Vibration Characteristics in Cantilever Stationary Syphons

Gregory L. Wedel  
President  
Kadant Johnson Inc.

Gerald L. Timm  
Vice President, Research & Development  
Kadant Johnson Inc.

Alan T. Ives  
Director, Product Development  
Kadant Johnson Inc.

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EXECUTIVE SUMMARY

Most high-speed paper machine dryers operate with stationary cantilever syphons and dryer bars. Modern cantilever stationary syphons are rigidly mounted to the dryer bearing housings and they provide a reliable system of support. Dryer bars provide for high rates of heat transfer with excellent heat transfer and profile uniformity.

Modern cantilever syphons have been applied on many paper machine dryer sections, with applications covering a wide range of machine speeds, dryer widths, dryer diameters, and paper grades.

Although most of these installations have been trouble-free, there have been occasions where the syphons have encountered problems with vibration. The vibrations have caused the syphons to fail, occasionally resulting in the syphon supports being torn out of the rotary joints. Many of these failures have been the result of resonant excitation of the natural frequency of the stationary syphon support.

This paper reviews the parameters that influence the vibration characteristics of modern stationary syphons and outlines the process for designing the syphon system to avoid operating problems.

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The earliest paper machine dryers were equipped with bent syphon pipes that were cantilevered from stationary supports. These syphons were used very effectively to drain the condensate from these slow-speed dryers.

As machine speeds increased, the mechanical stability of these bent pipe stationary syphons proved to be inadequate. The syphons would vibrate, contact the dryer shell, and break from their mountings. Also, these stationary syphons would "plow" through the rimming condensate and generate turbulence in that area. The high turbulence produced a higher rate of heat transfer and a corresponding non-uniformity in drying and moisture profile.

After the turn of the century, the paper industry began to use rotating syphons. These rotating syphons were mounted rigidly to the dryer shell, either with spring loading or by direct attachment to the shell. Various syphon shoes were developed to handle condensate in the near-rimming and in the non-rimming conditions. These syphons were used for many years to drain the condensate from the dryers, in some cases at speeds up to 1000 mpm (3280 fpm).
Above 1000 mpm, the insulating effect of the rimming condensate became very significant. The drying capacity was reduced and the dryer surface temperature profiles lost their uniformity.

Kadant Johnson pioneered the development of a new family of rotating syphon shoes, specifically for high-speed dryers. These close-clearance, large-perimeter rotary syphon shoes worked well with non-rimming condensate as well as with rimming condensate. The syphons produced thin condensate layers so that the heat transfer rate and uniformity were significantly improved.

As dryer speeds increased further, even the thin condensate layers began to be a significant limitation in the transfer of heat from the dryers. Further, the pressure difference required to evacuate the condensate from the dryer continued to increase, with corresponding increases in steam blow through. The pressure differential requirements would have been much less with stationary syphons, but the older stationary syphons did not have the mechanical stability and reliability to operate in a dryer with the close-clearances required to maintain a thin condensate layer and high heat transfer rates.

In the late-1970’s, dryer bars were developed to improve the rate of heat transfer from paper dryers with rimming condensate. Dryer bars cause the condensate layer in the dryer to resonate. This resonance in turn greatly increases the rate of heat transfer, even with significant amounts of condensate in the dryer. With this development, it was possible to reconsider stationary syphons.

Modern stationary syphons were developed and reintroduced in the early 1980’s. These new stationary syphons could reliably operate with a 4 to 6 mm clearance to the dryer shell. Even with these fairly close clearances, without dryer bars, the resulting condensate layer would have been too thick. The drying rates would have been quite poor and the heat transfer rates would have been very non-uniform in the cross-machine direction.

But, by combining the modern stationary syphon with dryer bars, the drying rates were even higher than those achieved by close-clearance rotary syphons, the heat transfer profile was very uniform, and the mechanical reliability of the syphons was very good.

Kadant Johnson developed a high-performance stationary syphon specifically for use with dryer bars. Kadant Johnson also developed a unique configuration of dryer bars, Turbulator® bars, specifically for use with this stationary syphon. A rotary joint and mounting bracket were also developed to insure a rigid mounting for the stationary syphon.

The combination of the joint, bracket, syphon, and Turbulator bars provide high heat transfer rates, rigid mounting, and ease of installation and maintenance.
In the process of developing this syphon and bar system, the vibration characteristics of the syphon and its mounting were carefully investigated. This report covers the highlights of the design considerations in the development of the Johnson stationary cantilever syphon.

FUNDAMENTALS OF NATURAL FREQUENCY

All mechanical systems have a natural frequency. This is the frequency at which the mechanism will naturally vibrate or oscillate if it is pushed out of position or hit by a hammer. A tuning fork is a simple mechanical system. It vibrates at a defined frequency (pitch) when it is hit.

Mechanical systems can be caused to resonate at their natural frequency by subjecting the system to an external force (or vibration source) that is close in frequency to the natural frequency of the mechanical system.

An example of resonant motion is pushing (external force) a person on a swing (mechanical system). In order to achieve a high amplitude of vibration (swinging height), the person on the swing must be pushed just as the swing starts to move away from you (that is, at the natural frequency of the swing). Energy is added to the mechanical system and the amplitude of the motion increases.

Examples of mechanical systems that can be found operating at their resonant frequencies are rocking horses, swing sets, clock pendulums, violins, and cantilever stationary syphons.

The external force or vibration can be a hammer hitting the system at a high frequency, a person pushing a swing, a dryer rotating with an imbalance, or a felt roll rotating with a varying stiffness. Any external vibration that is close to the natural frequency of the mechanical system can cause the system to resonate. If there is no natural damping and the external vibration continues, the amplitude of the vibration will continue to increase until the mechanical system fails.

Figure 3: Examples of Mechanical Systems
A cantilevered stationary syphon is also a mechanical system. It also has a natural frequency. It is also subject to mechanical resonance. The natural frequency can be determined by mounting the syphon on the machine and measuring its response when hit by a hammer. It will vibrate at its natural frequency. The vibration will decrease exponentially at a rate that depends on the damping characteristics of the system.

Typical cantilever syphons are rigidly mounted, so there is very little natural damping. That is, modern syphons will continue to “ring” for a long time and are very easy to excite. The challenge in designing a cantilever syphon is to insure that there are no external forces or vibrations on the paper machine that are large in amplitude and close in frequency to the natural frequency of the syphon support system.

There are several sources of external vibration that should be avoided in the design of a stationary syphon: Condensate vortex shedding, dryer rotation, and felt roll rotation. These sources are reviewed in detail in the following sections. First, however, the next section provides a brief overview of the natural frequency of the stationary syphon support system.

SYPHON SUPPORT SYSTEM

The natural frequency of a stationary syphon support system depends on a number of parameters: Mounting stiffness, support tube length, support tube stiffness (outside and inside diameters), amount of canti-
levered weight, and distribution of cantilevered weight. Four of these parameters are covered in the following paragraphs: Support tube length, support tube outside diameter, support tube inside diameter, and amount of cantilevered weight.

The most important parameters for developing support tube stiffness are length and outside diameter. The natural frequency (stiffness) of a cantilevered pipe decreases exponentially with increasing length. This is shown in Figure 5 for a 75 mm (3") diameter support tube. Increasing the length of the support tube from 1000 mm to 1800 mm (40" to 70") reduces the natural frequency from 35 Hz to 13 Hz (cycles per second).

The support tube, however, must be long enough to extend through the dryer journal. The natural frequency of the syphon supports in dryers with long journals (typically drive side journals) will be lower than the natural frequency of the same size support in dryers with shorter journals. The reduction in natural frequency that comes from increasing the length of the support tube can be offset by increasing the diameter of the support tube. This is shown in Figure 6 for a 1140 mm (45") long support tube. Increasing the diameter of the support tube from 65 mm (2.5") to 115 mm (4.5") increases the natural frequency from 18 Hz to 42 Hz.

Figure 5: Natural frequency of a cantilever support tube. Effect of tube length (tube diameter = 75 mm).
Figure 6: Natural frequency of a cantilever support tube. Effect of tube diameter (tube length = 1140 mm).

Figure 7: Natural frequency of a cylindrical support tube. Effect of tube wall thickness (115 mm OD x 1500 mm length).
The natural frequency can also be increased by reducing the inside diameter of the support tube. Reducing the bore, however, also adds more weight to the system and the impact on natural frequency is greatly diminished if the wall thickness is increased above a critical value. This is shown in Figure 7 for the 115 mm (4.5") diameter support tube. Decreasing the inside diameter of the support tube from 110 mm (4.3") to 80 mm (3.1") increases the natural frequency from 18 Hz to 33 Hz, but further reductions in the support tube bore provide very little improvement on the support tube natural frequency.

The amount of cantilevered weight also has a direct influence on the natural frequency of the support tube system. Increasing weight results in a lowering of the natural frequency. This is shown in Figure 8. Increasing the weight of the syphon and its vertical support system from 10 kg to 20 kg decreases the natural frequency by 25%.

CONDENSATE BEHAVIOR

The behavior of the condensate inside the drying cylinder can have a pronounced effect on the stability of the stationary syphon. This section reviews the fundamentals of condensate behavior.

As steam transfers its heat to the dryer shell, it condenses. Under nor-
mal operating conditions, this condensed steam, or “condensate”, is removed from the dryer through the dryer syphon. Depending on the dryer speed, the condensate may be in a ponding, a cascading, or a rimming condition (1, 2). These conditions are depicted in Figure 9.

If the dryer is rotating slowly, the steam will condense directly on the dryer surface, and the condensate will run down the sides of the dryer shell and into a puddle at the bottom of the dryer. This condition is called “ponding.” A stationary syphon that is positioned in this pond is not subjected to any disturbing forces from the condensate.

As the dryer rotates a little faster, a thin layer of condensate begins to follow the dryer surface, but the majority of this condensate falls back into the puddle rather than following the surface for a complete revolution. This condition is referred to as “cascading” and it occurs at speeds up to 365 mpm (1200 fpm). Unless the amount of condensate that is cascading in the dryer is very large, the forces on the stationary syphon remain small.

Modern stationary syphons are generally applied to dryers that are operating at higher speeds. At high speeds, the condensate rotates with the dryer shell, in a thin layer of water around the inside of the dryer cylinder. This condition is called “rimming”. The rimming condensate impacts the stationary syphon shoe as it flows past it. A stationary syphon is most susceptible to condensate-induced vibrations when the condensate is in the rimming condition.
VORTEX FREQUENCY

Rimming condensate impacts the face of the scoop-type stationary syphon shoes and deflects the syphon. Some of the condensate is scooped out of the dryer and the rest of it flows under and around the syphon shoe. The condensate that is not evacuated will create vortices behind the shoe. This is similar to the shedding of vortices behind a large semi-trailer on a highway. The shedding of these vortices produces vibrations and deflections of the stationary syphon.

The frequency and magnitude of these vibrations are dictated by the speed of the dryer, the size and contour of the shoe, and the amount of condensate in the dryer. These vibrations, combined with the deflection of the syphon by the rimming condensate, result in horizontal and vertical displacements of the syphon.

The stationary syphon and its support must be stiff enough to limit these displacements so that the syphon shoe does not contact the rotating dryer shell. That is, the natural frequency of the syphon support must be sufficiently higher than the vortex shedding frequency to avoid resonant vibration and stiff enough to minimize the magnitude of the deflections.

The performance of several stationary syphon configurations was determined using the Kadant Johnson Joco 4000 and Joco 6000 pilot dryers at the Three Rivers, Michigan Research Center.

The Joco 4000 and Joco 6000 are commercial paper machine dryers, with nominal diameters of 1.5 m (60") and 1.8 m (72"), respectively. They each have commercial face widths: 6.35 m (250") and 8.76 m (345") and are capable of operating at speeds up to 1220 mpm (4000 fpm) and 1830 mpm (6000 fpm), respectively. Tests were conducted with the dryers operating with Turbulator bars.

Vibration transducers were mounted to the stationary syphon inside the pilot machine dryers. A measured amount of water (condensate) was metered into the dryer and the dryer was increased in speed while monitoring the vibration of the stationary syphon. Vibration of the syphon indicated the frequency of the vortex shedding and the deflections of the syphon under operating conditions.

The mechanical performance of these syphons was then correlated with dryer speed, syphons contour, and condensate quantity to establish the design limitations for each syphon design. These correlations are used to insure that the syphon support system has a natural frequency well above the vortex shedding frequency.
DRYER ROTATION FREQUENCY

The paper machine dryers are another source of external vibration. The frequency of this vibration is equal to the rotational frequency of the dryer:

\[ F_D = \frac{S}{\pi D} \]

Where \( F_D \) is the rotational frequency of the dryer, \( S \) is the dryer surface speed, \( \pi \) is equal to 3.1416, and \( D \) is the outside diameter of the dryer cylinder.

The dryer cylinder will transmit vibrations to its support framing at this frequency. The support framing in turn transmits the vibrations through the stiff syphon mounting to the cantilever support tube. The amplitude of these vibrations depends on the amount of imbalance of the dryer, the stiffness of the dryer framing, and the speed of the dryer.

The amount of allowable imbalance depends on the dryer speed, dryer weight, and balance specification class. Paper machine dryers are normally balanced to an ISO G2.5 specification. For high-speed operation, the allowable imbalance is typically less than 2 to 4 Kg. Dryers that have lost their balance weights may be out of balances by several times this amount. The corresponding amplitudes of vibration can be very large.

Normally, only the first rotational frequency of the dryer is a significant source of vibration. Dryers are considered to be inflexible rolls. Their diameters are quite large with respect to their length. There is little deflection of the shell during normal operation, even if the dryer is half-filled with condensate. For this reason, paper machine dryers are normally balanced by adding weight only to the dryer heads. For slow speed dryers, the weight is often added to only one dryer head, as a static balance. For high-speed dryers, the weight is generally added to both heads, in order to be dynamically balanced.

FELT ROLL ROTATION FREQUENCY

The paper machine felt rolls are a third source of external vibration. Felt rolls are often the most significant source of the vibration forces, even though they are much lower in mass than the dryer cylinders. This is because felt rolls run at a much higher rpm (frequency) and they have much higher deflections than dryer cylinders.

Felt roll vibrations can result from one of three sources: Its rotational
Felt rolls are often the most significant source of the vibration forces, even though they are much lower in mass than the dryer cylinders.

Rotational Frequency. The first of these three vibrations is the rotational frequency of the felt roll:

\[ F_d = \frac{S}{\pi d} \]

Where \( F_d \) is the rotational frequency of the felt roll, \( S \) is the dryer surface speed, \( \pi \) is equal to 3.1416, and \( d \) is the outside diameter of the felt roll. Any imbalance in the felt roll can induce a vibration of the syphon support tube. As with the dryer cylinders, the amplitude of the vibration depends on the level of imbalance and the speed of the machine.

The amount of allowable imbalance depends on speed, weight, and specification class. Paper machine felt rolls are normally balanced to ISO G1.0 specification. For high-speed operation, the allowable imbalance is typically less than 1 kg.

Older felt rolls may be significantly out of balance, particularly if the machine is operating above its original design speed. For this reason, the rotational frequency of the felt rolls should generally be avoided.

Many paper machines have two different felt roll diameters. The pocket felt rolls in the top felt run might be one size smaller than the pocket felt rolls in the bottom felt run. This is because felt roll diameters are based, in part, on a deflection criteria (mm per meter of width). The deflection of a top felt roll is less than that of a bottom felt roll, because the felt tension lifts the felt roll rather than pulls it down. If the machine has felt rolls with different diameters, the rotational frequencies of both sizes should be checked.

Half-Critical Speed. The second source of felt roll vibration is the half-critical speed. This corresponds to one-half the critical speed of the felt roll. The “critical” speed occurs when the rotational frequency of the roll is equal to the natural frequency of the felt roll itself. At the critical speed, the felt roll experiences resonant vibrations with large amplitudes.

A “half-critical” vibration occurs because the felt roll shell thickness varies in the circumferential direction.

The inside surfaces of felt rolls are rarely machined. The rough bore may not be quite concentric with the finished roll outer surface. Internal balance weights are used to compensate for this eccentric bore, but the felt roll is left with non-uniform bending stiffness. The bending stiffness of the shell will vary in the circumferential direction. If the felt roll stiffness varies, the roll will deflect to varying degrees, twice per revolution, due to the force of the felt tension and gravity.

A felt roll may be perfectly balanced, but when it is placed into service, it can still induce vibrations with large amplitudes, particularly if the
operating felt tensions are higher than the original design. The amplitudes of this vibration are naturally much larger if the felt roll is operating near its critical speed, but they may also be large if the felt roll is operating near its half-critical speed.

**Critical Speed.** The third source of felt roll vibration is the felt roll critical speed. This is the speed at which the rotational frequency of the felt roll approaches the natural frequency of the felt roll itself. Paper machine felt rolls are “flexible” rolls. Even though they are in balance, they deflect due to gravity. If they are rotating too fast, they begin to vibrate. This is a resonant phenomenon. If the felt roll is approaching its natural frequency, then the vibration amplitude of the felt rolls will be very large. Operation of a machine with the felt rolls close to their natural frequency will generally result in bearing, journal, and felt roll shell failures. Such high amplitudes also impose a much higher risk of inducing a vibration in the stationary syphon support.

**CANTILEVER SYPHON DESIGN**

As indicated in the equations above, the rotational frequency of the dryer increases with machine speed. The rotational frequency of the felt roll also increases with machine speed, but is a much higher value (due to its small diameter). The natural frequency of the stationary syphon support tube, however, is fixed. There are two ways of avoiding having the rotational frequency of the dryers and felt rolls excite the natural frequency of the support tube:

- **High tune**
- **Low tune**

A syphon assembly that is “high-tuned” has its natural frequency significantly above the rotational frequencies of all of the adjacent rolls (dryers and felt rolls in this case). A syphon assembly that is “low-tuned” has its natural frequency significantly below the rotational frequencies of one or more of the adjacent rolls, including the 2x rotational frequency of suspect felt rolls.

The safest design, of course, it to have the syphon assembly high-tuned. This is common practice in paper machinery design, as it provides the widest range of operating conditions.

With a low-tuned system, the machine will pass through the rotational frequency of one or more of the adjacent rolls as the machine accelerates to its normal operating speed, at which point the rotational fre-
EXAMPLE CANTILEVER SYPHON DESIGN

Interference plots are generated to evaluate these various options. Figure 10 shows one such plot. In this application, the first rotational frequencies of a 1.5 m (60") dryer are shown as a function of the machine speed. These frequencies increase from 0 to 4.2 as the machine speed increases to 1200 mpm (3940 fpm). The first and second rotational frequencies of an adjacent 510 mm (20") diameter felt roll increase to 12.5 and 25 Hz, respectively.

Also shown is the rotational frequency that corresponds to the critical speed of a 510 mm (20") diameter felt roll with a face width of about 7.6 m (300"). Ideally, the natural frequency of the stationary syphon system would be safely above any frequencies that could induce a vibration. If the syphon has a natural frequency of 30 Hz, the syphon would be high-tuned in a dryer section that is running at 1200 mpm (3940 fpm).

The machine could accelerate to its intended operating speed and neither the dryers nor the felt rolls would induce a resonant vibration in the stationary syphon support system, anywhere along this path. Even the 2x felt roll rotational frequency would not be high enough to cause resonant vibration.

Alternatively, the stationary syphon system could be designed such that its natural frequency was safely below 25 Hz and safely above 12.5 Hz. At this point, the syphon system would be low-tuned with respect to the second rotational frequency of the adjacent felt roll and high-tuned with respect to the first rotational frequency of the adjacent felt roll. The machine could accelerate to its intended operating speed without the rotational frequency of the dryers or felt rolls reaching the natural frequency of the syphon.

The second rotational frequency of the felt rolls, on the other hand, would pass through the natural frequency of the support tube. As the machine goes through this point, the felt rolls would tend to induce a resonant vibration of the support tube. If there is little condensate in the dryer if the machine passes quickly through this resonant point, if the amplitudes of felt roll vibration are small, and if the natural frequency

quences will be above the natural frequency of the support tube.

In those cases where it is impossible to fit a support tube of adequate stiffness, the syphon assembly should be designed such that its natural frequency is as far as possible from the rotational frequencies of the adjacent rolls, under the expected range of operating machine speeds.
of the support tube is not close to the critical frequency then the risk of resonant failure of the syphon will be greatly reduced.

In many cases, it is possible to low-tune the stationary syphon. In these cases, care must be taken in the design to avoid frequencies that could induce a resonant vibration. In other cases, there is insufficient “room” between the various rotational frequencies to comfortably low-tune the syphon. In these cases, the dryer journals could be bored to accept a larger diameter support tube for the stationary syphon, an internal bushing could be installed to limit the movement of the support tube, the syphon clearance could be increased to reduce the probability of contacting the shell, or the machine could be equipped with rotating syphons.

The stationary syphon may also be sized based on the size of the journal bore. This approach is very risky. The resulting syphon support may be too small for high-tuning and be too large to achieve safe low-tuning performance. Typical paper machinery is designed to avoid the resonant frequency of the major machine rolls by at least 20%. Appropriate safety bands are also required around the syphon frequencies in order to avoid resonant vibrations.

For simplification, it has been assumed that the vortex shedding is not a contributing factor to the stability of the syphon in the above example.
OTHER CONSIDERATIONS

There are a number of older machines that are operating successfully with stationary syphons that are low-tuned. These machines experience infrequent failures because they do not operate at speeds where either the dryers or the felt rolls will induce a resonant vibration. As the machine is accelerated to operating speed, it passes through one or more harmonics. This will cause the support tube to vibrate, at least until the machine speed is sufficiently high. The amount of vibration depends on the amount of overhanging weight on the support tube (the syphon and its vertical support) and also on the amount of vibration (imbalance) of the felt rolls and dryers.

When these machines are increased in speed, however, there is a risk that the stationary syphon will encounter one of the rotational frequencies. Continuous vibration of the support tube can then cause the fasteners to loosen. Once the fasteners loosen, they are very susceptible to fatigue failure. For this reason, syphons should be designed with some consideration for the current as well as for the anticipated operating speed range for the machine.

Note that the felt roll “balance” is not the only consideration. Even a well balanced felt roll can cause problems if it has non-uniform bending stiffness. Older felt rolls were notorious for having non-uniform bending stiffness because the roll inside diameter is in an “as-cast” condition and it often was not perfectly concentric with the outside diameter.
SUMMARY OF DESIGN CONSIDERATIONS

All cantilevered stationary syphons have one or more natural frequencies and, when excited by an external force, will vibrate at the natural frequency that is closest to the frequency of the exciting force. The external force (vibration) could be supplied by the motion of condensate flowing past the shoe, by joint misalignment, by roll imbalance, or by other miscellaneous vibrations present in the paper machine. If, by chance, the frequency of the external force happens to be at or near the natural frequency of the syphon (or an even multiple thereof), large amplitude vibrations are likely (up to 10 times the normal steady state amplitude). Resulting failures of the syphon can be expected.

By proper selection and sizing of the stationary syphon support system, the frequencies of the external forces can be avoided and the syphon will operate without problems.

The natural frequency of the syphon depends on the weight of the syphon assembly, the length of the support tube, the inside and outside diameters of the support, and the stiffness of its external support.

REFERENCES


Kadant Johnson is a global leader in the design, manufacture, and service of dryer drainage systems, rotary joints, syphon systems, and related equipment for the dryer section of the paper machine. For more information about Kadant Johnson products and services, email info@kadant.com or visit www.kadant.com.

- Steam and Condensate Systems
- Dryer Section Surveys
- Dryer Management System® control software
- Stationary Syphons
- Rotating Syphons
- Rotary Joints
- Turbulator® Bars
- Thermocompressors
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