ABSTRACT
This paper presents an experimental program which investigates how turning gear operation influences thermal distortion and start quality of a power generation combustion turbine. It presents results which quantify how taking a turbine off turning gear under hot or cold conditions influences rotor distortion. It further shows how time on turning gear reduces rotor eccentricity. This paper uses available unbalanced sensitivity data and rotor eccentricity measured on turning gear to estimate the margin for vibration trip on start-up. The paper discusses how rotor eccentricity data can be independently obtained with limited additional non-intrusive instrumentation, and how the data can help guide turning gear operational strategies for different utility load profiles.

INTRODUCTION
Turning Gear Operation
After shutdown, top-to-bottom thermal gradients, driven by natural convection, of over 150°F will develop in combustion turbine casings. Experience has shown these gradients cause rotor eccentricities that render the unit incapable of starting due to high vibration. For this reason, large turbo-generators have almost always required turning gear to keep the unit in a "ready to start" condition. After a combustion turbine and it's rotor cool to ambient temperatures, the benefit of continuing turning gear is uncertain.

Most modern combustion turbines achieve restraints at blade attachments by centrifugal forces. While on turning gear some blade attachments are loose and allow fretting and wear to occur as gravity causes the blades to move in their slots. Thus, whenever the turbine is on gear, fretting damage accumulates at the blade roots, shrouds and retention features, particularly for heavy blades. Eventually the accumulated damage can affect unit availability and repair costs. At the same time continuous turning gear operation minimizes the gravitational bow or the thermal bow of daily temperature variation which can cause vibration trips on start-up.

A reliable strategy to minimize time on gear without sacrificing readiness to start could allow utilities to mitigate down time and repair costs. Turbine users must be comfortable that the approach they implement is reliable and fits their philosophy of operation. In practice, utility approaches to this conflicting demand vary depending upon experiences and economic perceptions. Some utilities use no turning gear once the turbine is cool assuming that the turbine will almost always get to speed at least on the second try. Many utilities elect to leave all power generation turbines continuously on gear when not at speed. A few turbine users elect a middle ground position and operate the turning gear one hour every shift. There is an unfulfilled need for documented, quantitative data to guide combustion turbine operators in selecting a turning gear strategy. This paper presents and interprets data which shows how temporary eccentricity or rotor bow develops when a unit is off gear and how the bow reduces when the unit goes back on gear.

INSTRUMENTATION SYSTEMS
A recent experimental program sponsored by the Electric Power Research Institute (EPRI) (Smalley and Simmons, 1988) provides a significant body of information on turning gear operation. In this study, several measurement systems were designed to define casing distortion, bearing lift, and rotor deflections (Figure 1). Deflection measurement instrumentation (Simmons, et al, 1992a) was specifically selected and positioned to quantify bow and ovalization of the casing. To measure rotor motions, proximity probes were installed at locations close to the bearings and coupling, and at two compressor blade tip locations mid-span between the bearings (Simmons, et al, 1992b). In addition, linear variable differential transformers (LVDT's) were installed to record rotor and cylinder axial growth and surface-mounted thermocouples were positioned around the case to quantify temperature gradients.

Data recorded from a representative W501AA combustion turbine at the Baltimore Gas and Electric Perryman Station, documents casing distortion, top-to-bottom thermal gradients, and rotor eccentricity during steady state operation and after shutdown. In addition, bearing vibratory excursions are recorded during start-up.

To assess the potential for blade rubbing, a system to measure changes in blade tip clearance was installed at compressor stages four and nine. Developing and mounting sensors that would measure clearances up to 0.25 inches for a...
blade tip target no more than 0.3 inches wide moving at velocities up to 1100 ft/sec presented a challenge. To meet the specified requirements, custom eddy current proximity probes were developed by Bently Nevada Corporation. To accommodate the blade tip target size and velocity, the system was designed with an ultra high frequency carrier and 16 mm probes. To minimize signal absorption, 1-inch diameter holes were bored through the turbine case and the probe cases (Figure 2) were designed to fill in the void. A high temperature thermosetting plastic was used to accommodate the 415°F maximum temperature expected. The mounting brackets were designed to recess the probe tip about 0.010 below the inner surface of the casing. The system has operated successfully for over two years with no need for extensive maintenance.

An electronic peak hold detector (shown schematically in Figure 3) captures the highest value of the voltage pulse as each blade passes the probes. This value represents the point of closest approach between blade and probe. The peak hold readings of all blade pulses within one revolution constitutes a series of blade tip clearances. These values are evaluated by Fourier analyses to extract condensed information and trend rotor vibration, bow eccentricity, and casing distortion. For the purposes of this program, each probe signal is evaluated for first and zeroth order Fourier components of rotation. The first order component is related to rotor eccentricity (on turning gear) or to synchronous rotor vibration (at speed). Inspection of the fourth stage blade tip signals in Figure 4 reveals a peak-to-peak variation of 38 mils that is more consistent with random blade length variation than with rotor dynamics. It is recognized that this length variation will corrupt the dynamic signal information in much the same way that "electrical run out" corrupts conventional shaft proximity signals and that eliminating this substantial noise source requires subtracting a well averaged run out reference vector from all subsequent data.
Reliability of the measurement and data analysis system is demonstrated by overall signal repeatability errors of less than 0.5\% from one revolution to the next for any given probe and less than 5\% resultant once-per-revolution error between any two probes shown in Figure 4.

**COLD ROTOR ECCENTRICITY**

The development of bow with the turbine off turning gear was measured by probes at the blade tips, bearings and couplings. Figure 5 presents the once-per-revolution rotor excursion trends at the ninth stage blade after a cold rotor was taken off turning gear for 8 hours. The rotor was on gear for over 1000 hours since its last firing. As can be seen, a rotor bow of 1.8 mils clearly develops near rotor mid-span.

Figure 6 presents the results of a series of similar tests in which a cold rotor was taken off gear for periods between 1/2 hour and 64 hours. The general trend is for eccentricity to increase with time. The maximum eccentricity at the ninth stage of about 3 mils was recorded after one 16 hour test. The figure indicates considerable scatter and a repeat of the 16 hour test resulted in an eccentricity of less than 2 mils. No higher eccentricities were observed out to the maximum tested time of 64 hours. By combining fourth and ninth stage blade eccentricity with eccentricities at all installed shaft probes, a gravity sag mode shape (Figure 7) is obtained which appears to reasonably match the expected first bending critical speed mode shape. Maximum cold rotor deflection occurs very near to the ninth stage and a working maximum eccentricity of about 3 mils could be inferred from these tests.

Revisiting Figure 5 shows that the rotor recovered from gravity sag rather quickly once back on gear. Analysis of representative data implies a recovery function of:

\[
\text{ecc}(t) = 1.782 - 0.497 \cdot t + 0.0557 \cdot t^2 - 0.003 \cdot t^3 + \ldots
\]  

(1)

where \( t \) is hours from shutdown

Practically, gravity sag eccentricity reduces by a factor of 2 about every 2 hours or down to a completely negligible amount in no more than 6 hours.

Installation of blade tip sensors is not practical for production utility combustion turbines. The OEM installed bearing probes are readily available, but present a less certain basis for making a ready to start decision due to their low eccentricity (only about 1/8 that at mid-span) and about twice the relative noise ratio (Figure 8). Based on the test experience described in this paper, a reasonable alternative would be a shaft proximity probe added at the coupling (Figure 9). By properly conditioning to subtract base line run out, these sensors measure approximately 1/4 of the blade tip excursion (Figure 10). Considering that shaft slope information also becomes available when both coupling and bearing probes are used, a units predisposition to start based on mid-span eccentricity could be determined with greater assurance.

**HOT ROTOR ECCENTRICITY**

There are situations when the turning gear must be stopped while the turbine is still hot. Such cases usually involve balancing, where return to service time is critical and the rotor cannot be allowed to cool completely. Furthermore, emergency situations might arise such as loss of bearing lubricant or lubricant fueled fire. Figure 11 presents the air temperature trends at the exhaust section. These values should be fairly representative of internal turbine shell temperatures. As can be seen, the rotor environment quickly reaches a temperature differential of about 170°F within 2 hours after shutdown and...
maintains a differential of over 50°F for at least 21 hours. The rotor itself will develop a gradient top-to-bottom when exposed to this environment. However, the high conductivity of steel combined with convective heat transfer resistance will limit the metal temperature differential to substantially less than the air differential.

During the investigation the instrumented unit was taken off gear once while hot, about 21 hours after shutdown for about 3 hours of repairs. The rotor eccentricity that developed was over 10 times that due to gravity sag, as shown in Figure 12. Based

on a simply supported 275-inch long rotor, 33-inches in diameter, the maximum 22 mils observed would result from a 13°F differential top-to-bottom; somewhat less than the 50°F observed in Figure 11. Figure 12 shows that observable eccentricities at the bearing probes represent only about 1/10th to 1/5th the maximum eccentricity at close clearance locations, such as, the compressor blade tips.

Figure 12 also shows that much like gravity sag, thermal bow recovers quickly. Thermal eccentricity reduces by a factor of 2 about every 2 hours and down to less than one mil in no more than 8 hours. The recovery function can be represented by:

\[
ecc(t) = 20.863 - 7.884 \cdot t + 1.314 \cdot t^2 - 0.114 \cdot t^3 + \ldots
\]

TURNING GEAR STRATEGY

To develop turning gear strategies which minimize wear, keep the turbine "ready to start" and allow reasonable operator work schedules, each utility will need to consider their own particular operation. Heat rate, dispatch priorities, penalties, seasonal and daily peaks help define a unit's "readiness to start" requirements. Operator work schedules, proximity to other facilities and personnel, and overhaul and maintenance costs are all cost constraints which must be considered when trying to meet these requirements. The data presented in this paper, combined with these requirements and constraints, supports development of workable strategies which will reduce turning gear wear, and minimize damage to blade retention mechanisms.
Turning gear is used to keep rotor eccentricity low and to enable rapid start-up with minimal vibration. Two primary sources of rotor eccentricity are:

1) Air stratification within the turbine shell which can thermally deform a stationary rotor during cool-down.

2) Gravity sag that develops with time or daily thermal variations.

To manage the first source requires keeping the turbine on turning gear until the entire turbine is sufficiently cold. Figure 13 shows that following shutdown, approximately 72 hours on turning gear are required for the turbine casing and rotor to return to a condition where tip clearances are stable. Normally, the turbine should not be stopped before that time has elapsed. For a unit which runs frequently and regularly with typically less than 72 hours between starts, most of all turning gear is productive and continuous turning gear operation is a reasonable strategy. However, units that are run only occasionally or only over short seasons each year can benefit from a reduced turning gear schedule. Figure 14 shows how "non-productive" turning gear time varies with the number of starts per month. The basis is that 12 hours of turning gear before the run and 72 hours afterwards are productive - either ensuring readiness to start or ensuring uniform cool-down. The assumed run time itself is 3 hours. Outside of this 87 hour window per run, turning gear time is unproductive except to maintain "readiness to start" and to guard against the second source of eccentricity. If the eccentricity can be maintained at or below an acceptable level without continuous turning gear, then the amount of unproductive time on gear can be reduced.

The ability of the turbine to start without tripping on transient high vibration defines "acceptable eccentricity." Temporary rotor eccentricity is a form of unbalance, which adds vectorially to the rotor's residual unbalance. The gravity sag will assume a random direction relative to imbalance. So when allowed to rise above the acceptable level, rotor eccentricity will cause intermittent failures to start, as temporary eccentricity and unbalance align or mis-align at random. Table 1 makes the worst case assumptions that unbalance and temporary eccentricity align. In this table, residual unbalance is represented by maximum vibration at the first critical on start-up. The difference between the maximum level and the allowable limit is the margin for gravity sag or temporary eccentricity. If start-up vibration is at its limit (the first example in Table 1), then there is no margin. In the remaining examples, each with progressively less residual vibration (and unbalance), there is increasing tolerance for temporary eccentricity. In this table, vibrations due to eccentricity are estimated by multiplying effective rotor modal mass, times the eccentricity, times a typical influence coefficient (Gunter, 1986) used for rotor balancing.

Table 1. Allowable Vibration and Run-out (Eccentricity) for Safe Starts.

<table>
<thead>
<tr>
<th>Residual Unbalance</th>
<th>Allowable Eccentricity (MILS TIR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration Bearing 5</td>
<td>9th Blade Coupling Bearing 4</td>
</tr>
<tr>
<td>MILS P-P on Start-up</td>
<td></td>
</tr>
<tr>
<td>8.0 (limit)</td>
<td>0.0 0.0 0.0</td>
</tr>
<tr>
<td>5.4</td>
<td>1.0 0.2 0.1</td>
</tr>
<tr>
<td>4.1</td>
<td>1.5 0.3 0.15</td>
</tr>
<tr>
<td>2.8</td>
<td>2.0 0.4 0.2</td>
</tr>
</tbody>
</table>
This table may be used to estimate the allowable eccentricity, depending on typical vibration of bearing 5 (turbine end bearing). If for example, the vibration at bearing 5 is to reasonably achievable 4.1 mils when passing through the first critical, then the allowable eccentricity at the 9th row is 1.5 mils. Figure 6 shows that 1.5 mils of eccentricity can develop within 5 hours after a cold rotor is taken off turning gear, but on average approximately 24 hours is required to develop this much eccentricity. Figure 5 shows that 4 hours on turning gear will reduce the 1.8 mils eccentricity at the blades to less than 0.4 mils. If carried on continuously with a timing mechanism, then a turning gear schedule of 4 hours on and 4 hours off should maintain this turbine with these unbalance conditions in a "ready to start" attitude at all times yet reduce unproductive turning gear time and associated wear by a factor of two. The on-off cycle period will have to be shortened for units that are marginally balanced, but can be increased for units that are well balanced. An automatic timing controller might provide further reduction of unproductive turning gear time especially if some period can be identified when the turbine is seldom needed: e.g., the first four hours of the morning shift.

An effective strategy is also needed to control the effects of bow when balancing; here there is often pressure to make a trial run as soon as possible after putting in each balance shot. However, if the turbine is started too soon after returning to turning gear, then the resulting balance data will probably be misleading and cause more delay than the time saved by rushing the roll out period. Excessive bowing that might occur when a very hot rotor is removed from gear too soon after turbine shutdown or when the turbine is left off gear too long will likely cause the unit to trip on start-up. Figure 12 makes it clear that temporary bow quickly develops to a substantial level when the bearing 4 journal and at the generator/turbine coupling is hot. Also, a number of hours on gear are necessary to minimize its effect. Ideally 8 hours or more are needed to reduce the observed 22 mils to a safe condition.

An alternate turning gear strategy is to monitor shaft run-out during rotor bow recovery from gravity sag and thermal distortion as shown in Figures 5 and 12, respectively. While the blade tip sensors are the most accurate indications of maximum eccentricity, their installation difficulty make it unlikely that they will become popular for the average utility turbine. A more practical approach is to rely upon indirect eccentricity indications from shaft proximity sensors. Fortunately, the data in Figure 7 confirms a nearly linear relationship between rotor mid-span eccentricity and the eccentricity measured with proximity probes at the bearings and coupling.

The major corrupting factor in all shaft proximity measurements is the electrical and mechanical run-out errors inherent in the shaft surface. To minimize these errors, the once-per-revolution vector component must be characterized at a steady base line condition and then subtracted vectorially from all subsequent signals. As implied by Figure 8, the desired precision for eccentricity measurements at the bearing 4 journal is in the order of 0.1 mils. An acceptable precision at the coupling could be approximately twice this value. Run-out errors of combustion turbine journals (typically 1.5 mils) will often overwhelm the rotor bow deflections such that these readings would be quite misleading if the baseline vector is not subtracted. Reduction of bearing run-out to within 0.05 mils of normal run-out would likely be a satisfactory starting condition.

Unfortunately, many commercial monitoring systems installed on combustion turbines cannot operate in the 3 rpm turning gear speed range due to data storage and handling problems for sample rates consistent with operating speed (3600 rpm). In order to address the total range in frequencies, a shifting in sample rate is required. An EPRI program to automatically diagnose start-up faults as reported by Baldwin et al, (1992) describes a PC based data acquisition and analysis system with digital control of sample rates, and anti-aliases filter cutoff frequency proportional to rotor speed. Rotor run-out is an important diagnostic parameter of this program.

**SUMMARY**

This research program conducted for the Electric Power Research Institute provides reliable data on the influence of turning gear on the control of rotor eccentricity for the W501AA combustion turbine. Specifically, the recorded data reveals:

- the development of gravity sag of a cold rotor as a function of time off gear
- the recovery of cold rotor gravity sag as a function of time on gear
- the development of thermal bow of a hot rotor as a function of time off gear
- the recovery of hot rotor thermal bow as a function of time on gear
- the correspondence of temporary unbalance caused by rotor bow to run-out measurements at the bearing journal and at the generator/turbine coupling

Similar combustion turbine models should exhibit similar eccentricity behavior.

Procedures for developing strategies to optimally operate the turning gear are put forth to address excessive blade root wear issues and hot turbine balance runs.

**ACKNOWLEDGEMENTS**

Appreciation is extended to the Electric Power Research Institute for sponsoring the research program and releasing the data for publication. Appreciation is also extended to Mr. Wayne Seifert, BG&E Plant Manager, for permitting Perryman Station to be used as the utility site host.

**REFERENCES**


