms of torsional vibrations, maximum angular deflections and their relationship for certain rotational speeds and characteristic damage frequencies. Traditional but modern measurement and analysis methods and procedures are shown to help detect increased torsional stresses to prevent expected system failures.

Keywords: torsional vibration, measurement, analysis

1. IDENTIFYING POTENTIAL PROBLEMS

Torsional vibrations are oscillating angular motions that occur along the rotating parts of a mechanical system. In general, torsional vibrations occur in power transmissions, e.g. in crankshafts, camshafts, alternator shafts and transmissions. If torsional vibrations are not controlled, it can cause major damage.

Torsional vibrations are harder to measure than lateral vibrations because the shaft rotates. Analytical procedures are similar to those used for lateral vibrations. When solving problems caused by torsional vibrations, the analyst is limited to places where measurements can be made. Until the last few years, the torsiograph was the only instrument that had to be connected to the end of the shaft in order to be able to perform measurements for torsional vibrations. Today, the torsional response can be measured elsewhere in the shaft system with supporting structural elements. [1]

Fig.1. shows an example of rotational vibration measurement, where the shaft begins to rotate at a speed of 0 rpm and up to 3000 rpm and then again up to 0 rpm. The upper curve shows the speed of rotation (rpm), and the curve below is the deviation, i.e. the angle of rotation in degrees. The arrows on the graph show more intense deviations of the rotation angle caused by torsional vibrations that exceed the natural torsional frequency of the axis, which means that at this moment in the rpm range, the resonance of the axis is higher than normal [3].

It is difficult to determine the resonance caused by torsional vibrations before there is more intense damage to any element of the system. Torsional vibrations occur in the form of torsional stresses on the shaft and can be measured by the relative motion of the solid masses attached to the shaft. Indicators of early warning that excessive failures have occurred at the couplings, such as slippage of the coupling hub are amplified vibrations on the transmission system construction. These indicators can be used to determine if there is a problem caused by torsional torques before a shaft failure occurs. In order to be able to establish this, it is necessary to perform direct torsion measurements at characteristic points of the structure.

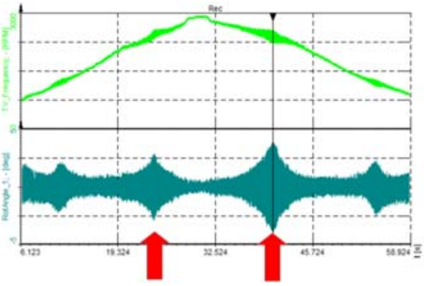

Figure 1. Example measurement of torsion vibrations [2]

The time required for routine inspections of the plant during maintenance, when the plant ceases to operate, is used to examine causes that would indicate a higher probability of occurrence of torsional vibrations, e.g. to check gear wear on the unloaded side of gear teeth due to excessive twisting, as vibrations could cause impact gear teeth in engagement. A similar situation could occur with wear on both sides of the coupling. Also, fatigue and cracking can occur with any changes in geometry when high stress concentrations occur, especially at specific loads in heavier forms of work. Torsional vibrations failures show a shear crack that spreads helically at a certain angle to the longitudinal axis.

Some authors also use the term "torsional vibration analysis" for torsional vibration measurement procedures, although it more often refers to calculations performed using a computer program. In any case, the limit and deviation from the torsional natural frequencies are determined or checks of previous calculations are performed. If a torsion problem is identified, the system needs to be modified. Once a model of mass distribution and torsion springs of a certain stiffness is formed to match the measurements, torsional vibration analysis software is used to evaluate all proposed solutions, all in order to avoid torsional resonances. This procedure includes changing the torsional stiffness of the couplings, moments of inertia of the flywheel, other procedures for changing the design parameters, etc.

Torsional vibrations measurements help engineers to increase the reliability and safety of rotary systems. The more advanced methods for identifying torsional natural frequencies are based on defining the current rotational speed of the shaft and its subsystems at different points via pulse signal counters, so that data is captured at the same rotation speed at different points of interest on shaft subsystems. Thus, the difference in signal between different current measurements can be subsequently processed to obtain the resulting torsional excitations.

2. MEASURING INSTRUMENTS AND METHODS

There are traditional torsional vibration measurement methods such as direct stress measurements and methods that use different types of sensors. Output values for these methods can be: angular position, speed and acceleration, torsion angle and speed and torque. The most common sources of torsional vibration excitation are always inertial forces (e.g. oscillating and rotating masses).

A direct measurement method that uses stress and strain detectors determines the strain due to the applied force or torque. A typical example of measuring deformations on an object are strain gauges attached by the appropriate method [4]. When measuring the deformation on the shaft under the influence of torque, the main goal is to determine the shear stress in the shaft through which the torque in the shaft is calculated. When the shaft is subjected to torsion, the main normal stresses occur at an angle of ± 45 ° with respect to the cylindrical planes (Fig.2a).

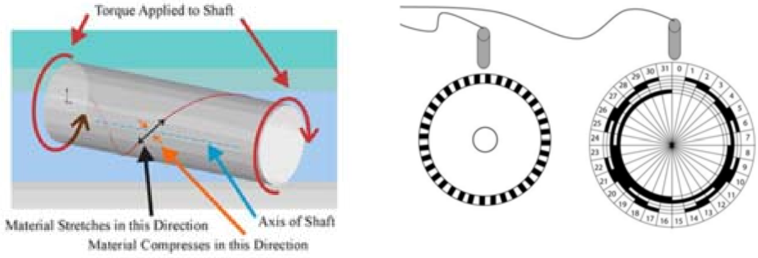

Figure 2. a) Example of shaft exposed to torsion, b) Basic principle of encoder [2]

The second measurement method uses torsion sensors (encoders) whose basic principle of operation is shown in Fig.2b. A torsion encoder is an electromechanical device that converts angular position or motion into an analog or digital signal. It can be used to measure the position or twist of the shaft (Fig.3a).

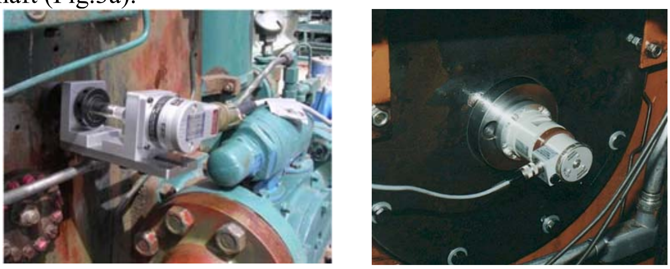

Figure 3. a) Example of a torsion encoder [5], *b) Example of a torsiograph* [6]

While different types of accelerometers are used to measure lateral vibrations, special equipment such as torsiographs, sensors/encoders, telemetry systems and frequency modulation systems are required to measure torsional vibrations.
The most common instruments for measuring the natural frequencies of torsional vibrations, the amplitude of the response and the voltage of the system shaft during operation are torsiographs and frequency modulation measuring systems that use contact and non-contact sensors.
A torsiograph is an instrument that rotates with an axis and is used to measure the unevenness of rotation on rotating parts of the system by generating virtual channels for movement and speed of movement. These channels are used for further analysis via appropriate programs as a display of the measured angular displacement and displacement velocity using data from the selected channels at the output of the oscilloscope (Fig.3b).
Some types of torsiographs operate on the principle of a seismometer, with the mass retained by springs whose relative motion relative to the stator by inductive proximity detectors is converted into an electrical signal. Their frequency range is approximately 3-1000Hz. In the lower frequency range, internal masses and springs have a resonance close to 3Hz. The device must be placed on the free end of the shaft, preferably near the position of the maximum torsional vibrations in the least stressed operating conditions. However, the strength of the vibrations is sometimes not a true indicator of the axle stress, e.g. large oscillations can occur in a system with a soft coupling, but the stresses can be small. Thus, the torsion signal represents the absolute motion at the point of attachment and is converted into angular velocity. However, the data obtained by the torsiograph do not define the severity of the torsional vibrations

because the output torsional vibration wave is at one point in the axis system. Since stresses are a function of the relative displacement between two masses on a shaft, the torsiograph data do not reveal the stress conditions within the shaft. First, the complex wave needs to be analyzed by a spectrum analyzer to determine the amplitudes of the vibrations at each frequency. Using mathematical analysis that calculates the normalized modal shape, the measured amplitude from the torsiograph can define the absolute amplitudes of torsional vibrations at each mass. Relative angular deflections can be calculated and converted into torsional stresses and dynamic torques. The torsiograph will not give accurate data when the system is currently running at high acceleration, as it typically has a peak limit of approximately six degrees pk-pk and a torsional response to 3-5Hz. Therefore, torsional vibrations measured below 5Hz may be incorrect. An instrument calibration curve is used to obtain accurate data over a wide range of frequencies.
Telemetry systems are devices used to measure shear torsional stress whose value can be converted into stress and/or torque by knowing the geometry and material properties of the shaft part. E.g. the transmitted moment can be determined from the average value of the time waveform. The optimal measurement location depends on the shape of the torsion mode, and these are the locations near the zero position on modal system shapes. An example of such a system is the configuration of Binsfeld Engineering, a TorqueTrak 10K telemetry unit with the OPDAQ Field Test 2 data acquisition system (Fig.4) for measuring and storing data on a computer with a built-in high-frequency mode at speeds up to 2400Hz. This allows users to perform frequency analysis to determine resonant frequencies where torsional deformation is greatest and, if necessary, perform corrective action to reduce the torsional deformation to a safe level. [7]

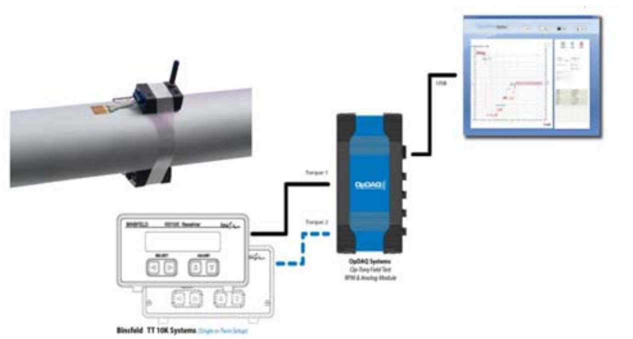

Figure 4. Torsional vibration test kit from Binsfeld Engineering [7]

Frequency modulation (FM) measuring systems measure pulse intervals (pulse rate) and perform signal conversion that is proportional to the characteristic frequency, e.g. gear failure in the grip that can be torsional vibration sources. In this method, the sensors generally measure the time or period between the passage of each tooth that produces a frequency modulated signal (Fig. 6). The signal is demodulated and converted into an angular displacement. By analyzing torsional vibrations and using their modal forms, relative amplitudes and stresses can be determined. [6]
The FM method has several limitations. This can best be explained by the example of a torsional vibration gear engaged with a fault in the gear teeth. In this case, torsion signals can be generated by both lateral gear vibrations (sidebands) and axial vibrations in helical gears.
FM can best be explained through a state-of-the-art torsional vibration analysis method, which is the spectral or Fourier analysis, which is used to look for faults on rotating elements that bind the fault to the torsional resonance range and to the characteristic frequencies and its harmonics. E.g. if a fault is localized on the surface of the gear tooth when rotating at a constant speed,

when the damaged surface comes into contact, sudden changes in torque are generated. These changes excite the torsional resonance of the gear shaft system, but it quickly disappears due to the damping properties before the next resonance occurs, which affects the amplitude modulation (AM). In one repeating cycle, the resonance exists in the early part, and the current frequency is approximately equal to the resonant frequency, while in the latter part, the resonance disappears due to attenuation and the current frequency becomes 0. This means that the current frequency changes periodically, resulting in FM. Therefore, the torsional vibration signals that cause disturbances around the resonant frequency can be modeled as AM-FM with a carrier frequency equal to the resonant frequencies, and the modulation frequency is equal to the harmonics of the gear failure frequency.

3. ANALYSIS OF TORSION VIBRATIONS

The model of torsional vibration signals in the resonant range for one resonant frequency and the fundamental frequency of gear failure can be written as [8]:

$$x(t) = \left[1 + A\cos\left(2\pi f_g t + \phi\right)\right]\cos\left[2\pi f_n t + B\sin\left(2\pi f_g t + \varphi\right) + \theta\right] \ldots (1)$$

where A and B are magnitudes AM and FM and ϕ, φ and θ are phase angles. In the Fourier spectrum peaks appear at frequency sites $f_n \pm n f_g$ where n is an integer order. They form sidebands around the resonant frequency f_n, with the spacing of the sidebands equal to the gear failure frequency f_g. Based on such characteristics, a gear failure can be diagnosed according to the presence or change of sidebands, and in particular the associated lateral band spacing in the resonance frequency range. The application of the Fourier transform gives the Envelope spectrum: [3,8,9]

$$e(f) = \delta(f) + A\delta(f - f_g)\exp(j\phi) \ldots (2)$$

at which the peak appears only at f_g. If we consider harmonics of higher order of frequencies AM, peaks will also appear on harmonics kf_g. Therefore, we can detect gear failure according to the existence of kf_g harmonics or an increase in their magnitudes in the Envelope spectrum (Fig.6). [10][11]

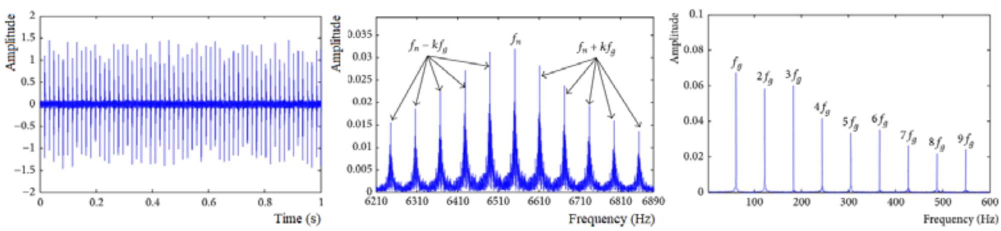

Figure 6. Analiza vibracija: a) Signal waveform, b) Fourier spectrum, c) Envelope spectrum [8]

Fig.7. shows a flow diagram of the proposed spectral method. First, torsional resonant frequency is identified by time-frequency analysis of torsional vibration signals during a variable speed process. Then the symptoms of gear failure are extracted by analyzing the sidebands around the resonant frequency in the Fourier spectrum. Next, the resonant component is separated by band-pass filtering around the resonant frequency and the gear failure indicator is recognized in its Envelope spectrum. Finally, a gear failure is diagnosed by combining sidebands analyses in the Fourier spectrum and AM and FM analyses.[12]

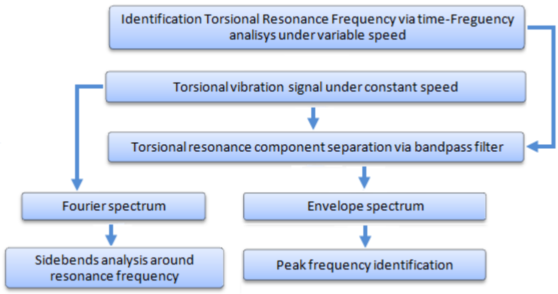

Figure 7. Spectrum analysis flow diagram

4. CONCLUSION

Torsional vibration are dynamic deviations from the speed of rotation of the shaft. In some areas, depending on the speed of rotation, the deviations can become too large and thus create problems. If torsional vibrations are suspected, their analysis and measurement should be performed to define the causes of the problem, i.e. sources of dynamic torque and vibration intensity, but also negative effects such as: reduction of noise and accompanying sound during operation, performance impairment of the entire system, avoiding unacceptable vibrations transmitted to other parts of the machine and the environment and adverse effects on engine control or other machine control functions. In addition to various methods, the most effective method for detecting torsional vibrations that helps in the error detection process is the spectral method.

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