String Testing a Typical Machine Train – Part 1

A string test is an important tests undertaken on critical machines prior to installation on-site, and Compass plays an important role here. This article is the first of a two-part series that demonstrates the kind of vibration measurements that are used for evaluating a typical machine train (a completely assembled unit) prior to shipment to site. Part 2 will appear in the next issue of Uptime.

Introduction

Many petrochemical and power projects include large productions machines, such as the propane and mixed refrigerant compressor trains in an LNG plant or the turbo-generator sets in a power plant. These are referred to as machine trains since there are several machines connected in series. These typically consist of the:

- Driver (power turbine, motor, steam turbine, etc.)
- Transmission component (gearbox, coupling, etc.)
- Driven production machine (compressor, generator, pump, fan, extruder, mixer, etc.).

In addition to this, there can be other components mounted on the machine train such as a lubrication system, control system, inter-stage coolers, monitoring system, overspeed governor, shutdown system, etc. All the individual components of a large machine train are generally critical to the process; if just one machine or machine component fails, the entire train is shut down and there is no production.

Each component in the machine train could be manufactured by a different company. Normally each of these is individually tested at the respective factories, but this is not sufficient. To ensure operational integrity of the entire machine train, it is important to test all the machine components assembled together as an entire unit. This is called the “string test”, and is generally performed at the package vendor’s facility prior to the machine train being shipped to the customer’s location.

The system packager typically manufactures one or more of the machine components themselves. If problems are detected, the factory has the necessary facilities to rectify one or more of the individual machines in the train to resolve the problem. This would be difficult to do on-site, especially if there are
several identical machine trains with the same design error, as the site facilities for making major on-site modifications is limited.

The monitoring system that is intended to be installed on the machine train plays a vital role in the actual string test. Firstly, the monitoring system is initially commissioned on the machine train to ensure it is functioning as expected. Then the condition monitoring part of the system is used to test the machine train to ensure the machine train is performing in line with design specifications. Lastly, baselines are established for all the important measurements.

Once the string test is successfully completed, the machine train is shipped to site where it is installed and a site acceptance test is undertaken. This can include a full integration test for communications and a performance test at site conditions, which also utilizes the monitoring system, making it an integral part of the machine throughout the commissioning process.

**Machine train tested**

String tests are undertaken on many different kinds of critical machine trains, but this article we will focus on a steam turbine generator as shown in Figure 3. The components to be tested as an assembled unit include the steam turbine, generator, baseplate, lubrication and control oil system, governor, overspeed trip
device, control systems and the vibration monitoring system. The test facilities typically provide their own in-house test boiler and condenser for the string test as it is neither necessary nor practical to test the actual components that will be installed on-site together with the machine train. The test facilities also include a load bank and a circuit breaker for the string test at load. For large machines the tests are sometimes undertaken at partial load conditions due to limited facilities at the packager factory.

**Test procedure**

There are numerous tests involved to determine if the entire machine train is functioning correctly, but this article will focus on those parts related to vibration measurements. There are two purposes for the vibration measurements:

- Identify any problems with the machines, such as incorrect thermal expansion or misalignment.
- Establish baselines for future monitoring purposes (i.e. the new, clean condition of the machine).

The steam turbine generator will generally operate at the line frequency, but there are a number of other operating points where monitoring is also undertaken. Therefore the test procedure ensures all these different operating speeds and regimes are tested, as shown in Figure 4.

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**Figure 3.** String test of a 40 MW steam turbine (left) and generator (right). An overview of radial and axial vibrations are shown in this particular display for no-load conditions at 3600 RPM.
Test Results

Vibration measurements are normally made on our Compass condition monitoring system at different machine speeds, and plots are used to evaluate the machine condition. The typical plots used are summarized in Table 1, together with a description of what can be detected.

Plots are presented for the governor side of the steam turbine portion of the machine train. Plots for the other steam turbine bearings and the generator will not be shown for simplicity.
### Table 1. Summary of plots used for string testing a steam turbine.

<table>
<thead>
<tr>
<th>Machine state</th>
<th>Plot</th>
<th>Setup</th>
<th>Purpose</th>
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</thead>
<tbody>
<tr>
<td>Steady-state (running)</td>
<td>Vector</td>
<td>1st order µm-PP and phase vs. time polar, 1st order, µm-PP vs. time</td>
<td>Detection of running speed harmonic related faults such as misalignment and unbalance</td>
</tr>
<tr>
<td>Spectrum waterfall</td>
<td>µm-PP vs. orders vs. RPM</td>
<td>Useul for identifying most of the faults associated with a steam turbine, such as unbalance, coupling misalignment, bearing misalignment, oil whirl, looseness, etc.</td>
<td></td>
</tr>
<tr>
<td>Orbit and dual time signal</td>
<td>X-Y µm vs. time</td>
<td>Identifying non-stationary vibration, impacts, rubs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>X-Y µm, unfiltered</td>
<td>Especially useful for identifying bearing stability, oil whirl, runout</td>
<td></td>
</tr>
<tr>
<td></td>
<td>X-Y µm, 1x filtered</td>
<td>Identifying unbalance and misalignment</td>
<td></td>
</tr>
<tr>
<td>Transient speed (run up, coast down)</td>
<td>Shaft centre-line</td>
<td>X, Y linear trend, DC Voltₓ, DC Voltᵧ vs. RPM</td>
<td>Identifying misalignment and shaft preloading</td>
</tr>
<tr>
<td></td>
<td></td>
<td>X, Y circular, DC Voltₓ, DC Voltᵧ vs. RPM</td>
<td></td>
</tr>
<tr>
<td>Bode</td>
<td>1st order µm-PP and phase vs. RPM</td>
<td>Identifying resonance, unbalance, damping, etc.</td>
<td></td>
</tr>
<tr>
<td>Spectrum waterfall</td>
<td>µm-PP vs. freq. vs. RPM</td>
<td>Same as for spectrum waterfall for orders, but well suited for visualization of sub-harmonic symptoms like oil whirl</td>
<td></td>
</tr>
<tr>
<td></td>
<td>µm-PP vs. orders vs. RPM</td>
<td>Identifying resonance and all other faults mentioned in steady state condition</td>
<td></td>
</tr>
<tr>
<td>All machine states</td>
<td>Axial</td>
<td></td>
<td>Observing the influence of speed, load and other operating conditions on the axial position of the rotor during the complete string test period</td>
</tr>
<tr>
<td></td>
<td>Radial</td>
<td>1Hz/10Hz-1kHz RMS</td>
<td></td>
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<tr>
<td>Overview</td>
<td>Figure 2</td>
<td>For judging the severity of the overall vibration levels of the axial and radial vibration measurements and for comparing them in a single glance</td>
<td></td>
</tr>
</tbody>
</table>
In the next issue of Uptime, Part 2 in this series will present the actual plots during the string test.

**Acknowledgement**
We would like to thank Ajayan Madhavan from our International Service Organization for his contribution in making this article. The string test is one of many added value services that service engineers offer from our world-wide network of sales & support centres. Contact your local sales representative for more information on this and other services.

Contact info@bkvibro.com if you would like the complete article as a single PDF document.
String Testing a Typical Machine Train – Part 2

A string test is one of the important tests undertaken on critical machines prior to installation on-site, and Compass plays an important role in this testing process. This article is the second part of a two-part series that graphically demonstrates the kind of vibration measurements that are used for evaluating a typical machine train, as a completely assembled unit, prior to shipment to site. Part 1 appeared in the previous issue of Uptime (www.bkvibro.com).

Introduction
Part 1 of this article provided background information on a typical string test for a steam turbine generator machine train. In this issue, the final part of the article, examples of the actual plots used during the string test are presented.

Test Results (cont. from Part 1)
Plots are shown for the governor side of the steam turbine portion of the machine train.

Figure 4. Axial position (top) and radial vibration (bottom). These critical measurements are monitored across all machine states during the complete string test period. The axial displacement measurement is especially important since a thrust bearing rub could result in catastrophic damage to the machine within a few short moments.
Figure 5. Vector plot (1x filtered) during running. The first order vibration magnitude and phase at running speed provides a useful method for comparing the phase angle at different measurement points.

Figure 6. Spectrum waterfall plot (order scale) during running. This plot can help identify faults in machine components that are synchronously related to the running speed during steady state operation.
Figure 7. **Orbit plot (unfiltered) during running.** The orbit represents the AC dynamic motion of the shaft within the journal bearing. While the Shaft centreline plot (Figure 9) gives an idea about shaft clearances in relation to the fixed part of the bearing, the orbit gives a better picture about the actual motion of the shaft. The plot shown was recorded unfiltered, which means all movement and running speed harmonics are displayed. The individual time signals from each sensor used to construct the orbit are also displayed for providing another graphical method of viewing all influences.

Figure 8. **Orbit plot (1x filtered) during running.** This orbit plot is similar to that shown in Figure 7, except this one has been filtered to only show the shaft motion at running speed. This makes it easier to identify unbalance, misalignment, overloading, etc. The orbit plots can also be filtered to sub-harmonics to identify bearing stability problems, or other harmonics to detect various problems such as looseness.
Figure 10. **Bode and polar plot during coast down.** These plots display order magnitude and phase as a function of rotational speed or frequency. These are important tools in transient speed analysis (analysing non-stationary signals). The Bode plot is used to identify, confirm or monitor changes in the shaft resonant frequencies, or to examine the rotor dynamics on an order basis. It also enables changes in the damping properties of the shaft to be identified, caused by shaft cracks, etc. The polar plot presents the same information in polar coordinates.
Figure 11. **Spectrum waterfall plot (frequency scale) during coast down.** This plot is similar to that in Figure 6, except this is monitored during transient speed conditions and with respect to frequency. In addition to identifying the faults that can be detected during running speed, transient phenomena, such as passing critical speeds, can also be detected.

Figure 12. **Spectrum waterfall plot (order scale) during coast down.** This plot is similar to that shown in Figure 11, except it is based on synchronous data (harmonics of the running speed) recorded during transient speed conditions. This plot can be used to detect changes in the running speed harmonics for the duration of the transient machine state.
Conclusion
The comprehensive string testing process is an important part of machine commissioning and ensures the operational integrity of the machine train at the packager’s facility where remedial actions can be performed easily, before shipping to site. This ensures a smooth on-site commissioning process and operation of the machine. Compass, together with Brüel & Kjær Vibro’s service team play an important role in this process by monitoring all the important machine train vibration parameters and issuing a report that typically includes a list of potential failure modes that have been detected and recommendations to remedy these. For a few string tests, a consultant is contracted by the customer to evaluate the test information that we collect instead of us. In such a case it is the consultant who decides what is acceptable and if repairs or modifications are necessary. This is also the case for the example given in this article. We can report, however, that the string test revealed the machine to be operating within the design parameters specified by the customer.

Some test conclusions specific to the string test described in this article, as an example, are:

- The overall vibration level on the steam turbine was less than 20 μm peak-peak, even at maximum speed; well within the customer acceptance level of 25mm um peak-peak.
- There was no evidence of non-synchronous symptoms in the frequency spectrum plots (acceptance limit is 6 μm peak-peak).

Acknowledgement
We would like to thank Ajayan Madhavan from our international services organisation for his contribution in making this article. String tests are one of many value added services provided by our qualified service engineers located across the global network of Brüel & Kjaer Vibro sales and support centres. Contact your local sales representative for more information on this and other services.

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