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IMPACT OF ELECTRICAL NOISE ON THE TORSIONAL RESPONSE OF VFD COMPRESSOR TRAINS

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ABSTRACT

The popularity of VFD motors in compressor trains has increased in recent years. Increased process flexibility is a primary consideration for implementation of VFD systems. However, this comes at a cost of increased mechanical and electrical complexity. Problems rarely experienced with single speed motors have become more likely with VFD's. These include impacts on the torsional behavior leading to component failure and extended downtimes.

VFD's can excite the torsional system in several ways. This paper examines the impact of white noise on the torsional response of VFD compressor trains and contrasts it against the response to single frequency harmonic excitation. The characteristics of white noise, noise modeling characteristics for torsional response, and noise generation techniques are examined. Generation of a frequency banded noise signal is presented using a commonly used math modeling code.

Two case studies are presented representing VFD compressor trains found in the LNG industry. Both experienced torsional problems related to the VFD and, in one case, led to a coupling failure and release of parts from the train. In the examination of these trains, a single frequency harmonic (SFH) sweep and banded Gaussian white noise (GWN) encompassing the dynamic response envelop of the 1st TNF, are used as inputs to the torsional analysis.

INTRODUCTION

The use of variable frequency drive (VFD) motors has increased in recent years. Applied in drive applications ranging from pipeline pumps, fans, ethylene compression and large liquid natural gas (LNG) plants, the increase is attributable to the advantages offered by the VFD over single speed motors and other variable speed drivers such as steam and gas turbines. These advantages include:

- Variable speed capability - Reduces equipment damage possible from off-design operation of pumps. Increases the operability range of the application. Eliminates the need for damper/louver systems in fans.
- Soft start - Eliminates the starting current in-rush and resultant oscillating torque produced by synchronous motors simplifying the transient torsional considerations of the train design, Ritter (2007).
- Increases overall thermal efficiency - Used with a combined cycle design in power generation or process compression, thermal efficiency gains can be realized, Richardson (2001). Higher thermal efficiency also reduces greenhouse gas emissions.

- Start assist - VFD motor used in conjunction with a gas turbine can provide the starting torque necessary to overcome compression inertia.

- Reduction in train complexity - VFD provides the capability of running the motor super-synchronously eliminating the need for a speed increasing gear box.

The focus of and examples presented in this paper will be of trains configured with a VFD starter motor, either as the primary or an assist drive. However, the findings are presumed to be applicable to all applications of VFD driven equipment trains.

Special considerations result from the use of VFD driven machinery trains. System design, Baccani (2007), and initial sizing of the starter motor, Heckel (1999), represent some of the project considerations. Torque modulation produced by the pulse width modulation (PWM) is the principle concern for the analyst when examining the train torsional behavior. Torque modulations can result from harmonic, Allen-Bradley (2010), and interharmonic, Yong (2008) distortion of the created AC voltage to the motor.

The impact of these torque modulations on the torsional behavior of machinery trains has been studied. Recent publications include work by Feese (2008), Kaiser (2008) and Hutten (2008). Kaiser (2008) studied the level of interharmonics produced by various VFD architectures. The magnitudes ranged from as high as 8% for Load Commutated Inverter (LCI) VFD's to <1% for Pulse-Width Modulation (PWM) VFD's. A torsional analysis of a VFD driven pump train was performed studying the effect of harmonics and interharmonics on shaft stress and concluded that for all but the LCI-VFD's, state-of-the-art VFD driven trains should be considered torsionally safe and the torsional rotordynamic analysis of such shaft trains be omitted.

Recent publications in the area of compressor driven trains indicate that useful information may be obtained from torsional analysis of VFD driven compressors. In these studies, torsional analysis methods for VFD driven compressor trains are increasing in complexity, Feese (2008), Kita (2007), Hütten (2008) and Rotondo (2009). Feese (2008) studied coupling failures related to the harmonics of a PWM-VFD driven fan train. Kita (2007) presented a method to extract the alternating torque magnitude from gear vibrations witnessed on a VFD driven compressor train. Hütten (2008) and Rotondo (2009) developed torsional methods including both the mechanical and electrical systems in a combined analysis. Sihler (2009) introduced a novel active damping scheme. A feedback system is employed in which the motor provides oscillating torque to counteract torsional vibrations experienced by the train. This methodology is also the subject of a recent patent application, Rotondo (2010).

Largely ignored in these efforts has been the impact of noise on the torsional response of compressor trains. Given the propensity of compressor trains to excitation of the torsional natural frequencies (TNF) to discrete VFD torque modulation, the same must be true of torque pulsations originating from white noise. The typically larger magnitudes of discrete frequency excitation are offset by the white noise excitation over the entire dynamic response envelope of TNF's especially in lightly damped systems. This paper presents a simple method to generate white noise. Expressed as points of torque vs. time, the white noise is supplied as input data to a commercially available torsional analysis code. This study will compare the response of the 1st TNF to both white noise and discrete excitations for two typical LNG compressor trains.

COMPRESSOR TRAINS

Two compressor trains were selected to study their torsional response to VFD generated excitations. Both trains are fairly typical of the LNG industry. The first compressor train is driven solely by a VFD motor. The second train uses the VFD motor as a starting assist and to provide additional power during operation. Both trains experienced torsional and radial vibrations associated with the VFD.

For compressor train 1, Figure 1, interharmonics and signal feedback led to a failure of the pinion to LP compressor coupling, Figure 2. Base excitation of the 1st TNF is believed to be caused by white noise and amplified through feedback of the speed signal to the VFD. Endurance limits of the coupling were exceeded when with small speed changes; an interharmonic sideband of the VFD became coincident with the 1st TNF. Feedback and dynamics amplified the response of the combined signal to a magnitude greater than the sum of the parts, Figure 3.

During string testing of compressor train 2, Figure 4, gear vibrations were noted that were coincident with the 1st TNF. The VFD was again identified as the cause of the vibration. (Both vibration and excitation ceased following a trip of the VFD.) As confirmed by the reconstructed air gap torque, no discrete frequency excitation was present, Figure 5. However, strain gage measurements of the coupling torque/stress showed a strong component at the 1st TNF.

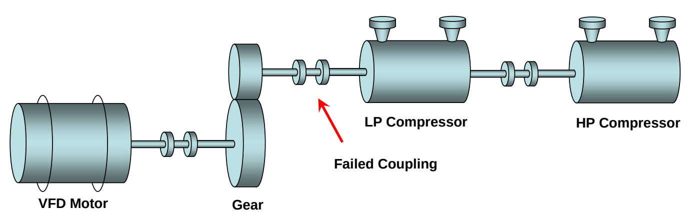

Figure 1) VFD Driven Compressor Train

Figure 2) Spiral Failure of Spacer - Typical of Excessive Torsional Stress

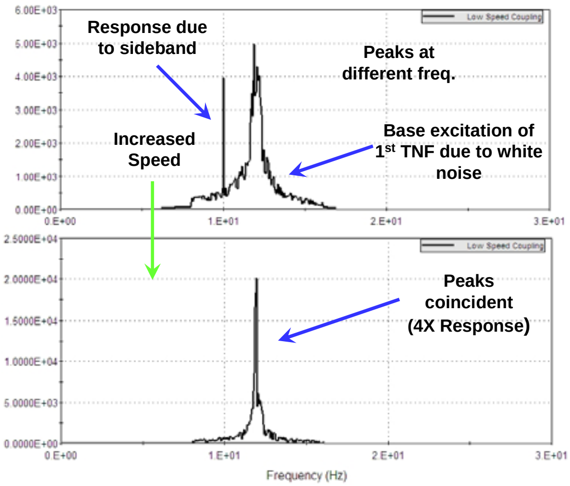

Figure 3) Stresses in Coupling due to VFD Excitation

Since the use of VFD's is a common practice in petrochemical facilities and with two problems related to VFD generated torque fluctuations, a study of the impact of white noise was warranted. Additionally, the development of guidelines concerning the magnitude of white noise may prove beneficial to the reliability and operability of VFD driven compressor trains.

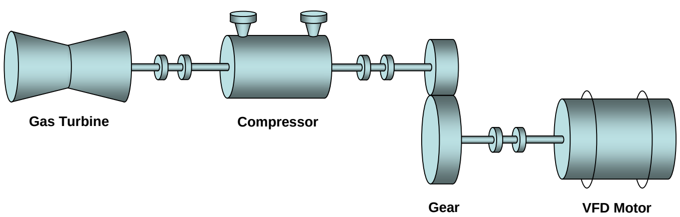

Figure 4) VFD Start Assist Compressor Train

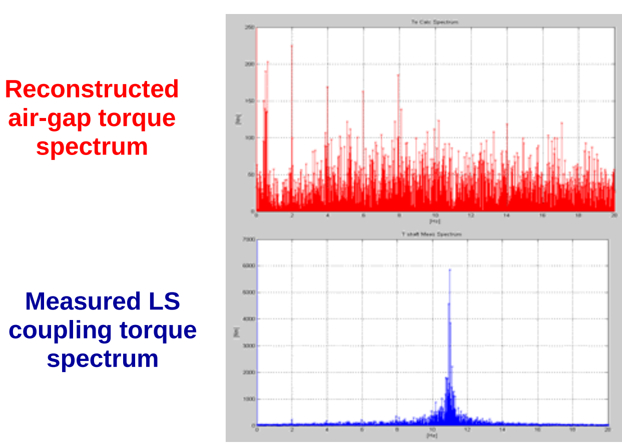

Figure 5) White Noise Excitation of the 1st TNF

WHITE NOISE

For the purposes of this study, we will define white noise as a zero-mean signal made up of independent identically-distributed (IID) random variables with a flat power spectral density (PSD). In terms of mathematical definitions, this can be described as:

Term	Mathematical Definition	Explanation
Zero mean	$\mu_w(t) = E\{w(t)\} = 0$	Expected value over entire process is zero
IID	$R_{ww}(t_1,t_2) = E\{w(t_1)w(t_2)\} = \frac{N_0}{2}\delta(t_1 - t_2)$	Consecutive points have no correlation
Flat PSD	$S_{xx}(\omega) = \frac{N_0}{2}$	All frequency content is equally likely

Most physical noise can be described using a Gaussian (normal) distribution known as Gaussian white noise (GWN). GWN can be generated using several techniques each of which has advantages. For this effort, phase-randomization was selected, Kafadar, 1986. This procedure applies uniformly-distributed random phasing to the sinusoidal functions within the frequencies of interest. The result is low frequency response variability which is easily band-limited.

The sinusoidal functions, S, will take the form, $S = A\varepsilon^{i\phi}$, where A>0 (amplitude to be scaled in the torsional analysis) in the desired frequency range around the 1st TNF and φ is a uniformly distributed random number between 0 and 2π. To evenly space these functions in the frequency domain, 2^{13} points are selected over the time range of 15 seconds. Since the sampling rate must be at least twice the Nyquist frequency, this combination provides coverage up to 273 Hz with a resolution of 0.0667 Hz. An inverse Fourier transform of the vector of sinusoids is performed using the IFFT function in MathCad® from PTC. Given the even spacing in frequency of the complex samples, S, a real valued vector at equal time intervals, every 0.001831 seconds, is generated. Figure 6 plots the signal in the time domain for a given seeding of the random phasing. Figure 7 presents the FFT and can be seen to be flat over the desired frequency range. Finally to show that the signal has the normal distribution property of GWN, a histogram is plotted on Figure 8.

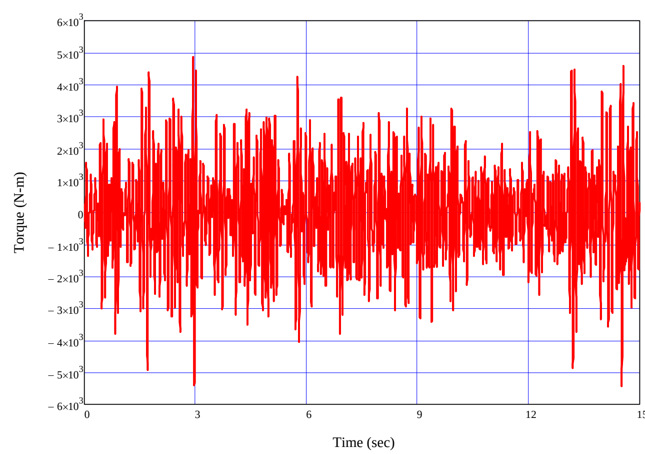

Figure 6) Time Constructed White Noise Signal (Arbitrary Amplitude)

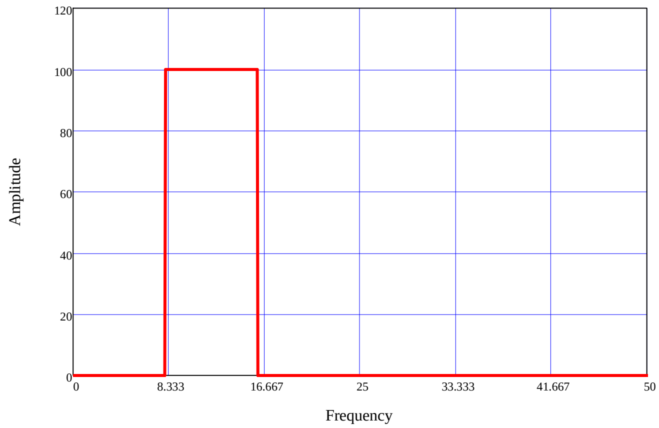

Figure 7) FFT of Time Signal

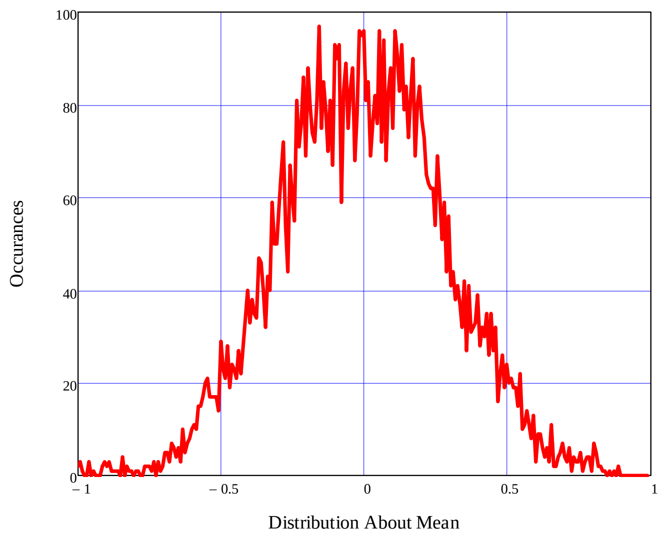

Figure 8) Approximate Normal Distribution of Noise

TORSIONAL ANALYSIS

The torsional analysis of the trains was performed using ARMD software developed by RBTS, Inc. Assumptions concerning stress concentration factors, damping levels, stress criteria and penetration factors follow common industry practices for compressor trains without elastomeric couplings. Szenasi, 1990, provides a good overview of torsional analysis of VFD's with description of these assumptions.

Of interest in the analysis, is the response of the torsional systems to white noise especially in comparison to single frequency excitation. Since the problems experienced by the authors have involved the re-excitation of the 1st TNF, the single frequency and the white noise will be defined to excite that mode in particular. Figure 9 illustrates the 1st TNF for both trains.

The white noise is constructed, as previously noted, to cover dynamic response envelope of the 1st TNF with an amplification factor ≈30 or equal to a damping value of 1.67% of critical damping. (Field measurements of the response envelope of the second compressor train confirmed the validity of this damping assumption.)

Single frequency excitation is accomplished by applying a harmonic forcing function at the excitation source, in this case the centerline of the motor windings. The software calculates the steady state response to this excitation for each component in the train. For white noise, the user supplies a discretized input excitation of the form torque = *f*(time). The software calculates a transient response of the train to this input, which is also applied at the motor winding centerline.

To ensure that the software or procedure is not introducing unintended changes in the torsional response, the steady state response to a single harmonic excitation was compared to the transient response of that harmonic excitation expressed as torque versus time. For the first compressor train, the harmonic excitation at the 1st TNF is shown in Figure 10 in discretized format. The magnitude of the harmonic excitation is arbitrarily set.

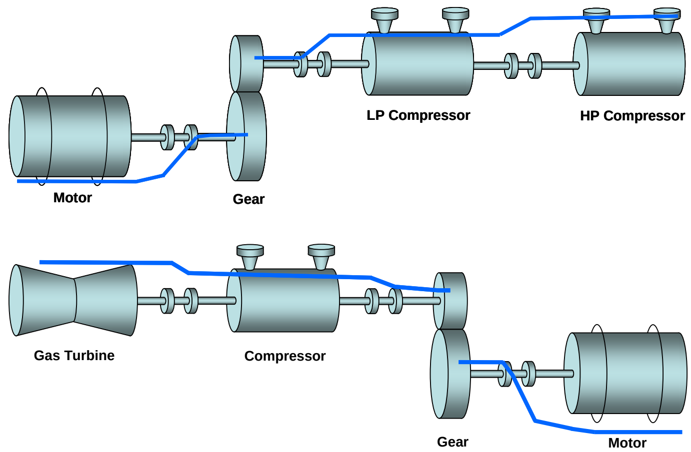

Figure 9) 1st TNF Mode Shape for Compressor Trains

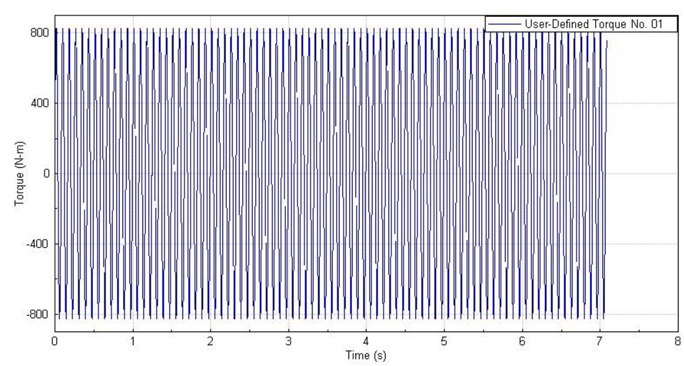

Figure 10) Torque Input vs. Time for the Harmonic Excitation

The torsional response of the low speed coupling expressed in torque was calculated for both excitations. The steady state response of the coupling is presented on Figure 11. The transient response of the train to the discretized harmonic excitation is shown on Figure 12. As expected, the software calculates the same level of response in both cases after the transient response reaches a steady state level.

Satisfied that the software is behaving as expected, the study of the two compressor trains' response to the harmonic and white noise excitation was undertaken. Magnitudes of the excitation were set at "typical" levels guaranteed by VFD vendors. Note that these do not reflect a recommendation for magnitude but merely represent relative magnitudes selected for the purpose of this investigation. Since the analysis is linear (an assumption that holds providing that the oscillating torque does not exceed the drive torque in the train), the absolute magnitudes of the excitations are not critical. What is important is the magnitude of the response produced by each. In our study, the harmonic force, representing a PWM produced excitation, was set at 1% of the train rated torque. The VFD generated white noise averaged 0.25% of the rated torque or ¼ of the harmonic excitation.

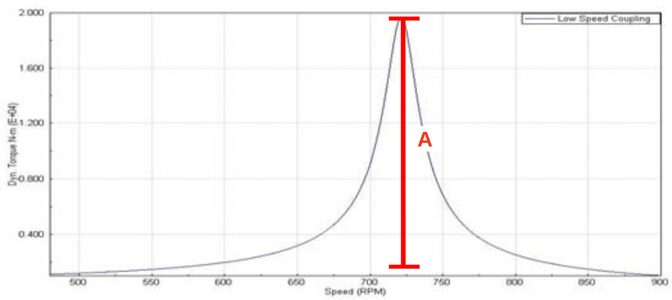

Figure 11) Steady State Response of Compressor Train I

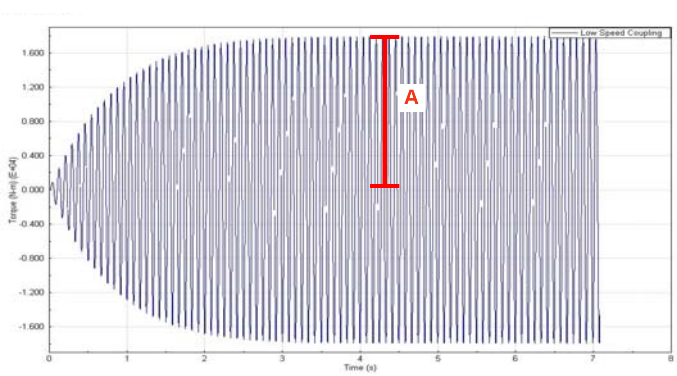

Figure 12) Transient Response of Compressor Train I

COMPRESSOR TRAIN I: VFD DRIVEN TRAIN

For the VFD driven compressor train, the single harmonic and average white noise excitations were set at 828 and 207 N-m p-p, respectively. To ensure that the transient effects of the analysis start are eliminated, the transient calculations were performed over a 15 second period. The length of analysis was restricted due to the small time steps needed to adequately describe the time waveform of the white noise and the input size limitations of the software. Since the time waveform produced varies with each seeded generation, several runs studying the transient response to the waveform were performed. A typical result is shown below and does not reflect the maximum response calculated. Figure 13 plots the white noise input in the time domain for this case. Figure 14 shows the same signal in the frequency domain with an average value of ≈207 N-m.

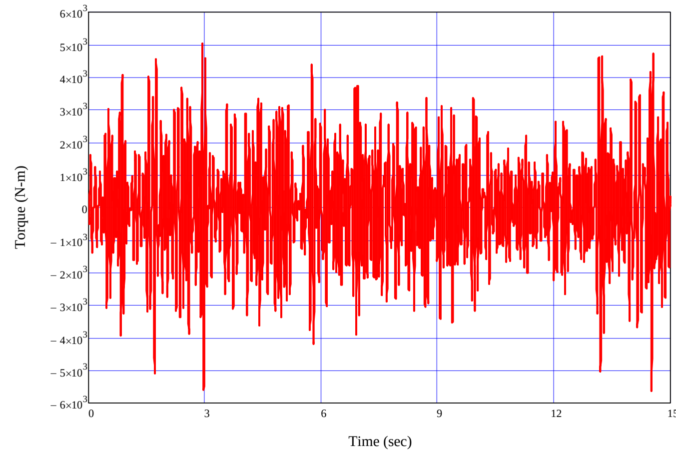

Figure 13) Noise Input in Time Domain

The calculated steady state and transient response for the torque in the low speed coupling are shown on Figures 15 & 16, respectively. For this white noise input, the transient response has a 0-peak value of nearly 1.5 times the steady state response. The peak value of the individual torque oscillations in the transient response is critical since this determines damage done to the components should they exceed the HCF limit. Assuming this level of torque ($3.0x10^4$ N-m) exceeds the HCF limit of the coupling and, further, that this cycle occurs twice every 14 seconds (period of the analysis), then failure of the coupling (>1,000,000 cycles) would occur in roughly ¼ year.

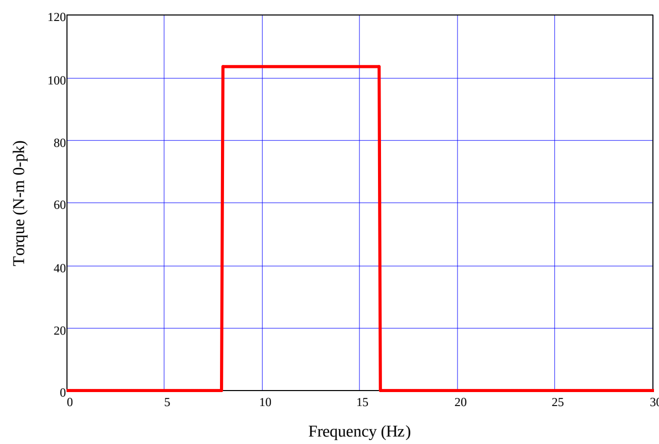

Figure 14) Noise Input in Frequency Domain

The maximum 0-pk magnitude found during the multiple runs of different white noise input was nearly 2X the steady state response. An FFT of the low speed coupling response is shown on Figure 17. As expected, the response is centered near the 1st TNF with an amplification factor ≈35.

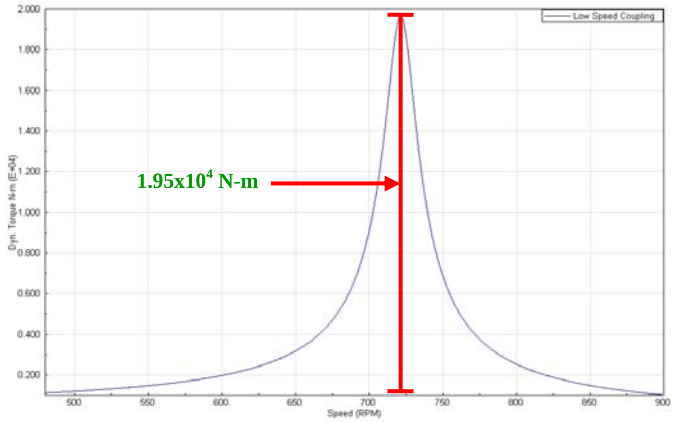

Figure 15) Steady State Response of the Low Speed Coupling VFD Driven Train

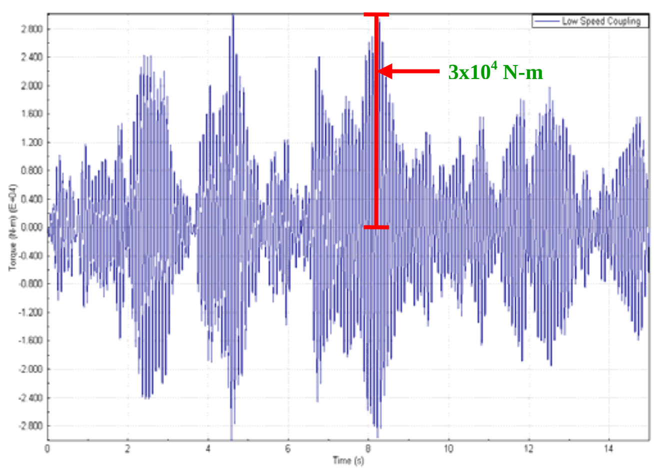

Figure 16) Transient Response of the Low Speed Coupling VFD Driven Train

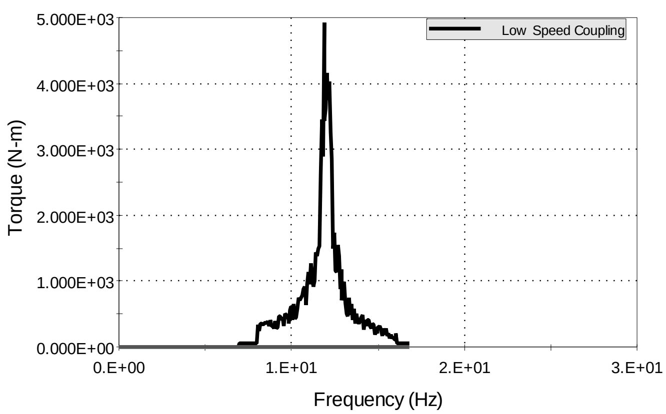

Figure 17) FFT of Low Speed Coupling Response

COMPRESSOR TRAIN II: VFD START ASSIST TRAIN

For the VFD start assist compressor train, the single harmonic and average white noise excitations were set at 1072 and 268 N-m p-p, respectively. As with the previous case, the transient calculations were performed over a 15 second period. Several runs studying the transient response to the waveform were performed. A typical result is shown below. Figure 18 plots the noise input in time domain for this case. Figure 19 shows the same signal in the frequency domain with an average value of ≈268 N-m.

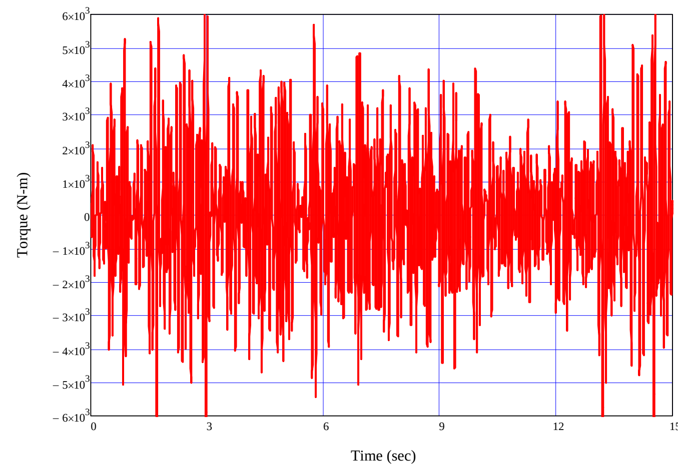

Figure 18) Noise Input in Time Domain

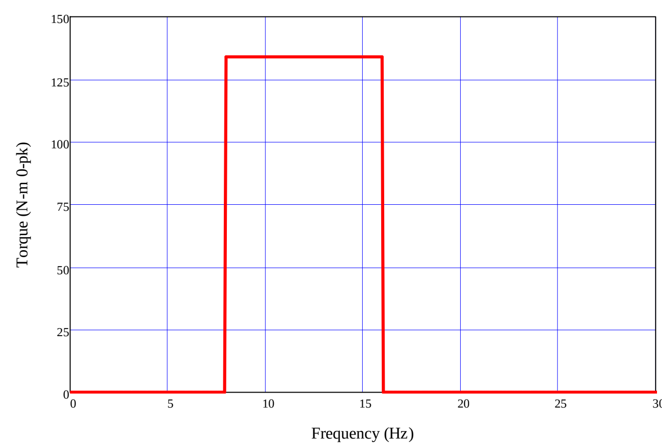

Figure 19) Noise Input in Frequency Domain

The calculated steady state and transient response for the torque in the low speed coupling are shown on Figures 20 & 21, respectively. For this white noise input, the transient response has a 0-peak value of nearly 1.3 times the steady state response. As before, multiple runs produced varying results with the maximum transient reading exceeding 1.8x the steady state response.

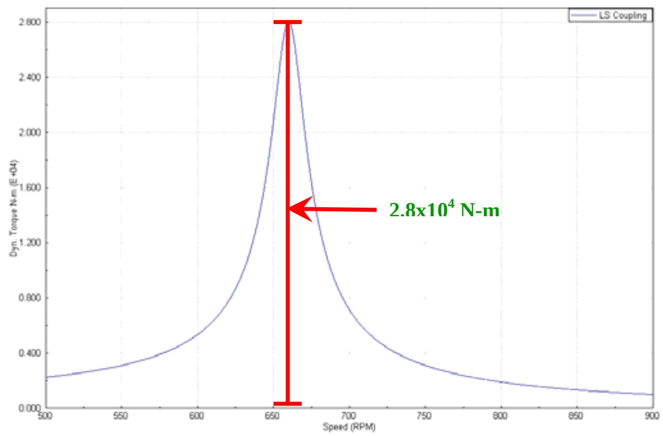

Figure 20) Steady State Response of the Low Speed Coupling VFD Driven Train

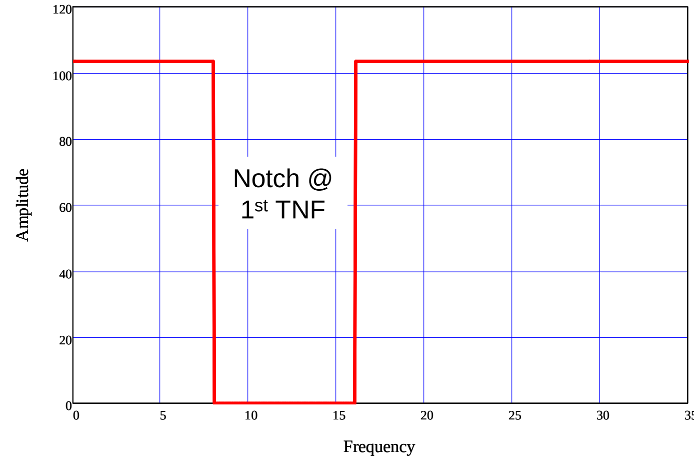

Figure 22) Noise Input Notch Filtered Around 1st TNF

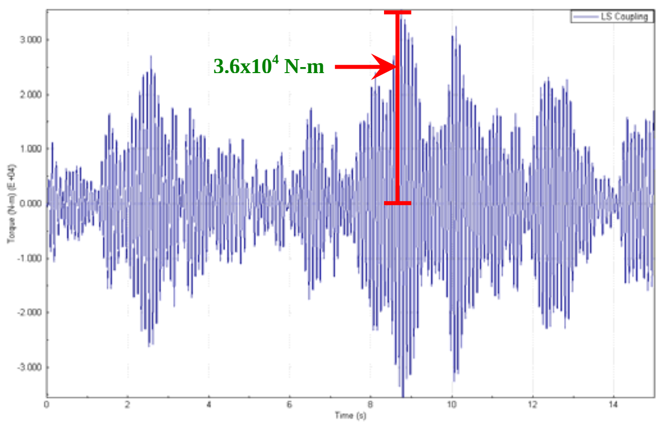

Figure 21) Transient Response of the Low Speed Coupling VFD Driven Train

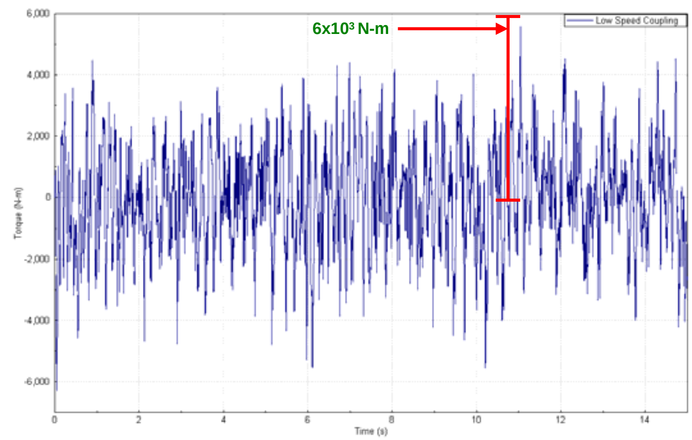

Figure 23) 5X Reduction in Coupling Response

EFFECTIVENESS OF NOTCH FILTERING OR ACTIVE DAMPING

A study of the effect of eliminating the white noise near the 1st TNF by "perfect" notch filtering or active damping, Rotondo 2010, was also performed. In either case, the white noise excitation is assumed to be eliminated within a band centered on the 1st TNF. Figure 22 plots the "notch-filtered" white noise signal in the frequency domain. The signal is composed of a larger frequency domain to ensure that the majority of the response identified in the earlier analyses is attributable to the white noise frequency components within the dynamic response envelope of the 1st TNF. Applying this excitation, the transient response for the Case I compressor train is shown on Figure 23. Notice that a 5X reduction in peak response is achieved.

CONCLUSIONS

Much attention in literature has been given to the harmonic and interharmonic torque modulations produced by VFD's and their impact on the torsional behavior of geared compressor trains. While that attention is warranted in most cases, it has ignored the effects of the white noise generated by those same systems. In at least one recent incident in the authors' experience, white noise has been identified as the source for torsional oscillations of the train. Had this situation gone unmitigated, a coupling failure would have occurred.

As part of this effort, a straightforward method was developed to produce and study the impact of white noise on the torsional response of two "typical" centrifugal compressor trains equipped with a VFD. A single frequency harmonic and white noise excitations were applied to the torsional model and the subsequent torque oscillations compared. The response of the 1st TNF at the low speed coupling was found to be 1.5 to 2.0 times larger for the white noise excitation at ¼ the magnitude of the harmonic forcing function.

As a result of this work, the authors recommend the following actions be taken when considering purchasing new equipment trains with VFD's.

- Purchase specifications for machinery trains incorporating VFD's should specify or seek guaranteed upper limits on the torque modulations from harmonic, interharmonic and white noise produced by the VFD electrical systems.
- Torsional analysis of VFD driven or start assist trains (especially geared) should include the calculations of the response of the system to harmonic, interharmonic and white noise. The method developed here can be used to generate a white noise signal to be used as the input for the analysis. As noted, several runs should be made to get a complete understanding of the system response.
- Speed feedback signals used in the drive electrical system should be adequately filtered to reduce the possibility of re-excitation of the 1st TNF. Active damping has also demonstrated effectiveness in eliminating excitations of not only harmonic origin but also white noise. These are typically focused on frequencies near the 1st TNF and, thus, need to be tuned for each application.

NOMENCLATURE

FFT	= Fast Fourier transform
HCF	= High cycle fatigue
IFFT	= Inverse fast Fourier transform
PSD	= Power spectral density
PWM	= Pulse width modulation
TNF	= Torsional natural frequency
VFD	= Variable frequency drive (motor)

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