The Morton Effect

and Light Rubs in Rotating Machinery

Synchronous (1X) vibration is typically present on all types of rotating machinery. Common causes or sources of this vibration component include mass unbalance, mechanical bows, thermal bows, shaft surface runout, and rubs. When vibration levels from one of these sources becomes unacceptably high, corrective action must be undertaken.

In some cases, the synchronous vibration levels do not simply increase and remain at a constant amplitude and phase angle. Instead, significant variations of the 1X vectors occur where the amplitude may assume a cyclic trend that alternately increases and decreases while the phase changes as well. The plot types typically used to observe this activity are trend files (1X amplitude and phase versus time), polar plots, and shaft orbits. These allow the diagnostician to determine, among other things, the magnitude and period of the cycles. This article discusses two different mechanisms whereby these 1X amplitude and phase variations can be observed: light rubs and a more recently described phenomenon known as the Morton Effect.

Mechanism #1 – Light Rubs

There are a variety of rubs that can occur in machinery, with different rub locations (seals, bearings, etc.), different initiating conditions, and different rub classifications (full annular, partial, bouncing, etc.). Here, we confine our discussion to light rubs that create a thermal bow condition. It is these types of rubs that often result in a modulating synchronous vibration response.

The friction caused by light rubbing on a rotor gives rise to localized heating (a so-called rotor “hot spot”) that is not uniformly distributed around the shaft circumference. This causes the shaft to expand longitudinally in a non-uniform manner, resulting in a bow (Figure 1).

While one might reasonably conclude that the ensuing shaft bow acts as a positive feedback mechanism, causing the rotor to rub even more, heat up even more, and subsequently bow even more, there is actually another mechanism at work in the case of light rubbing that counteracts this. In practice, the conditions that gave rise to the initial rub are frequently related to loading conditions, such as partial load operation, transient changes in load, or operation at higher-than-normal capacities. As a result of the loading, thermal distortion occurs in the machine and a rub ensues. However, as the load changes or the machine assumes thermal equilibrium in the new load condition, clearances open, and the rub stops. The rotor hot spot then cools, the bow relaxes, and the vibration decreases. When the load changes again, a rub is initiated and the cycle repeats itself. In such situations, the amplitude trend will exhibit a cyclic increasing/decreasing behavior. If the rub initiating mechanism is somewhat periodic, as in a load change that occurs at regular intervals, the periodicity in the amplitude trend may be regular as well. In cases where the initiating mechanism is not periodic, the amplitude trend will show variations, but there will be

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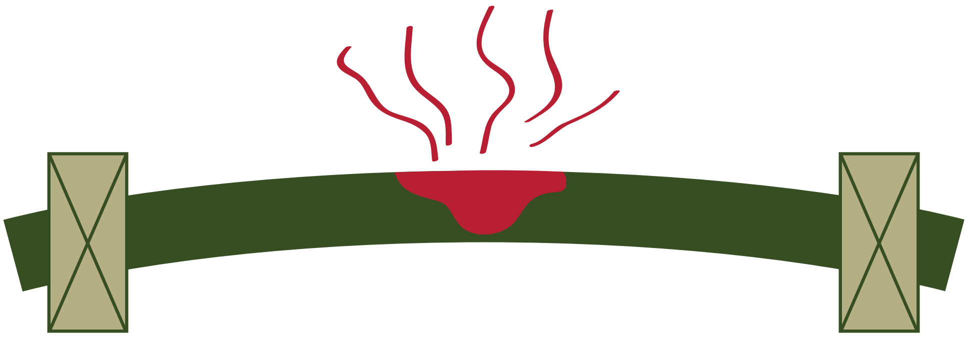
Figure 1 – Rubbing results in localized hot spots on the rotor where contact is occurring. This causes one side of the rotor to expand longitudinally more than the other, resulting in rotor bow.

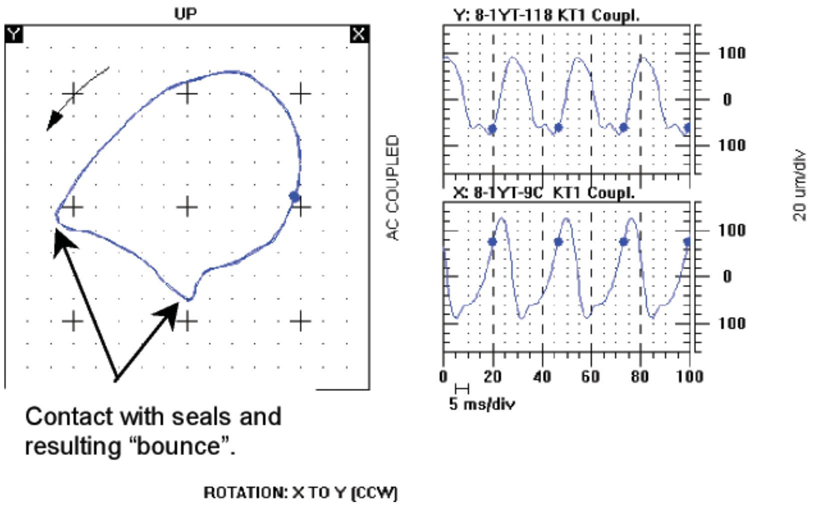


no repeatable periodicity. However, the diagnostician must use caution because the response from the rub mechanism is highly non-linear and periodicity may not always be readily observable, even when the initiating mechanism itself is highly regular. This is discussed in more detail later in this article.

Several diagnostic plots are useful when diagnosing a rub. Chief among these is the shaft orbit plot. Although not always the case, shaft orbit presentations can give quite dramatic indication of a rub as evidenced by flat spots on portions of the orbit where contact is occurring and orbital motion is constrained. Figure 2 shows an orbit obtained from a machine experiencing a seal rub. One can readily see the portion of the orbit where the rub is occurring as the shaft “bounces” away from the contact location. Visual examination of the seals later confirmed the diagnosis, as rub tracks were evident on both the shaft and the seal.

[Editor’s Note: If Figure 2 looks familiar, that’s because it also appears in the case history on pages 34–43 in this issue of ORBIT. Please refer to that article for photographs of both the shaft and seal surfaces, which were taken during visual inspection to confirm that a rub was indeed occurring.]

Figure 2 – Shaft orbit plot from a mechanical drive steam turbine experiencing a seal rub.



Contact with seals and resulting “bounce”.

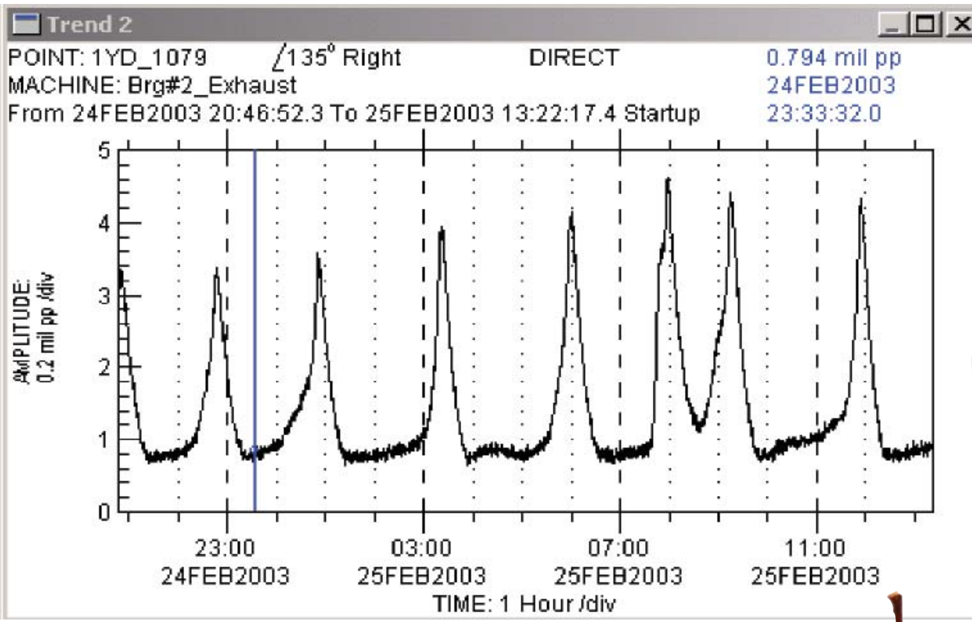
ROTATION: X TO Y (CCW)

While rubbing conditions will sometimes be readily apparent from the shaft orbit plots, particularly for moderate to heavy rubs, the indications in the orbit from light rub conditions may be more subtle. Other plot types are thus useful.

A multivariable trend plot that allows the diagnostician to examine vibration amplitude and load conditions simultaneously can be particularly helpful when it is suspected that a rub is occurring and is being initiated by load conditions. Correlations between amplitude (and phase) changes and load changes can be easily observed using this plot type. If an increase in vibration is always accompanied by a transient change in load conditions, or occurs only when the machine is in certain load conditions (such as partial load), a light rub and corresponding thermal bow is a strong possibility.

Figure 3 was obtained during a field machinery diagnostics job conducted by the author and shows the amplitude trend plot collected from a gas turbine experiencing a light rub during steady-state base load conditions. The trend plot shows the classic cyclic behavior discussed earlier, where the amplitude alternately increases and then decreases. In this instance, however, the rub-initiating mechanism turned out to be unrelated to load. It was found that the machine had a leaky oil seal. As the oil leaked, it would slowly heat until it became hardened (i.e., formed coke) and continue to build up until a rub ensued. The coke would be abraded away through the rubbing action until the rub disappeared, but the leaking oil would form more coke and the cycle would repeat itself.

Figure 3 – Trend plot showing cyclic amplitude oscillations resulting from a light rub. The vibration reaches a peak approximately every 2-3 hours and then temporarily subsides again.



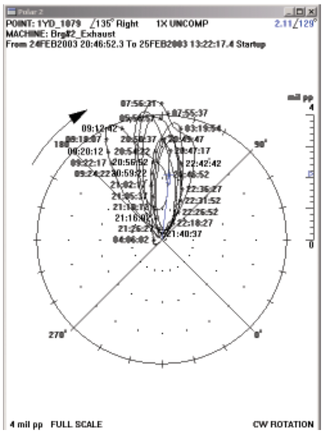
POINT: 1YD_1079 ∠135° Right DIRECT 0.794 mil pp
MACHINE: Brg#2_Exhaust 24FEB2003
From 24FEB2003 20:46:52.3 To 25FEB2003 13:22:17.4 Startup 23:33:32.0

Because rub is a non-linear response mechanism, it is important to note that changes in phase and amplitude may not be repeatable from one cycle of the oscillation to the next. The rub may be more severe, less severe, or absent entirely—as can be the case when the rub has sufficiently eroded the contacting locations to permanently alter clearances. Nor will the peaks and valleys of the amplitude trends be perfectly periodic, even if the initiating conditions (such as load changes) are themselves perfectly periodic.

The polar plot of Figure 4 illustrates this non-linearity quite dramatically and is taken from the same machine and proximity probe as the trend plot of Figure 3. The "loops" in the polar plot are indicative of changes in both amplitude and phase, but notice that these changes do not "retrace" themselves from one cycle to the next.

[Editor's Note: Why does a light rub result in not just amplitude changes, but continually changing phase as well? The answer to this question will appear in the next issue of ORBIT magazine.]

Figure 4 – Polar plot from the same probe location as Figure 3, showing non-linear (non-repeatable) vibration and phase response. Such response is typical of a light rub.



Mechanism #2 – Journal Thermal Gradients (Morton Effect)

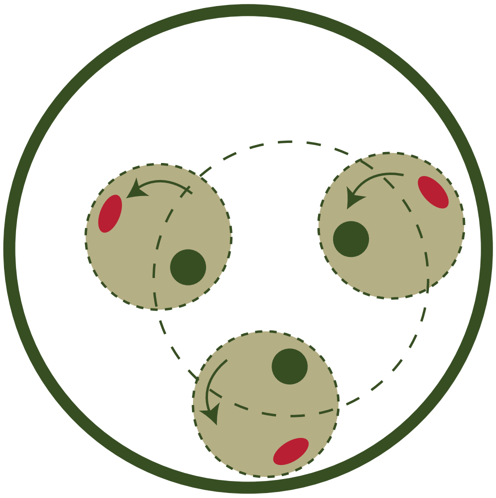
Another phenomenon can occur in rotating machinery and give data similar to that resulting from a light rub. Inspection of the machinery affected by this condition will show that no rub is in fact occurring. Instead, it has been postulated that temperature gradients ("hot spots") occur on the shaft's journal surface as the result of high viscous shear stress in the bearing lubricant. Consequently, the shaft bows just as if a hot spot occurred from a rub, and a very similar vibration response is observed.

This mechanism was first described in a 1994 paper by P.S. Keogh and P.G. Morton, and has subsequently become known as the "Morton Effect". It generally occurs only under very specific conditions; in particular, on machines incorporating an overhung rotor design and which are heavily loaded. Here, only a brief overview of the so-called Morton Effect is provided so the reader can be familiar with the phenomenon should it be encountered in practice. The reader is strongly encouraged to obtain additional information on the Morton Effect and its underlying hypotheses using the references at the end of this article.

To understand how the Morton Effect occurs, refer to Figure 5. Here, it is assumed that the dominant force acting on the machine is residual unbalance, and that the bearing stiffness is symmetrical about the centerline. This results in predominantly synchronous (1X) vibration with a largely circular orbit as the shaft vibrates within its bearing clearance. Vibration of this form orients the rotor surface in the same position each time it rotates as long as loading and speed remain constant. This means that the same segment of the rotor's circumference will always be subject to the minimum clearance (the red spot on the rotor in Figure 5) while another segment of the rotor's circumference will always be subject to the maximum clearance (the black spot on the rotor in Figure 5). Although this condition creates a thermal gradient instead of a uniform heat distribution about the rotor's circumference, unless the shear stresses are suitably large, the gradient will not be large enough to result in a shaft bow. However, when the shear stresses are sufficiently large, the heating effect is appreciable and the shaft bows, just as if a rub was occurring at the location of minimum oil film thickness. As a result, the 1X vibration amplitude increases.

As the effect (i.e., a hot spot on the shaft) of this mechanism is quite similar to that of a light rub, it is not surprising that the vibration response may be quite similar as well. However, because the Morton Effect occurs inside the bearing area where lubricant is present to provide cooling, the thermal rate of change tends to be more linear than that which occurs under true rub conditions. As such, the vibration pattern is more repeatable from cycle to cycle and typically results in a polar plot with one of two distinct patterns:

Figure 5 – The Morton Effect. Under certain conditions, the shear stresses in the bearing lubricant can be sufficiently large to create localized heating on the rotor, causing it to bow.



1. Repeating Loops

When the machine is under highly steady-state conditions without even minor variations in speed or load, the shaft attitude angle (i.e., location of the shaft on the supporting oil-film wedge in the bearing) remains highly steady as well. Consequently, the “hot spot” on the shaft remains in the same location. As the machine undergoes its cyclic changes in amplitude and phase due to the repetitions of the shaft bowing and then relaxing, the stationery location of the hot spot results in changes in amplitude and phase that are so repeatable as to trace nearly the same pattern on the polar plot from one cycle to the next. This is shown in Figure 6. Compare this response with the non-linearity (non-repeatability) of the response for an actual light rub condition as shown in Figure 4.

2. “Spiral” Vibration

When the machine is experiencing small fluctations in speed and/or load, the shaft attitude angle will experience small changes as well, causing the shaft hot spot to shift slightly. This moving hot spot gives rise to spiral pattern in the polar plot as the shaft bows and relaxes cyclically. Figure 7 shows a polar plot from the same proximity probe as Figure 6, but with the machine undergoing slight changes in speed/load. Now, the loops no longer exactly retrace themselves, but instead appear as expanding/contracting spirals.

Although the Morton Effect is far less common than light rubbing in machinery, there are certain indications that can lead the diagnostician to suspect this mechanism when other, more common, malfunctions have been ruled out:

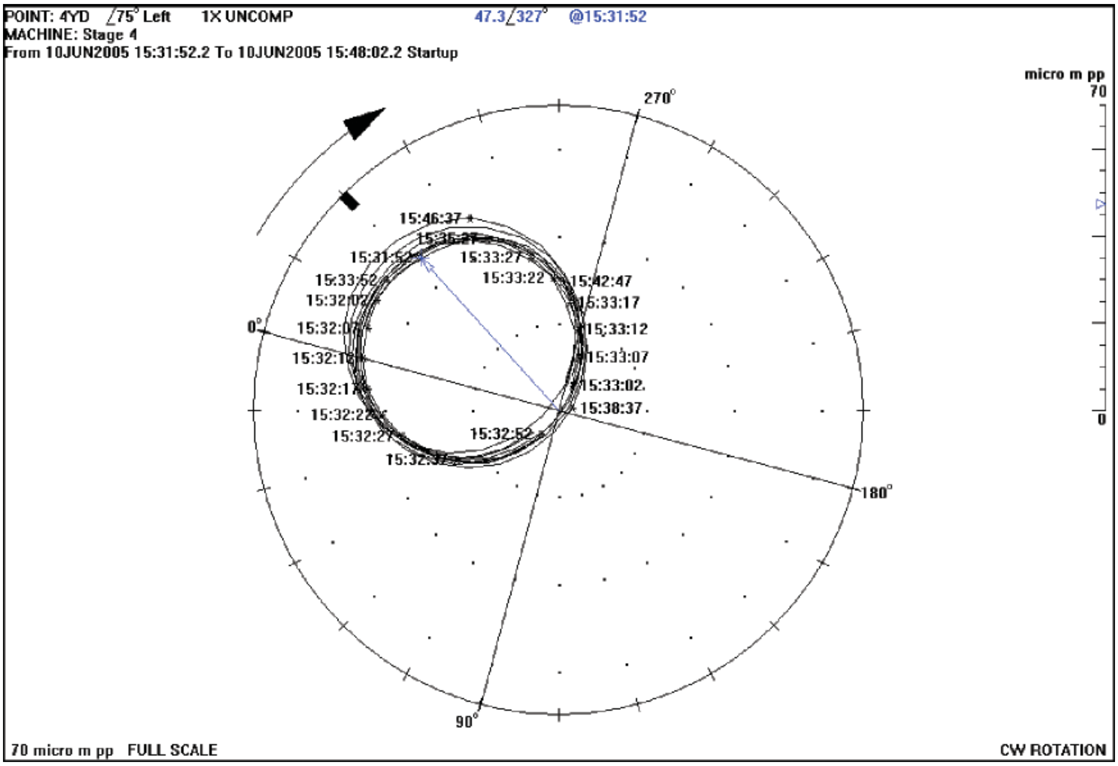
A. When the machine under investigation incorporates an overhung design and is heavily loaded.

B. When the 1X amplitude and phase variations appear to be quite repeatable and smooth from one cycle to the next—far more repeatable than would be expected from a rub. These will appear either as re-traced loops (Figure 6) or as spirals (Figure 7).

C. When visual inspection of the machine gives no evidence of a rub.

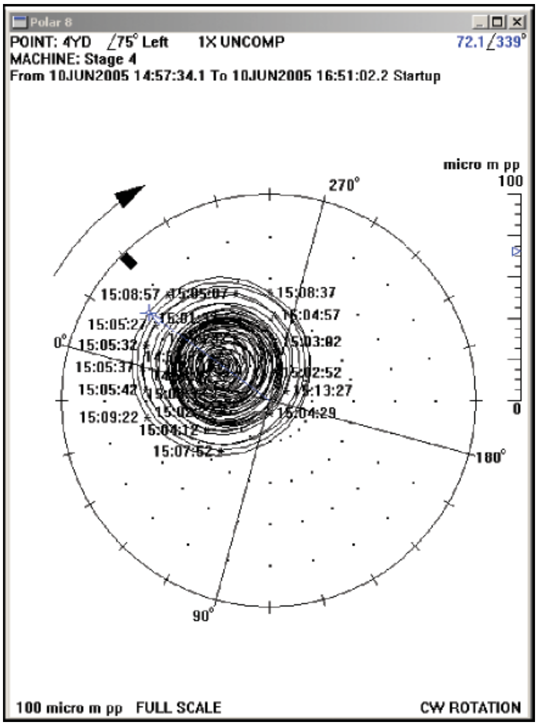
D. When changes in the lube oil temperature affect the cyclic vibration periodicity and amplitude.

Figure 6 – Polar plot showing evidence of the Morton Effect as noted by the highly repeatable changes in amplitude and phase during each limit cycle.



> “ALTHOUGH THE MORTON EFFECT IS FAR LESS COMMON THAN LIGHT RUBBING IN MACHINERY, THERE ARE CERTAIN INDICATIONS THAT CAN LEAD THE DIAGNOSTICIAN TO SUSPECT THIS MECHANISM WHEN OTHER, MORE COMMON, MALFUNCTIONS HAVE BEEN RULED OUT.”

Figure 7 – Polar plot of same probe as Figure 6, but with machine undergoing slight variations in speed/load, leading to spiral vibration patterns rather than the repeatable looping of Figure 6.

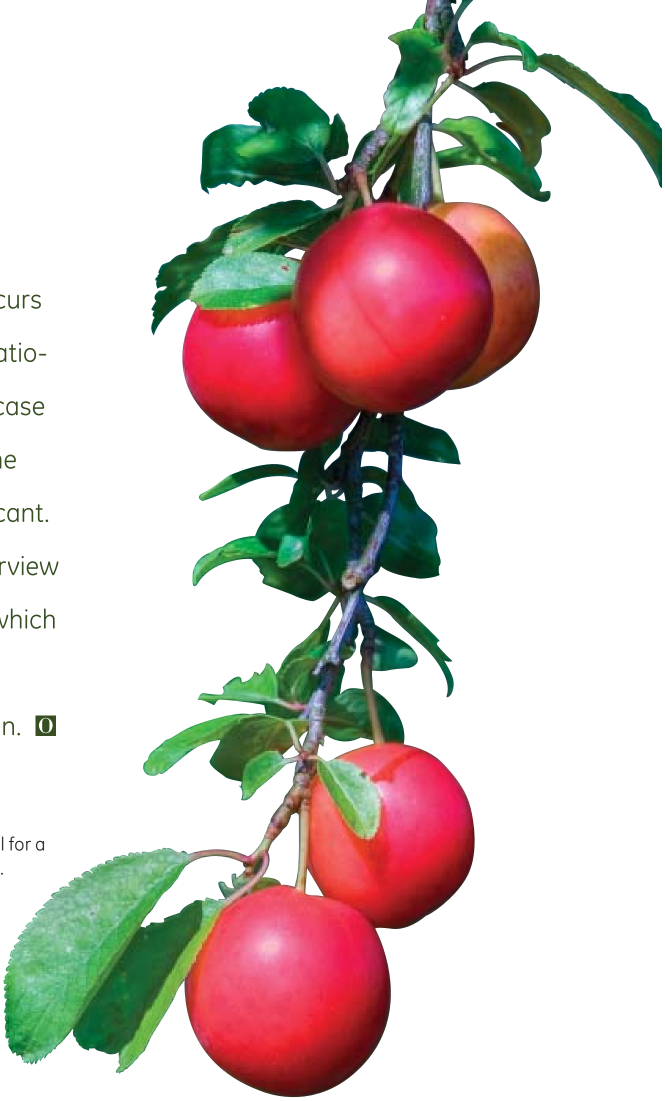


As part of the a machinery diagnostics job carried out by the author on the machine used for Figures 6 and 7, criteria A, B, and D were met. Both repeatable loops and spiral vibration patterns were observed in polar plots from the machine, depending on speed fluctuations and loading conditions. Changes to the lube oil temperature were conducted and corresponding changes to the amplitude and periodicity of the magnitude trend was observed. The machine was reasonably heavily loaded. And, the machine was an integrally geared air compressor where the impeller was overhung from a high-speed pinion. Combined, these factors pointed strongly towards the Morton Effect as the underlying cause of the elevated vibration levels. The operator was advised to avoid certain lube oil temp ranges and machine loading conditions until a more permanent remedy could be applied.

Summary

Light rubs are commonly encountered in rotating machinery and often give rise to a distinct, cyclical pattern in amplitude and phase trend plots, as well as polar plots. Shaft orbit plots are likewise valuable as they may give direct evidence of more pronounced rubs, observable as flat spots where motion is constrained or "bumps" where the shaft actually bounces against a stationery surface such as a seal. The Morton Effect yields data similar to a rub because the underlying mechanism (localized heating) is the same.

However, in the case of a rub, the heating occurs due to mechanical friction as rotating and stationery parts contact one another, while in the case of the Morton Effect, the heating occurs as the result of excessive shear stresses in the lubricant. This article has provided an introductory overview of the Morton Effect and shown the ways in which polar plots may be used to differentiate this phenomenon from that of a true rub condition.



*Denotes a trademark of the General Electric Company.

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