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Technical Paper

Lateral Vibration Measurements Validates Torsional Frequency

Machinery systems contain both lateral and torsional natural frequencies. These resonances remain dormant until they are stimulated by a modally effective excitation force. During machine design, resonant frequencies are computed and compared against potential excitations. In most machines lateral resonances may be directly measured and controlled by changes in bearing or rotor geometry. Torsional resonances are more difficult to measure, and sustained excitation may cause catastrophic failures such as broken gear teeth or shafts. The following case history discusses the computation and field validation of a torsional natural frequency.

Torsional Model

The mechanical system under consideration consists of a 4-pole synchronous motor coupled to the bull gear of a single helical speed increasing gearbox. The bull gear mates to a high speed pinion with an overhung compressor wheel. Large synchronous motors are economically attractive due to higher efficiencies versus equivalent induction motors. However,

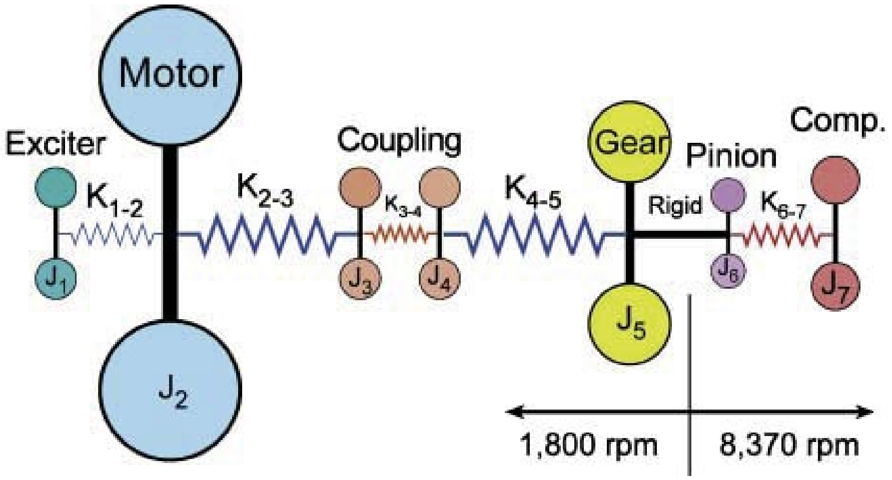


Fig. 1: Undamped torsional system model

synchronous motors produce an oscillating torque during start up that may excite torsional critical speeds. Due to this potential interaction, it is mandatory to perform a torsional analysis of the machinery system.

The fundamental analysis consists of the computation of the undamped torsional natural frequencies. These resonances are primarily dependant on the polar inertia of each major machinery element, plus the torsional stiffness of the interconnecting shafts. Fig. 1 is a torsional rendition of the mechanical system under consideration. The major machine elements of Exciter, Motor, Coupling, Gear, Pinion, and Compressor wheel are identified with polar inertias of J1 through J7. The interconnecting shafts are defined with torsional stiffness of K1-2 through K6-7. For simplicity, a rigid connection is assumed between the bull gear and pinion teeth. As noted, the low speed end of the train operates at the synchronous speed of 1,800 rpm, with 8,370 rpm for the pinion and compressor wheel.

Note that journal bearings do not influence torsional behavior, and they are not included in the torsional model. Based on the physical parameters for inertia and torsional stiffness, the undamped torsional natural frequencies may be computed. There are various commercially available analytical programs using transfer matrix or finite element computational techniques. For this simple system either technique is acceptable, and the first five natural frequencies were computed and optimized. The calculations revealed a first mode at 966 cpm with a nodal point located at the middle of the torsionally compliant coupling. This torsional natural frequency is clearly separated from the synchronous motor operating speed of 1,800 rpm, but it does appear within the start up speed envelope.

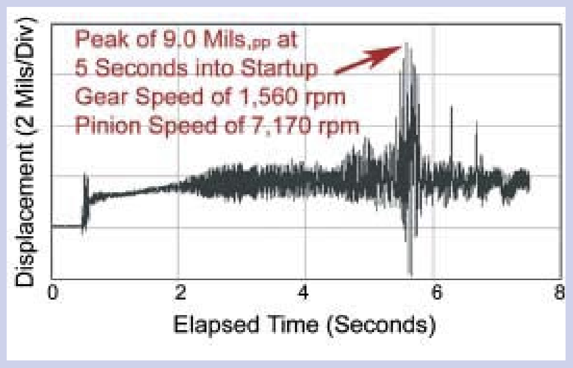
Mechanical Interaction

If a synchronous motor is directly coupled to a pump or compressor, the torsional resonances may never be noticed. However, when a gearbox is included in the machinery train, the gears teeth provide a physical mechanism for translating the torsional (twisting) motion into lateral (radial) vibration. A synchronous motor will produce an oscillating torque at a frequency that is equal to the number of poles times slip frequency. This relationship may be stated as:

Torsional Frequency = Number of Poles X (Sync Speed - Running Speed)

For a 4-Pole synchronous motor at zero speed, the torsional frequency is equal to 7,200 cpm. At full speed, the synchronous speed and running speed are numerically equal, and the torsional excitation frequency is zero. Hence, the oscillating torque frequency generated by the motor will vary from 7,200 to 0 cpm as the motor speed increases from 0 to 1,800 rpm. As this frequency intersects the system torsional natural

Fig. 2: Time domain record of start up transient capture.



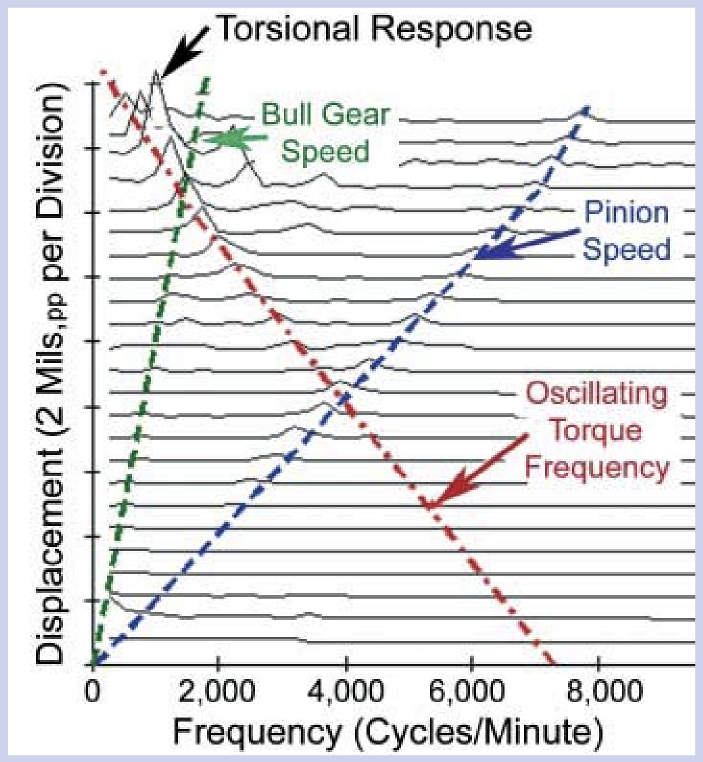


Fig. 3: Frequency domain presentation of start up transient capture

frequency, high torsional and lateral vibration will occur.

Field Measurements

The machinery train was equipped with radial X-Y proximity probes at the journal bearings, plus axial position on the pinion and a timing probe. Acquisition of start up vibration data is complicated by the fact that the motor accelerates from zero to synchronous speed in approximately 6 seconds. This rapid acceleration rate makes it very difficult to accurately acquire vibration data using conventional techniques. The field solution consisted of using a digital data acquisition system for sampling of vectors and gap voltages during start up. A separate FM tape recorder was used to acquire the overall or unfiltered signals from each transducer.

The waveform data captured by the tape recorder was reproduced at a slower tape speed into a digital signal analyzer configured for high speed transient capture. Operating in this mode, the analyzer sampled, digitized, and stored the vibration data into memory. After sampling, the data was formatted and exported into ASCII files for post processing with a commercially available computational program. Fig. 2 is representative of the acquired start up time domain records where the peak lateral vibration appears at a bull gear speed of 1,560 rpm

The time record consisted of 30 time blocks sampled with 1,024 points per block. Additional processing of each block into spectrum (or Fast Fourier Transform) data allows the production of the waterfall plot shown in Fig. 3. This diagram was annotated with the bull gear and pinion speeds, plus the oscillating torque frequency. Note the high torsional response peak at a bull gear speed of 1,560 rpm. This peak is slightly less than 1,000 cpm, but the frequency accuracy is limited by the sample resolution of this transient data.

The occurring frequency of this lateral response may be determined from the previous expression for torsional excitation frequency. Since the motor contains 4 poles, the synchronous speed is 1,800 rpm, and the running speed associated with the high vibration is 1,560 rpm, the torsional frequency is computed as follows:

Torsional Frequency
=
No. of Poles X (Sync Speed - Running Speed)

Torsional Frequency
=
4 X (1,800 - 1,560) = 4 X 240 = 960 cpm

This torsional frequency of 960 cpm is virtually identical to the previously calculated undamped first torsional natural frequency of 966 cpm. It is clear that the high radial vibration response is the re-excitation of the first torsional critical speed by the oscillating motor torque during start up. Fortunately this event occurs during a short period of time, and minimal mechanical damage occurs. It should be recognized that a torsionally compliant coupling is required between the motor and the bull gear. If a traditional hard coupling was installed, this machinery train would have a limited life span.

Final Conclusions

The existence of oscillating motor torque during the start up of synchronous motors is a well documented phenomena. This behavior must be considered as an integral part of the design process for new machinery train installations, and the selection of acceptable couplings with torsional isolation capabilities. During field troubleshooting of existing installations, the diagnostician must also be aware of this behavior. This will be a significant factor in the selection of analytical instrumentation, the methods used for data processing, and the accurate interpretation of the results.

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