

Measure and predict torsional vibration in rotating equipment

Excessive torsional vibration in rotating equipment trains can result in damage to, or failure of, equipment, leading to emergency shutdowns and costly downtime. It also increases the potential for major safety incidents, such as turbine overspeed events or coupling failures that generate dangerous shrapnel, as shown in **FIG. 1**.

When designing a torsional system, engineers typically use comprehensive torsional vibration analysis to avoid excessive vibration. API Standard 617, which specifies torsional system requirements, specifies a 10% separation margin between torsional natural frequencies (TNFs) and any excitation frequency. The method of achieving an acceptable torsional separation margin is generally limited to coupling selection and tuning. In some cases, modification of system inertia is acceptable. If an acceptable separation margin is not achievable, then design engineers must use stress analysis to demonstrate torsional system design acceptability.

The validity of the predicted TNF and associated stress analysis is dependent on the accuracy of the model. However, assumptions within the analytical data are always subject to a degree of uncertainty. To address this uncertainty, a case study of 10 torsional systems was conducted, looking at the effect of variation in mass-elastic data, and comparing differences between measured and predicted TNFs.

TORSIONAL ANALYSIS

Modeling and natural frequency prediction. The TNF of a rotating equipment train is predictable through analytical methods. One modeling method is the mass-elastic or inertia-stiffness model, which uses lumped inertias, springs and dampers. Each component in the torsional model has a specific function, accurately modeled by following readily available component modeling guidelines. As torsional damping is usually small, an undamped analysis is generally enough to predict the TNFs of most rotating equipment systems.

Uncertainties in models. Uncertainties are factors that cause a difference between the predicted TNF and the true TNF. If the lumped mass-elastic model accurately represents the equipment train, then the predicted TNFs will match the real system's TNFs.

For the purposes of this study, two types of uncertainties were considered: error and variation. Error uncertainties include an insufficient number of stations to predict natural frequencies in the mass-elastic model; inaccurate material properties; and improper modeling of complex shapes and connections, such as the motor core. Variation uncertainties include wear or deposit-induced inertia change, dynamic vs. static stiffness, variation in shrink fit, and material-induced stiffness change due to age.

Shaft-end modeling for penetration couplings is an area of concern for error uncertainties. Most coupling vendors consider the shaft end, which is inside the coupling, to be part of the coupling when determining coupling stiffness. Since the shaft end is the weakest part of the body, measuring stiffness in different ways can result in significant differences.

When modeled correctly, the uncertainties of the inertia of all bodies, including couplings, are accurate within 5%. The stiffness of the motor/gear/compressor is also accurate within 5% for most applications. Coupling stiffness is the least accurate, yet the most influential to the TNF, since it is the weakest part of the equipment train.

For couplings, both variation and error uncertainties are significant. Despite API 617 standards,¹ finite element analysis (FEA), a large volume of tests and strict installation instructions, a survey of coupling vendors has revealed that the uncer-



FIG. 1. Failed diaphragm coupling.

tainty accuracy of the couplings still averages between 15% and 25% (TABLE 1) and is based solely on a static test (FIG. 2).

Influence of uncertainties. It is possible to evaluate uncertainties in the predicted TNFs by using the estimation of uncertainties of each individual component. To determine this, sensitivity and worst-case scenario studies were conducted on the measured TNFs of seven motor gear compressor trains, all with partial or no load.

Sensitivity study. To determine whether discrepancies between prediction and measurement relate to parameter variation, each parameter, such as motor inertia or coupling stiffness, was varied sequentially to understand the change in the predicted TNFs. Observations include:

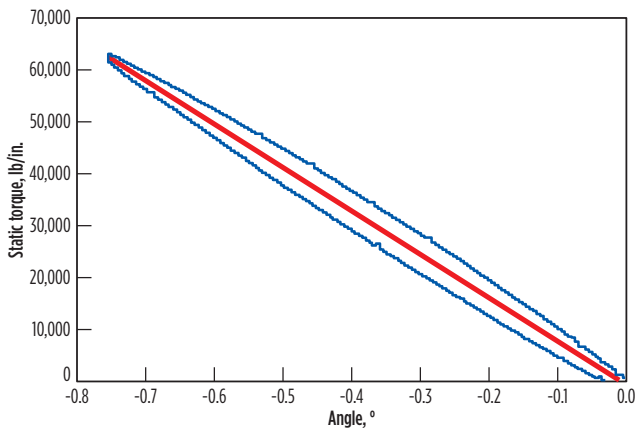


FIG. 2. Static load test of a disc coupling.

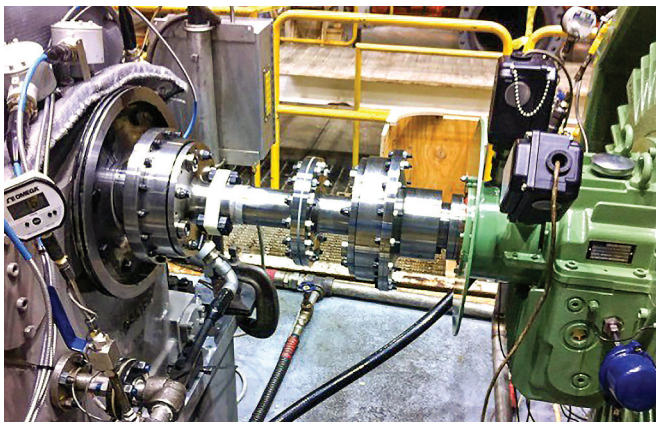


FIG. 3. Low-speed coupling.

- Increasing inertias always reduce TNFs. Typically, inertias affect the coupling mode that is next to them (e.g., the motor affects the motor-gear coupling mode), as shown in FIG. 3.
- Increasing coupling stiffness always increases TNFs.
- When the coupling sensitivity is within $\pm 0.3\%$, the discrepancies between predictions and measurements (prediction errors) are within 5% for all cases studied (all API turbomachinery equipment trains).

Worst-case scenario. In estimating the worst-case scenario for predicted TNFs, it was assumed that the uncertainties of all inertias were within 5%, and that the uncertainties of all stiffness were within 5%, except for the coupling stiffness. For the coupling stiffness, two sets of uncertainties were applied: 15% and 25%. Observations included:

- When the predicted coupling stiffness is accurate within 15%, and all other predicted inertias and stiffnesses are within 5% of the actual values, then predicted TNFs should be within 10% of the true values.
- When the predicted coupling stiffness is accurate within 25%, the prediction uncertainty approaches 15%.

Due to the discrepancies between the predicted and actual TNFs for coupling stiffness, a thorough review was conducted of the torsional analyses to ensure there was no human error. For several of the equipment trains, motor and gear vendors were asked to confirm/verify their numbers. One coupling vendor even performed a static test to verify its predicted coupling stiffness. Although this review did not reveal any major errors, the differences between the predicted and actual coupling stiff-

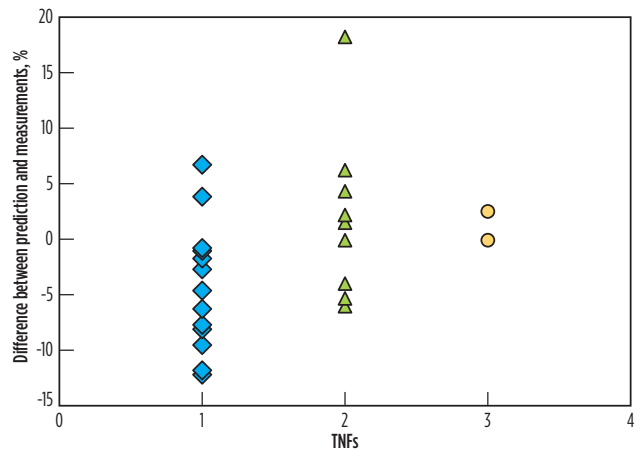


FIG. 4. Discrepancies between prediction and measurement for turbomachinery equipment trains.

TABLE 1. Coupling vendor survey result

	Vendor A	Vendor B	Vendor C	Vendor D	Vendor E
Accuracy of torsional stiffness	Short: 10%-25%	5%	10%	Regular: 5%-10%	25%
	Long: 5%-15%			Elastomer block: 15%	
Torsional stiffness test	Static testing	No in-house test	Static testing	Static testing	Static testing
Penetration model (keyed and hydraulic)	1/3 penetration				
Interference (in./in. diameter)	Hydraulic fit	0.002-0.0025	0.002-0.0025	0.002-0.0028	0.002
	Keyed Straight	0.0005-0.00075	0.0005	0.0005	0.0005-0.00075

nesses were greater than 10% on some of the equipment trains. Two possible explanations for the discrepancies are:

1. The variation uncertainties for the couplings, considering performance testing under partial or no load
2. The presence of unknown human errors, considering that some vendors may not be fully aware of torsional modeling techniques.

Measurement vs. predictions. FIG. 4 summarizes the comparisons between measured and predicted TNFs for 13 turbomachinery cases. The x-axis represents the order of the TNF (first TNF, second TNF, etc.). The y-axis represents the difference in percentage of the predicted TNFs vs. the measured TNFs. Due to measurement difficulties, the second and third TNFs are not always measured.

Impact. This case study of torsional prediction accuracy generated the following conclusions regarding error, sensitivity and repeatability.

- **Error and sensitivity**—For the 13 turbomachinery cases examined in this study, the standard deviation between the measured and predicted TNFs for the first natural frequency was approximately 5.5%, with the worst-case error of < 12% and > 7%. This is outside the previously assumed $\pm 5\%$ error used by many rotor dynamicists.² The primary contributor to the TNF error is uncertainty in coupling stiffness.
- **Repeatability**—As part of this case study, two torsional system designs were also studied for repeatability. The TNF for “identical” units varies between 1% and 2%.

The case study demonstrates the value of a torsional test, not only for verification of separation margin, but also for verification of low-stress amplitudes and low levels of excitation. It is important to note that stress is also a determinant in the safety and reliability of a torsional system.

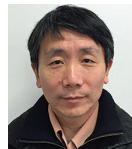
Torsional analytical accuracy is only as good as the accuracy of the test data, and the available programs and procedures. Additionally, the design of reliable systems is dependent on design standards. The 10% analytical separation margin requirement set by API provides conservatism, as evidenced by the overall lack of torsional failures in API machinery strings in which the separation margin from running speed was determined to be the root cause. In cases where additional conservative measures are required, parametric analysis, torsional measurement, stress analysis or a combination of these analytical tools can provide additional system verification. **HP**

LITERATURE CITED

- ¹ American Petroleum Institute Standard API 617, “Axial and centrifugal compressors and expander compressors,” 2014.
- ² Mondy, R. E. and J. Mirro, “The calculation and verification of torsional natural frequencies for turbomachinery equipment strings,” 12th Turbomachinery Symposium, Turbomachinery Laboratories, Texas A&M University, College Station, Texas, 1982.
- ³ Wang, Q., T. D. Feese and B. C. Pettinato, “Torsional natural frequencies: Measurement vs. prediction,” 41st Turbomachinery Symposium, Turbomachinery Laboratories, Texas A&M University, College Station, Texas, 2012.



BRIAN PETTINATO is Manager of product development for Elliott Group, where he has worked since 1995. His primary area of expertise is machinery dynamics. He has co-authored more than 20 technical papers, and holds three US patents. Mr. Pettinato is an ASME fellow, a member of STLE, and a registered Professional Engineer in the State of Pennsylvania. He also serves on the Turbomachinery Advisory Committee of Texas A&M and on the API 684 rotordynamics task force. He earned his BS and MS degrees in mechanical engineering from the University of Virginia.



QINGYONG WANG is a Senior Product Development Engineer at Elliott Group. He has been with Elliott Group since 2005, and his areas of expertise include lateral and torsional rotordynamics. Dr. Wang serves on the API 684 rotordynamics task force, and is a member of ASME. He received his BS and MS degrees in mechanical engineering from Tsinghua University in Beijing, China and his PhD in mechanical engineering from the University of Virginia.