Shake, rattle and grow – empirical data on the effectiveness of vibration supports in a thermal growth environment

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Abstract

Piping systems under high vibratory loads often require supports that can control vibrations while also allowing thermal expansion and contraction. Vibration service requires high stiffness, whereas thermal stress requires low stiffness. These two competing requirements can be challenging to manage, and there are few solutions on the market that can effectively accommodate both criteria.

This paper introduces a test procedure to help industry evaluate the suitability of different pipe support types to determine the effectiveness of a support in accommodating both vibration and pipe stress considerations.

The procedure is then applied to compare different pipe support options used in typical piping system designs. With a combination of empirical lab testing and analytical finite element analysis, each support is evaluated on its merits. Tabulated results are presented to provide piping designers and engineers with the information they need to make informed design decisions when working with piping systems in vibratory service.

Introduction

All piping systems are subject to thermal variations, whether due to process fluids or environmental conditions. Piping designers need to ensure that piping layouts are flexible enough to accommodate thermal expansion and contraction to avoid high stresses that can lead to low-cycle fatigue failures. Many piping systems also have dynamic loads due to process fluid flow fluctuations or mechanical excitations that can cause the piping to vibrate. Piping designers need to also ensure pipe supports are stiff enough to control vibration to avoid high-cycle fatigue failures. Accommodating the conflicting piping design requirements of thermal expansion and vibration control is a common industry challenge.

The design balance between thermal and vibration considerations tends to weigh more heavily to the thermal side of the scale, in the authors' experience. This is partially because many piping systems are not vibratory in nature and therefore do not require vibration design attention. If a vibratory system is not properly designed for vibration, however, it can plague the piping system with fatigue failures over the life of the facility. The authors' organization experiences the results of this every day in operating facilities around the world.

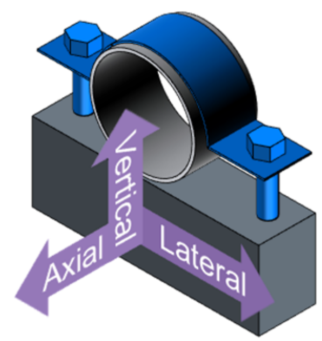
The root of many piping vibration problems comes down to the type and style of supports used in the system. There are many styles of pipe supports that work well for static support and thermal pipe stress. Some of these pipe supports also claim to control dynamic loads. However, there are no industry standards to categorize which supports are effective for vibratory service or how to evaluate these claims with a standardized testing regime.

This paper introduces new categories for piping supports and a testing methodology to evaluate their ability to meet thermal stress and vibration design requirements. The aim is to provide a quantitative evaluation approach that enables designers and engineers to create more reliable piping system designs. The paper also describes how the proposed methodology was applied to several common supports and presents the resulting empirical test data.

Terminology

For the purposes of this paper, the following terms are defined as:

Stiffness	Force required to move a component by unit length (lbf/in or N/cm)
Flexibility	The amount a component moves under a unit force (in/lbf or cm/N)
Support	The device used to connect the pipe to the structure. Examples include clamps, shoes, rollers, guides, hangers, u-bolts, etc.
Structure	The component that undergirds the pipe support and transfers the weight load of the pipe to the foundation, soil or underlying superstructure which is at least 10x stiffer or more massive than the structure
Axial	Parallel to the pipe at the support location (see figure to the right)
Vertical	Perpendicular to the pipe, directed from the structure towards the support. Not necessarily parallel with gravity (see figure to the right).
Lateral	Perpendicular to the axial and vertical (see figure to the right)
Transverse	The lateral and vertical directions, considered together
MNF	Mechanical natural frequency
Static load	A force that either remains constant over time or changes very slowly. This type of force induces a displacement (this definition lumps together the classical definitions of both 'static' and 'quasi-static' loads).
Dynamic load	A force that that changes with time. This type of force induces vibration
Excitation	A dynamic force input
Resonance	Coincidence of MNF with excitation frequency
Statically compliant	A pipe support that allows pipe migration under a static load
Dynamically fixed	A pipe support that restrains pipe subject to a dynamic load



Types of pipe supports

Pipe designers aim to ensure sufficient piping flexibility to prevent excessive stress from thermal loading. Piping flexibility is affected by both the piping geometry and the pipe support method. When flexibility is required in a piping system, the piping geometry can be modified to include offsets, bends, loops, expansion joints or flexible couplings. Pipe supports also play a role in piping flexibility, and different pipe support designs can be selected to allow thermal movement of the system. Piping designers are accustomed to selecting pipe supports that do not restrain pipe movement and thus result in pipe flexibility. These *statically compliant* supports typically take two forms:

- Supports that have a low-stiffness connection with respect to the undergirding structure, using springs or some other low-stiffness element. The pipe can move relatively freely with even a low-magnitude thermal load. Examples include spring supports, spring cans, hangers, etc.
- Supports that rest on an undergirding structure. There is no restraint holding the support to the structure (such as bolts), so the pipe can freely move once the thermal load at the support overcomes the friction load between the support and the structure. The friction load is typically a low-magnitude load and is easily overcome by the thermal load. Examples include rest supports, guides, limits, rollers, etc.

Though statically compliant supports are convenient for use on piping subject to thermal loads, they are *not* appropriate for use with piping systems subject to *vibratory* (dynamic) loads. This is because the static flexibility they employ as a benefit for static loading also leaves them 'dynamically flexible.' Vibratory loads on piping at the supports can easily be of high enough magnitude to overcome the low-friction or low-stiffness restraint of a flexible support. When this occurs, the support is not acting to control vibration, as they allow pipe movement from both *static* and *dynamic* loads.

It must also be noted that supports such as guides and stops do not control vibration in practice due to the inherent clearance between the support and the restraining hardware. Even small gaps can be enough to allow damaging vibratory motion to occur.

Piping systems subject to vibratory loads require supports that prevent dynamic movement. API RP 688, Section 3.2.7.9, provides helpful guidance on appropriate support types for vibratory loads. It requires the support to be 'dynamically fixed.' Supports need to "restrain the pipe to the structure and withstand dynamic loads without [dynamic] movement of the pipe relative to the supporting structure."

Based on the discussion above, we can differentiate between two broad categories of pipe supports:

1. Thermal supports: statically compliant, allowing pipe movement under thermal loads
2. Anti-vibration supports: dynamically fixed, preventing pipe movement under dynamic loads

However, API RP 688 continues to differentiate between two types of *dynamically fixed* supports:

- 'Clamps' – these supports do not allow movement between pipe and structure, neither dynamic nor static movement (note: the RP 688 term 'clamps' is not itself descriptive of this whole category of supports that resist both dynamic and static movement. Bolt-down pipe shoes or many of the various forms of pipe anchors, for example, would also qualify as resistant to both dynamic and static movement. Clamps are themselves a particular incarnation of this type of support)
- 'Hold-downs' – these supports are dynamically fixed and resist vibratory loads, but can still allow pipe migration with respect to the undergirding structure. These supports are dual-purpose, controlling vibratory loads <u>*and*</u> allowing the piping to migrate under thermal loads.

In distinguishing a difference between 'clamps' and 'hold-downs,,' RP688 acknowledges that 'dynamically fixed' and 'statically compliant' are not mutually exclusive characteristics and that they can be integrated into a single support. This means that we can describe, within the two broad categories of supports given above, three sub-categories of supports:

1. Flexible supports: supports that are both statically and dynamically compliant
2. Rigid supports: supports that are both statically and dynamically fixed
3. Dual-purpose supports: supports that are dynamically fixed and statically compliant

Figure 1 below shows the relationship between the support categories:

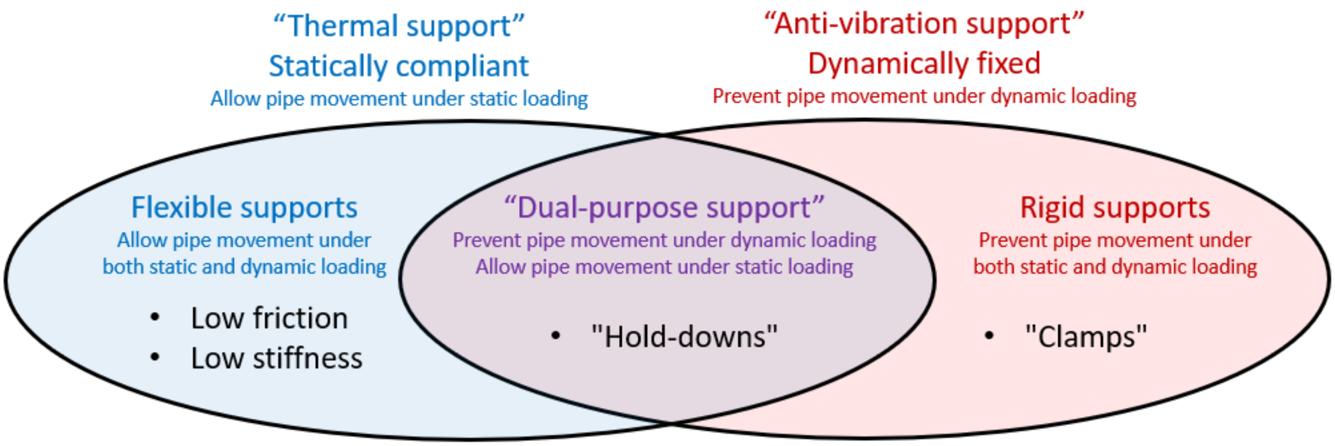


Figure 1: Type of piping supports

Each of these support types have their own particular function and application, as is noted in Table 1 below:

Table 1: Support types and appropriate applications

Support type	Function	Service
Flexible supports	Allow both static and dynamic pipe movement. Use where static loads must be accommodated and there is no significant dynamic (vibratory) load.	Non-vibratory service only
Rigid supports	Prevent both static and dynamic pipe movement. Use where dynamic loads must be resisted and there is no significant static load.	Both vibratory and non-vibratory service
Dual-purpose supports	Allow static movement but prevent dynamic pipe movement. Use where dynamic loads must be resisted *and* static loads must be accommodated.	Both vibratory and non-vibratory service

While industry standards acknowledge and differentiate between these types of supports, there is no standard that gives a strict method of categorization that organizes the multiplicity of available pipe supports by their appropriate use. As it stands now, piping designers are left to use their intuition and experience in selecting supports. In a better scenario, industry guidelines would prompt support manufacturers to categorize their supports according to the scheme described above and provide information about the support to enable an informed decision on their use.

In order to perform this categorization, however, definitions for the terms used above must be set. In the following sections, we will define the required criteria, give a rationale for the definition and introduce a sorting method based on performance and behaviour.

Defining ‘dynamically fixed’

Support nodality and stiffness

Dynamically fixed pipe supports can resist dynamic loads and prevent dynamic pipe movement (vibration). Multiple standards dealing with piping subject to dynamic excitation give guidance on the required stiffness at support locations. For example, the API 618 standard for the design of reciprocating compressors systems states:

> To accurately predict and avoid piping resonances, the supports and clamps must dynamically restrain the piping. Piping restraints are only considered to be dynamically restraining when they have either enough mass or stiffness to enforce a vibration node at the restraint (API 618, 5th Edition, Section 7.9.4.2.3.6, Note 2)

The API 674 standard for the design of positive displacement reciprocating pump systems gives similar guidance:

> The piping restraint is not considered to be rigid unless the restraints have either enough mass or stiffness sufficient to emulate a vibration node at the restraint and the pipe is attached to the restraint using clamps. (API 674, 3rd Edition, Section C.1.4)

A 'vibration node' is any point where there is little or no vibration for a particular mode (nodality is frequency dependent). The standards above say that a pipe support is dynamically fixed if and only it is able to force a vibratory node at the support location (this is taken to mean that the pipe support creates a vibratory node *for the first principal mode of vibration*). In achieving nodality, the support to resist participation in piping vibration. A perfectly nodal support does not participate in the vibration of the connected piping span, and acts as a perfect pinned boundary condition for the piping. The example below (Figure 2) shows a finite element model comprised of a long straight segment of piping supported at regular intervals. It shows the vibrating mode shape when the supports are high stiffness and acting as vibration nodes on the left, and when the supports are low stiffness and *not* acting as vibration nodes on the right.

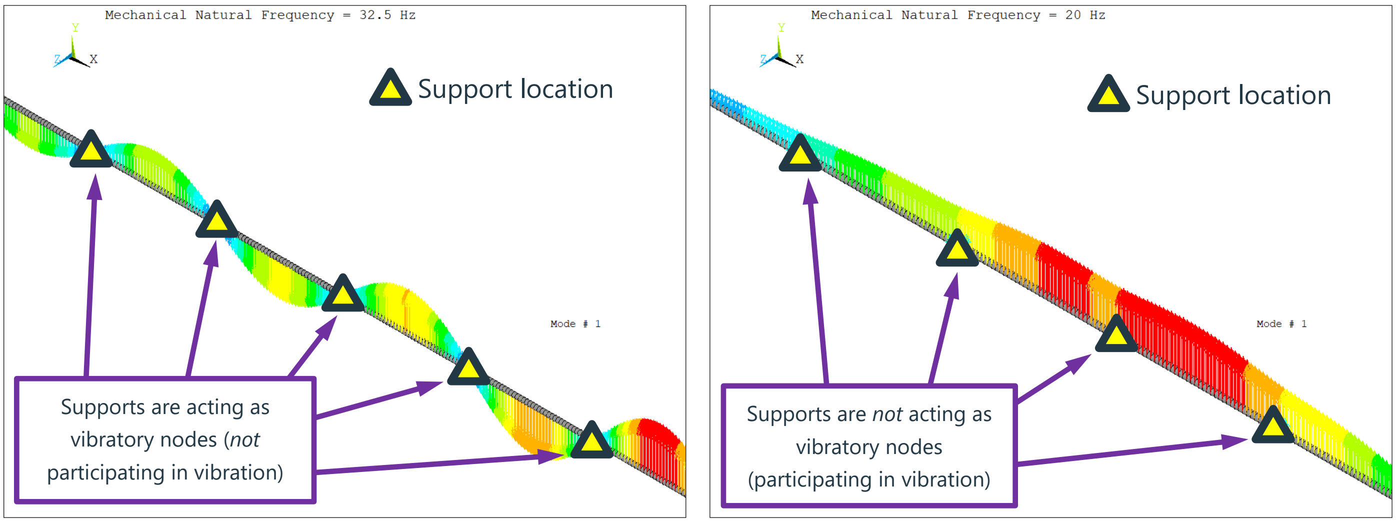


Figure 2: Nodality example

Appendix P of API 618 5th Edition gives guidance on calculating the minimum stiffness necessary at a pipe support location to create a vibration node, given below (note that (n-1/n) is a well-known typo in the standard. It should read (n-1)/n):

$$minimum\ K_s = C_{ks} * A^{0.75} * I^{0.25} * f_{n,T}{}^{1.5}(n - \frac{1}{n})$$

Where

C_{ks} is the constant dependent on support stiffness units (SI units: 1/130; USC units:25)

A is the pipe cross-sectional metal area in mm^2

I is the pipe cross-sectional area moment of inertia in mm^4

$f_{n,T}$ is the minimum transverse natural frequency in Hz

n is the number of active supports ($n = 2$ as a minimum)

Figure 3: API 618 5th Edition minimum support stiffness calculation

However, there are a few issues to be resolved to adapt this formula as a criterion to determine if a pipe support is stiff enough to generate vibratory nodes and thus be considered 'dynamically fixed:'

1. Research carried out by the GMRC (GMRC Project: Pipe support stiffness, 2015), subsequent to the publication of API 618 5th edition, has found that the stiffnesses calculated from the formula above are not sufficiently high to prevent rigid body pipe motion from manifesting in some cases.
2. The minimum stiffness is the stiffness required by the pipe itself. However, the stiffness that the pipe itself experiences will always be less than the stiffness of the support itself.
3. The minimum stiffness is dependent on pipe wall thickness that the pipe supports are acting on, with thicker walled piping spans requiring greater stiffnesses at the support locations to produce nodality.
4. The minimum stiffness is dependent on the transverse mechanical natural frequency (MNF) of the piping span that the pipe supports are acting to support. Piping spans with higher MNFs require greater stiffness at the support locations to produce nodality.

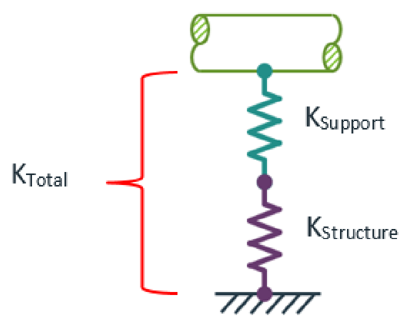
These four issues are resolved in the sections below:

Improvements to the API 618 'minimum stiffness' calculation

The first issue above regards research previously carried out by the GMRC (GMRC Project: Pipe support stiffness, 2015). This research found that by using the API 618 5th Edition minimum stiffness values (calculated for two active supports), the values were not sufficient to prevent either rigid body modes or undesirably low piping MNFs. Single span piping segments (a piping span with two supports, one at each end of the pipe span) were found to require a 2.3x stiffness multiplier to ensure that the first piping MNF is at least 90% of the value predicted by simple beam theory. More true to real piping systems, however, were the conclusions about multi-span piping segments, where a 1.5x multiplier was needed to meet the same 90% of theoretical MNF condition.

Interplay between support and structural stiffness

The second issue above observes that both the structure undergirding the support and pipe support together produce the total pipe stiffness at the pipe support location. The API 618 5th Edition minimum stiffness is the stiffness required at the pipe support location in order to produce support nodality – it is not the stiffness of the structural or pipe support considered alone. The total stiffness at the pipe support location is calculated by considering the stiffnesses of the structure and the support together. The total stiffness of the pipe can be calculated using the formula given below, which sees the support and structural stiffnesses acting in series (assuming no sliding between support and structure).



$$K_{Total} = \frac{1}{\frac{1}{K_{Support}} + \frac{1}{K_{Structure}}}$$

Figure 4: Total stiffness at a pipe support

Based on this relationship, the weaker of the two stiffnesses (structure or pipe support) will dominate the total stiffness of the pipe, with the total stiffness always being less than the lesser of the structure or support stiffness. This means that, if the structure itself does not have enough stiffness to meet the minimum, then nodality cannot be achieved, regardless of how stiff a pipe support is designed. If the structure provides enough stiffness to meet the minimum, however, then the pipe support needs to compliment the structure with a sufficiently high stiffness to achieve nodality at the pipe support location. This interplay between stiffnesses is illustrated in the figure below.

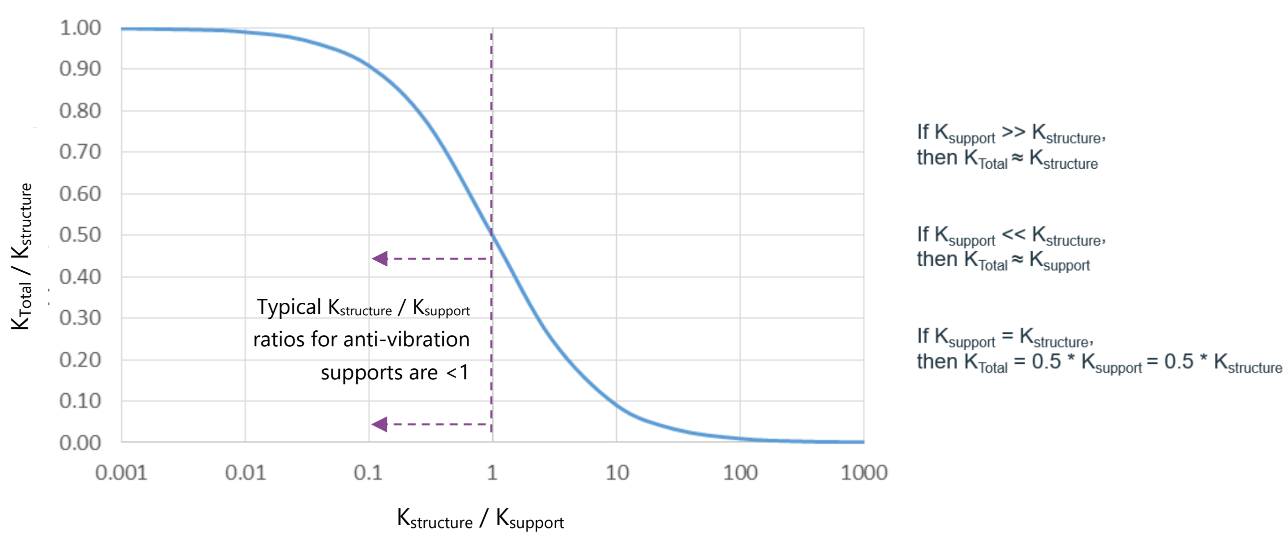


Figure 5: Dependence of total stiffness on the pipe support and structural stiffnesses

Typically, anti-vibration pipe supports are stiffer than the structure to which they are connected. That is, the $K_{structure}$ / $K_{support}$ ratios for anti-vibration supports are typically <1. This means that the structural stiffness is that which most determines the total stiffness, with the support only contributing a fraction of its stiffness. However, when the structure's stiffness is comparable in stiffness to the support, the support then contributes at higher ratios. At $K_{structure}$ / $K_{support}$ = 1, which is the realistic upper limit $K_{structure}$ / $K_{support}$, the support stiffness is at its minimum – the total stiffness is equal to half the support stiffness. This means that, to ensure that the total stiffness meets the API 618 minimum required stiffness, then support stiffness itself must be at least twice the API 618 minimum required stiffness.

Support stiffness and pipe wall thickness

The third issue mentioned above notes that the API 618 5th edition minimum stiffness formula is tied to the wall thickness of the pipe. The formula links the stiffness needed not to the support, but rather to the pipe being supported. Thicker walled piping spans require more stiffness at the support locations to produce nodality. Because this property is inherent in the pipe and not the support, then in order to calculate the stiffness that a pipe support must provide, we have indexed the pipe support stiffness per pipe size to a schedule extra strong (Sch. XS) wall thickness. This means that pipes with wall thickness of Sch. XS or thinner will achieve nodality at a pipe support for which the support stiffness meets the minimums calculated using Sch. XS, while thicker walled pipes would require additional pipe support stiffness to produce nodality than those calculated using Sch. XS.

Support stiffness and frequency

The fourth issue above notes that the API 618 5th edition minimum stiffness formula is tied to the transverse natural frequency of the piping span being supported. Spans with high MNFs will require high support stiffnesses to ensure nodality, while spans with low MNFs do not require much support stiffness to ensure nodality. API 618 gives guidance on which MNFs are acceptable and prescribes a limit of 2.4x compressor operating speed as the minimum MNF for any system element. The intent is to ensure MNFs are above twice the compressor operating speed to avoid the high excitation energy at the first and second orders of operating speed. For low-speed machines, however, this may leave piping with MNFs that, though not exposed to the first two orders of compressor operating speed, can still be excited to resonance by other vibratory excitation mechanisms, such as compressor cylinder base excitation or flow-induced turbulence. To protect against this, it is good practice to ensure that piping span MNFs are at least 15 Hz. Thus, as a minimum, a pipe support must be able to produce nodality for pipes with MNFs at 15 Hz to be considered dynamically fixed.

While 15 Hz serves as a minimum piping span MNF for which a pipe support must be able to produce nodality, there are situations when a pipe support would be required to generate nodes at even higher frequencies. What might be considered the most extreme of these situations would be a 1200 RPM compressor, which would require MNFs above 48 Hz on all piping spans to meet the API 618 guideline. (There are compressors that run at even higher operating speeds than 1200 RPM, but they are generally low power, and only the first order of running speed must be avoided – that is, a 1.2x compressor running speed MNF limit is applied.)

Selecting a support that produces nodality for 15 Hz would not be sufficient for a situation requiring nodality at 48 Hz. As such, if a support has enough stiffness to meet the 15 Hz minimum nodality requirement, then the further step of calculating the frequency for which a support will produce nodality should be carried out. This nodality frequency would be useful information for piping designers and engineers and should be reported by the support manufacturer. The frequency can be calculated using the formula below:

$$F_{Nodal} = K_{Support}^{2/3} / C_{pipe}$$

Where

F_{nodal} is the maximum frequency at which the support can produce nodality (Hz)

$K_{support}$ is the less of the two transverse directional stiffnesses (lbf/in or kN/m)

C_{pipe} is a constant, dependent on pipe NPS. See the table below, Table 2

Stiffness of a 'dynamically fixed' support

With these corrections and assumptions in mind, calculating the stiffness required for a support to act as a vibratory node is now possible per pipe nominal size. Table 2 below shows the minimum pipe support stiffness to be considered dynamically stiff at 15 Hz.

Table 2: Minimum pipe support stiffnesses to be considered 'dynamically fixed'

Nominal pipe size (indexed to Sch. XS)	Minimum support stiffness to be considered 'dynamically fixed' (15Hz)		C_{pipe}	
	(lb/in)	(kN/m)	USC units	SI Units
2″	2,800	500	13.30	4.20
3″	7,000	1,200	24.40	7.53
4″	11,700	2,000	34.48	10.58
6″	27,100	4,800	60.19	18.97
8″	47,200	8,300	87.03	27.33
10″	66,800	11,700	109.77	34.36
12″	87,300	15,300	131.17	41.09
14″	101,000	17,700	144.55	45.28
16″	124,200	21,800	165.96	52.03
18″	149,000	26,100	187.36	58.66
20″	175,200	30,700	208.77	65.36
24″	231,800	40,600	251.59	78.75

A pipe support that exceeds the minimums of all three of its directional stiffnesses in the table above is considered dynamically stiff and acceptable for use in vibratory service requiring pipe support nodality up to 15Hz. For supports that meet the minimums above, the further step of reporting the frequency for which the support is capable of maintaining nodality is required.

Defining 'statically compliant'

When flexibility is required in a piping system, piping designers rely on pipe supports that do not restrain pipe movement. This type of support is called 'statically compliant,' and these supports typically take two forms:

1. Supports that employ low stiffness
2. Supports that allow for sliding

These two forms are discussed below:

Low stiffness supports

Typically, low-stiffness supports take the form of spring supports or spring cans. Because these supports are low stiffness, they can be defined (in contradistinction to a 'dynamically fixed' support which has enough stiffness to force a vibratory node) as having a stiffness less than is required to generate a vibratory node at 30 Hz. This low stiffness can be in any of the three cardinal directions, and only one direction needs to be low stiffness. Thus, a pipe support that has one or more of its directional stiffnesses less than those given in Table 2 is considered to be statically compliant.

Sliding supports

The second form of statically compliant supports are those which allow pipe migration through the use of sliding. The sliding occurs at a purpose-built contact surface which serves to allow relative movement between the pipe support and the undergirding structure. The pipe support stiffness acts to restrain the pipe up until the friction load is overcome at the contact surface, at which time the pipe support starts to slide. This means that this form of statically compliant support has a bi-linear force/deflection relationship. This can be seen in the figure below, which shows an example of a shoe-style support with a bi-linear force/deflection relationship. The idealized force/deflection graphs for each direction are included.

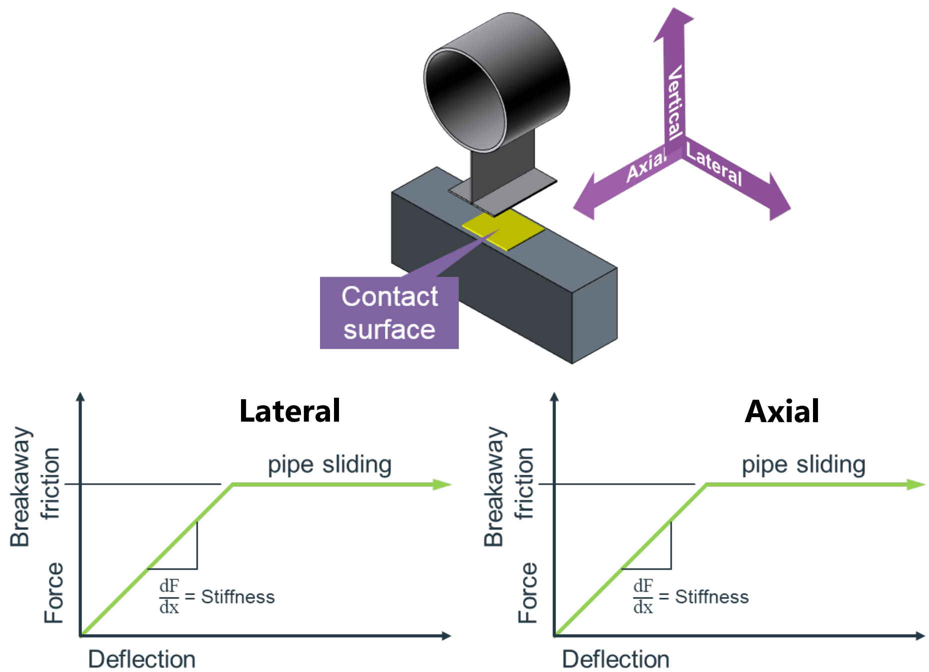


Figure 6: Sliding support force/deflection relationship per direction

In the figure above, if the piping system was to expand and the support was to experience a force in the lateral direction, the support would resist pipe motion up until the friction load at the contact surface was overcome. Until the friction is overcome, the friction at the contact surface is holding the support to the undergirding structure, and the force/deflection relationship has a slope equal to its stiffness of the support. After the friction at the contact surface is overcome, the force/deflection slope drops to almost zero, ie, the contact surface can bear no additional lateral force other than the base friction, so the force remains constant while the deflection continues to grow so long as the force is applied.

A pipe support that exhibits bi-linear sliding in any direction is to be considered statically compliant and suitable for thermal motion in those said directions.

Dual-purpose support distinctions

The characteristic that distinguishes dual-purpose supports within the broader category of statically compliant supports is that dual-purpose supports are dynamically stiff, meaning that they have sufficiently high stiffness in all three directions to force a vibratory node. This disqualifies dual-purpose supports from being the first form of statically compliant support discussed above, the low-stiffness support, as this is a contradiction. However, there is no contradiction in a dynamically stiff support employing the second form of statically compliance discussed above by allowing the pipe to slide. Dual-purpose supports are dynamically stiff when subject to dynamic loads, but still allow pipe migration by sliding under a static load. This is done by exploiting a peculiarity about piping system force magnitudes.

In typical piping systems, thermal loads at a support location are an order of magnitude greater than the dynamic loads. The reaction loads that dynamically stiff supports can experience when subjected to a thermal load can reach 10000 lbf or more, while the reaction loads due to a dynamic load would typically be much less than 1000 lbf. This means that a dual-purpose pipe support only needs to be dynamically stiff for a limited force range – that is, only for the range of dynamic forces that it experiences. A dual-purpose support would need a breakaway friction force that is designed to be high enough such that only static forces could initiate sliding. Figure 7 illustrates how a support could provide flexibility in a static load perspective but still provide rigidity for dynamic loads due to the bilinear behavior of stiffness.

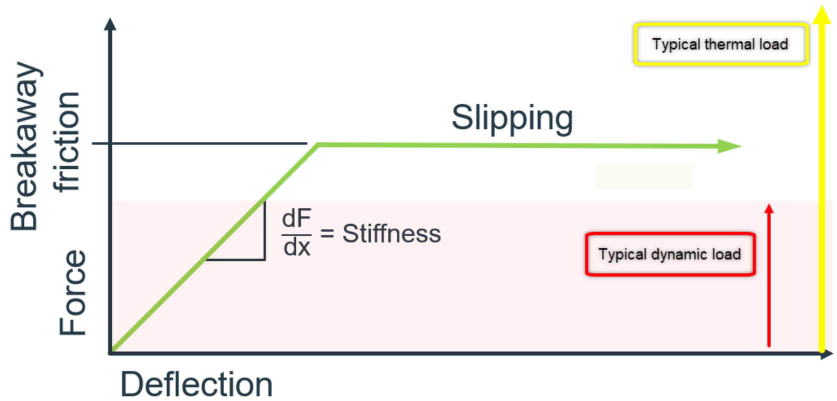


Figure 7: Typical dynamic and static load magnitudes at a pipe support

For the support to claim both titles of dynamically stiff and statically compliant, the breakaway friction force must exceed the 'dynamic load maximum,' which requires definition.

Defining 'dynamic load maximum'

One of the higher-magnitude dynamic forces that a piping system must resist are pulsation-induced shaking forces. In a pulsation analysis, a vibration analyst aims to minimize the pulsation-induced dynamic force in the piping, such that the force is less than some guideline level. A commonly used guideline for dynamic force in piping is to limit the dynamic force at a particular frequency to the level given in the equation below:

$$F_P = Min(500 \text{ or } 50 \times NPS)$$

where

F_P is the allowable pipe shaking force (lbf 0-pk)

NPS is the nominal pipe size (inches)

However, the dynamic force that a support must actually resist will be higher than the limit given above. This is because the overall force magnitude is composed of all the single-frequency forces, and there are typically forces at more than one frequency acting on a pipe span. Although the overall level will be higher than the single frequency limit given above, experience says that those overall levels typically do not exceed 4.0x the level given above for particular frequencies. This means that, even if a pulsation-induced shaking force were to reach guideline level, the overall would still be expected to be <4.0x. Thus:

Dynamic load maximum = Min (2000 or 200 x NPS) in lbf

If a support is to be considered dynamically fixed and statically compliant using a sliding mechanism, the breakaway friction force must be higher that the dynamic load maximum. That is, the breakaway friction force must have a minimum value of the dynamic load maximum, the values of which are tabulate below in Table 3.

Table 3: Breakaway friction minimum

Nominal pipe size	Breakaway friction minimum force	
	(lb)	(N)
2”	400	1,780
3”	600	2,670
4”	800	3,560
6”	1200	5,340
8”	1600	7,120
10” and greater	2000	8,900

A dual-purpose support has all three directional stiffnesses high enough to produce a vibratory node and has at least one direction that has a bi-linear force/displacement relationship, where the breakaway friction exceeds the dynamic load maximum that the support would experience.

Additional support considerations

While this paper is interested in providing criteria for sorting pipe supports into categories appropriate for their use, there are additional factors that should be considered for pipe support selection:

Damping

Damping can have a meaningful impact on support performance as related to its ability to minimize vibration. When piping is exposed to dynamic loading, the supports can play a significant role in vibration mitigation by acting to dissipate some of the vibratory energy that the pipe is experiencing. This ability to dissipate energy is defined as damping. Damping in piping itself is typically low, with typical damping ratios of 1% or less, but can be increased using various damping mechanism. Adding damping has been proven to mitigate vibration and is used widely in the automotive, aerospace and other industries.

In some cases, adding damping to a pipe supports can be counterproductive, as it may result in decreased stiffness. A support lined with an elastomeric damping material can be as much as 90% less stiff as compared to the same unlined support. The benefits of increased damping must be greater than negative effects due to the loss of stiffness. At resonance, the dynamic flexibility can be as much as 50x higher than the static flexibility. This amplification is reduced with damping as shown in Figure 8 below.

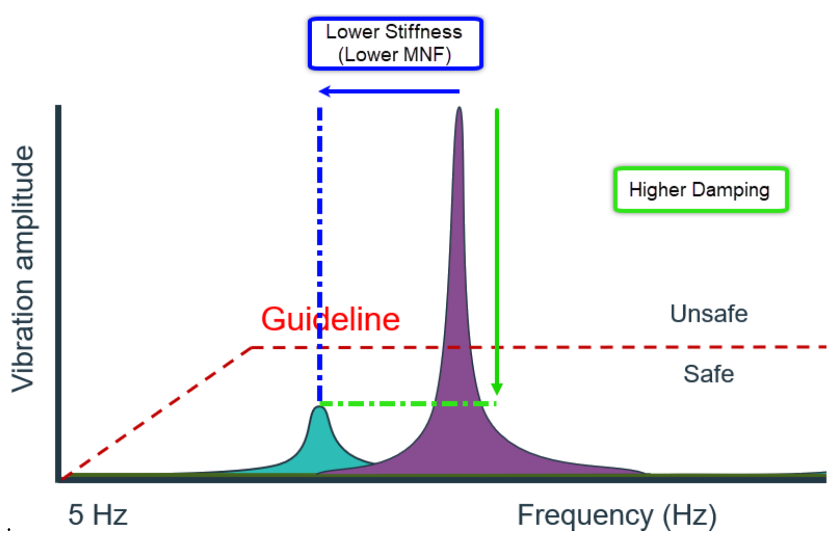


Figure 8: Typical comparison of a pipe support with and without damping

With damping support available on the market, piping system designers need to be able to quantify the performance of a support's damping properties. However, the use of damping to control vibration is unconventional in the piping industry, and benefits are often difficult to quantify based on the information available from manufacturers. Providing performance data would help piping system designers evaluate and select the right support to create an optimal piping design.

Support load maximums

Pipe supports, as all mechanical components, can only withstand a certain load before failure. It is important for piping designers to know that pipe supports can withstand the loads that are required of them. Ideally, supports would have a support load maximum published per direction, so that piping designers know if they are loading the supports appropriately during design.

Bolt loosening prevention

Pipe supports in vibratory service are typically subject to vibratory loosening of bolts. This disengages the support from the pipe, and the support no longer supplies the pipe with the required stiffness to act as a vibratory node. There have been many times where field vibration problems have been diagnosed as loose bolts on an anti-vibration support, and simply re-tightening the bolts eliminated the problem.

Ideally, anti-vibration supports would employ at least one form of bolt loosening prevention to ensure vibration problems do not manifest in the field. There are multiple forms of effective bolt loosening prevention available, such as wedge-lock washers, wedge ramp nuts, increased bolt stretch and many more. Anti-vibration supports, given they are employed in vibratory service, would benefit from the use at least one bolt loosening prevention mechanism, and it should be noted by manufacturers which methods are available and provided.

Pipe support classification process

Once the support performance is measured, pipe supports can be sorted by either a flow method or a graphic method, both of which are given below:

Flow chart

Figure 9 shows a flow chart that can be used for categorization of pipe supports to indicate their performance ability in different applications.

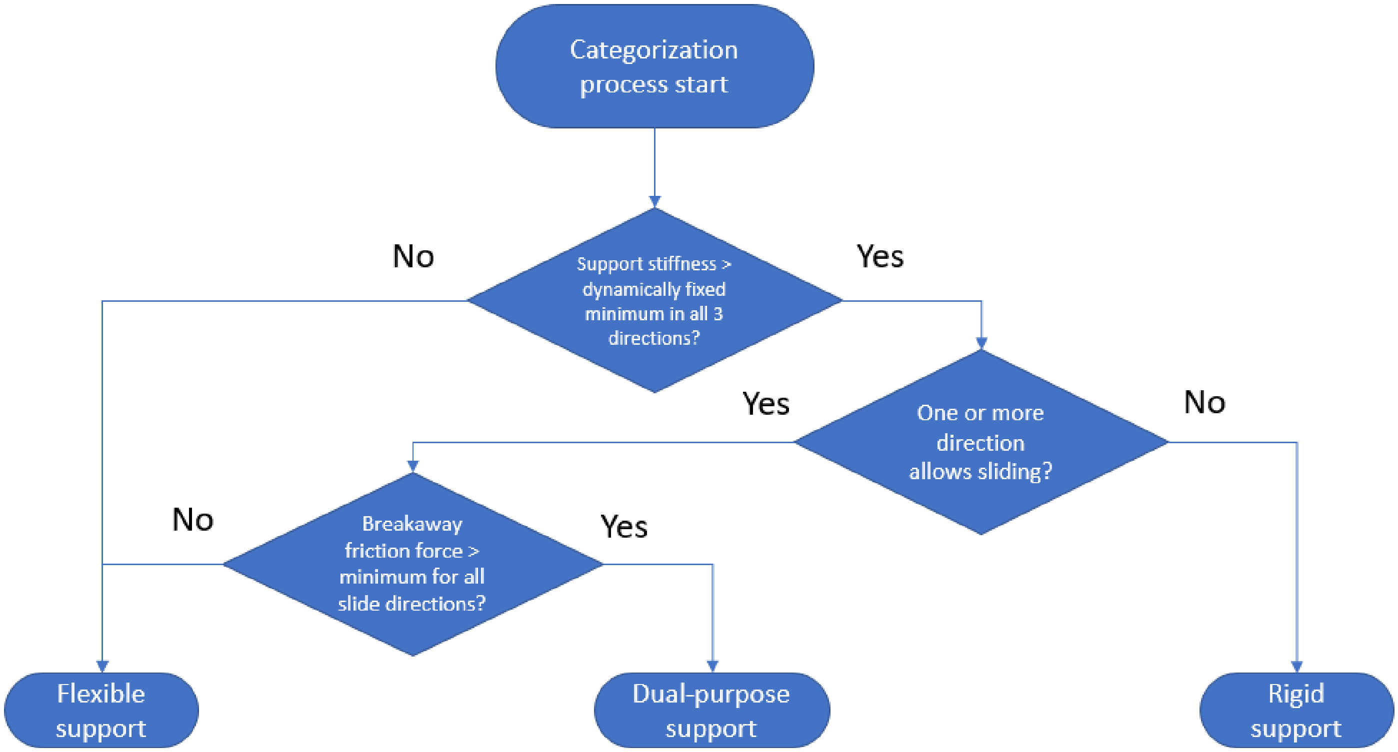


Figure 9: Pipe support classification flow chart

The pipe support classification can be completed quite easily as shown in Figure 9, as long as the stiffness, sliding and breakaway friction force characteristics of a particular pipe support are understood.

Force/deflection relationship

Figure 10 shows the force/deflection relationship for a single direction for various pipe supports and is an example that can be used in the categorization process shown in Figure 9. See Figure 10 and the commentary following to work through the example.

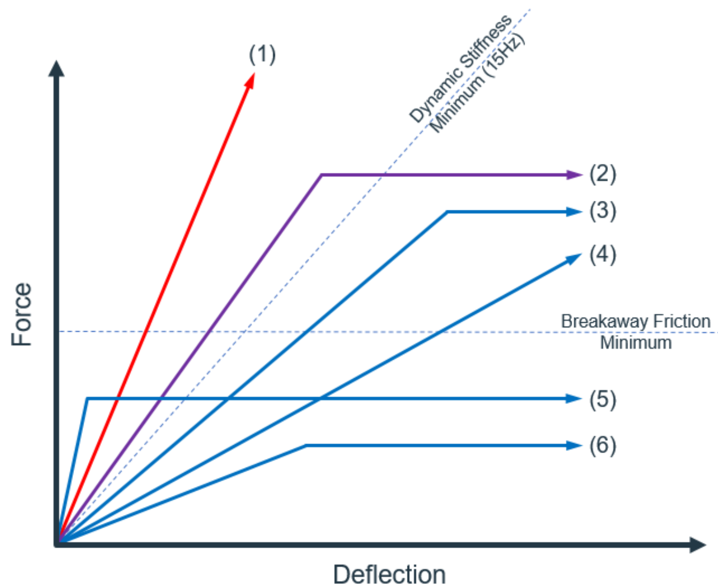


Figure 10: Force/deflection relationships for various pipe supports

- Support (1) has a linear force/deflection relationship with a stiffness greater than the dynamic stiffness minimum. If this support has this same character in the remaining two directions, then it is a 'rigid support.' It is appropriate for use in both vibratory and non-vibratory service.
- Support (2) has a bi-linear force relationship with a base stiffness greater than the dynamic stiffness minimum and a breakaway friction force greater than the breakaway friction minimum. If this support's remaining directions have force/displacement relationships similar to support (1) or (2), then this support is a 'dual-purpose' support and is appropriate for use in both vibratory and non-vibratory service.
- Support (3) has a bi-linear force relationship with a base stiffness less than the dynamic stiffness minimum. Even though it has a breakaway friction force greater than the breakaway friction minimum, and no matter what the other directional force/deflection relationships are, this support is a 'flexible' support. It is only appropriate for non-vibratory service.
- Support (4) has a linear force relationship with a stiffness less than the dynamic stiffness minimum. No matter what the other directional force/deflection relationships are, this support is a 'flexible' support. It is only appropriate for non-vibratory service.
- Support (5) has a bi-linear force relationship with a base stiffness greater than the dynamic stiffness minimum, but the breakaway friction force is less than the breakaway friction minimum. As such, no matter what the other directional force/deflection relationships are, this support is a 'flexible' support. It is only appropriate for non-vibratory service.
- Support (6) has a bi-linear force relationship with a base stiffness less than the dynamic stiffness minimum. It also has a breakaway friction force less than the breakaway friction minimum. No matter what the other directional force/deflection relationships are, this support is a 'flexible' support. It is only appropriate for non-vibratory service.

Methodology for determining pipe support performance

Given the categorization method proposed above, only two pipe support parameters need to be measured – the pipe support stiffness, and the breakaway friction force (if applicable). The following sections offer several options to collect these parameters.

Static support stiffness and breakaway force measurement – direct method

Direct measurement of the stiffness and the breakaway friction force can be made with the following relatively simple approach, using the following equipment:

- Pipe segment that can be pushed/pulled (translated) without having an induced moment (rotated)
- Method of measuring pipe displacement
- Method of applying a known force to the pipe
- Structural component to undergird the support. It is essential that the structure the supports are attached to is as stiff as practically possible compared to the pipe support itself. This creates the case in Figure 5 of pipe support stiffness << structural stiffness, leading to the total support stiffness being dominated by the pipe support itself. Such a configuration will ensure the evaluation focuses on the virtues of pipe support alone and not the structure below it.

The test procedure to determine the force/deflection relationship (stiffness and breakaway friction force) for the support is as follows:

1. Install the pipe support on the pipe segment and structural component, as per manufacturer requirements
2. Select the first direction of measurement and set-up pipe displacement equipment to capture displacement at the pipe centerline in direction of measurement
3. Apply force to the pipe in direction of measurement
4. Record deflection of pipe vs lateral force applied
5. Repeat steps 2-4 for the two remaining directions.

The stiffness and breakaway friction force can be identified from the plotted data, an example of which is shown in the figure below, Figure 11.

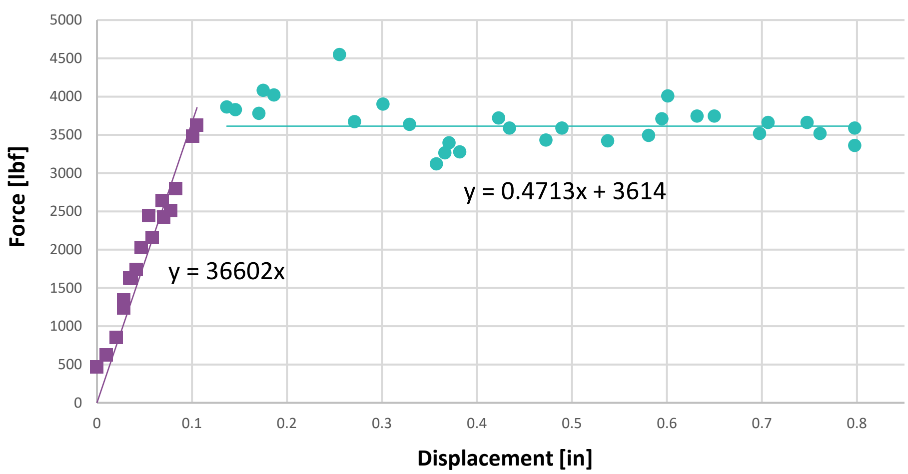


Figure 11: Force/deflection relationship for example support

The stiffness of the support is equal to the slope of the rising portion at the start of displacement. In the example above, the stiffness is 36602 lbf/in. The breakaway friction force is the force value at the point of intercept of the two lines, which is ~3614 lbf in this example.

(There may be a difference between the force at which sliding starts and the force at which sliding is maintained. This is the difference between static and dynamic friction. Static friction is the friction between two surfaces that are not in relative motion with each other, while dynamic friction is the friction between two surfaces that are in relative motion with respect to each other. Typically, dynamic friction is less than static friction, which is observed in this example. For materials for which the difference between the static and dynamic coefficients of friction are small, this effect will be negligible.)

Support stiffness measurement – indirect method, theoretical basis

Pipe support stiffness in the lateral and vertical directions can be measured indirectly from an impact test for a single piping span with two identical supports installed. For this, the structure undergirding the supports must be much stiffer than the supports for this test to be valid. Examples of structure that typically meet this requirement include concrete piers or W-beams with web gussets that are bolted directly to a concrete foundation.

For a single span of pipe with two supports, FEA modelling confirmed that pipe participation maps to pipe support stiffness no matter the pipe size or span length. Participation is defined as the vibration of the pipe at the support location as a percentage of the vibration at the center of the pipe span. Figure 12 shows pipe participation results for four different support stiffnesses.

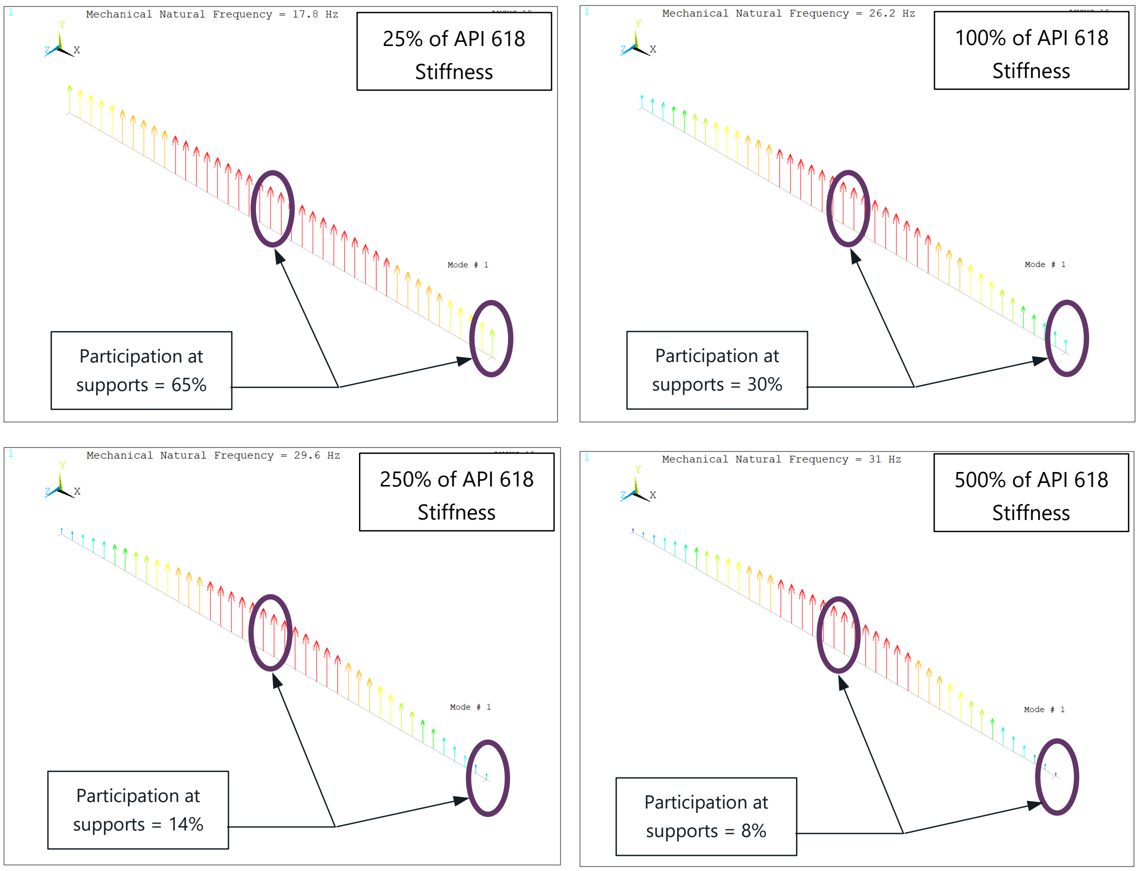


Figure 12: Support participation for various pipe support stiffnesses

The stiffnesses applied at the support locations were a percentage of the API 618 minimums, and were calculated as per the actual pipe diameter and thickness, for two active supports, and for the theoretical MNF for the span according to the formula:

$$f_n = 2201 \frac{r_g}{L^2}$$

where

f_n is the mechanical natural frequency for the span of pipe (Hz)

r_g is the radius of gyration of the pipe (in)

L is the length of the span (ft)

(assumes steel pipe with no fluidic contents)

Note that the MNF asymptotically approaches the theoretical MNF as the supports are made stiffer (17.8 Hz at 25% stiffness, 26.2 Hz at 100% stiffness, 29.6 Hz at 250% stiffness, and 31 Hz at 500% stiffness, all tracking towards the theoretical MNF of 32.6 Hz).

Figure 13 shows the stiffnesses of the support as a percentage of the API 618 minimums as it relates to the pipe participation.

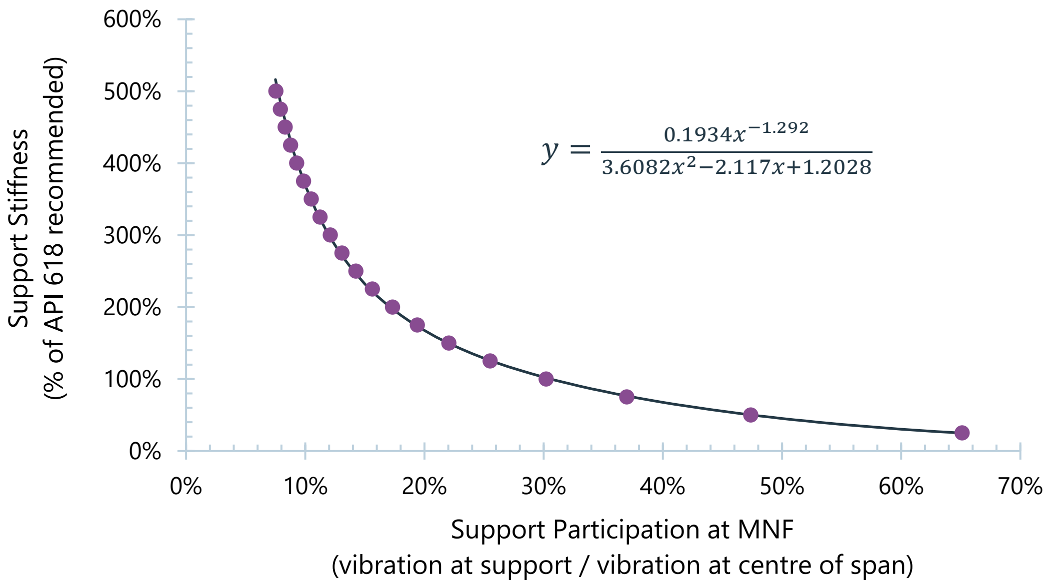


Figure 13: Relationship between support stiffness and pipe participation for a single span pipe

However, measuring the response on the pipe at the support location is not practical in most cases, as the support itself prevents access to the pipe. Measuring the response away from the support is required, but this results in a higher participation value than actual. A correction can be made that outputs pipe participation at the center of the support given the offset is known. The correction is according to the formula below (Offsets less than 5% of the span length are recommended):

$$P_{corrected} = \frac{L_{offset}}{L_{span}}\left(3.69P_{offset} - 3.724\right) + P_{offset}$$

Where

$P_{corrected}$ is the pipe participation at the center of the support (%, expressed as a decimal)

P_{offset} is the pipe participation at the measurement location (%, expressed as a decimal)

$L_{soffset}$ is the distance from the center of the support to the measurement location (in or mm)

L_{span} is the total span length, from the center of one support to the center of the other (in or mm)

Given these results, a bump test could serve as the basis to infer the support stiffness, according to the following method:

1. Set up a single span of pipe with two supports installed, one at each end. (The undergirding structure needs to be significantly stiffer than the pipe supports)
2. Measure the support span length, measured to the center of each support.
3. Calculate the theoretical MNF of the span, according to the formula above (or equivalent)
4. Calculate the API 618 minimum stiffness, as per the formula in Figure 3. Use the actual pipe properties, the theoretical MNF calculated in step 3, and two active supports (remember to use (n-1)/n instead of n-1/n).
5. Perform an impact test or a shaker test on the span of pipe. Measure the response of the pipe as near the supports as possible, and at the center span. (This procedure is filled out in the next section)
6. Identify the fundamental MNF. This MNF should correspond in frequency with the theoretical MNF. Check the phase to ensure you have identified the corrected mode.

7. Calculate the participation at the measurement location, using the response at the MNF identified in step 6. Take the average participation for the two supports. (support participation = max response at support / max response at center span)
8. Correct the participation at the measurement location to the participation at the support center location
9. Using the pipe participation at the support location, calculate the support stiffness %, using the regression curve given in Figure 13. (use decimals for percentages)
10. Calculate the actual support stiffness using the API 618 minimum calculated in step 4 and the support stiffness % from step 8. Support stiffness = API stiffness * support stiffness %

If so desired, a vibration test can replace the impact test in step 5. A shaker would replace the impact hammer as the source of excitation. The shaker would need to be able to input different frequencies of excitation in order to target the MNF of the pipe.

Support stiffness measurement – indirect method

The indirect measurement of the stiffness needs the following equipment:

- Two identical supports, for evaluation
- A pipe segment of appropriate length for the size of pipe (recommended minimum length of 30" * SQRT (NPS"))
- Four-channel data acquisition analyzer
- Four calibrated velometers/accelerometers
- Calibrated impact hammer, or Shaker
- A structural component to undergird each support. It is essential that the structure the supports are attached to is as stiff as practically possible, so that the supports are the component that determines the total stiffness that the pipe experiences compared to the pipe support itself for reasons discussed above.

The indirect support stiffness method of measurement has the same testing setup no matter if an impact test or a shaker is used. The test procedure is as follows:

1. Install the pipe support on the pipe segment and structural component, as per manufacturer requirements
2. Prepare data acquisition equipment for data capture
3. Select the first direction of measurement (lateral or vertical)
   Install velometers/accelerometers at the locations indicated on the figure below by the colored arrows. The velometers/accelerometers should be installed on the pipe only, and not the supports. Get them as close to the center of the support as possible.
4. Excite the pipe
   a. If using an impact hammer, strike at the mid-span
   b. If using a shaker, locate it at mid-span and sweep the frequency to find and record response at the fundamental piping MNF
5. Repeat for the remaining direction

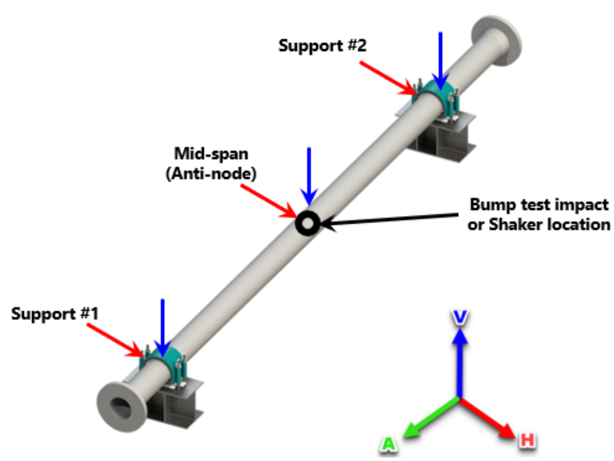


Figure 14: Stiffness measurement setup

An example impact test result is shown in Figure 15 for the lateral direction. The blue trace is the response at the mid-span, while the green and purple traces are the responses at the supports. The theoretical MNF, calculated using the natural frequency formula above, is noted with a dashed blue vertical line. Given the coherence between the theoretical and real-world MNFs and after performing a phase check to ensure all points are in phase (check not shown), we are justified in believing that this is the principal mode of the pipe. The vibration magnitudes at the real world MNF should be taken for use in the support participation calculation.

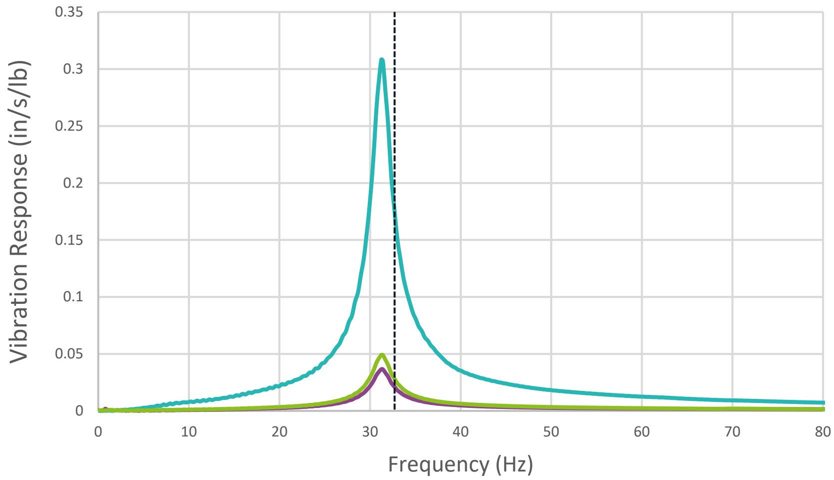


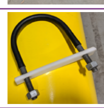
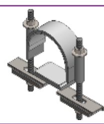
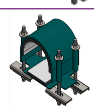
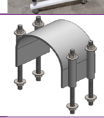
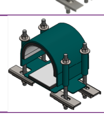
Figure 15: Impact test result for example support

Empirical data – categorizing and performance of real-life pipe supports

The following section presents the results of measurements that use the procedures outlined above to categorize 10 sample pipe supports commonly used in industry for both a 4"NPS and 10" NPS pipe. All testing was carried out with the methods prescribed above. Specifics on the equipment used to perform the testing is available in the appendix along with the detailed test results for each test performed. Table 4 summarizes the pipe supports tested with a description of their design.

Supports included in testing

Table 4: Tested supports

NPS	Support #	Image	Type	Liner/coating	Packer	Features
4"	#1		Lined U-bolt	Polymer coating	Damping polymer	Liner adds damping
	#2		Lined U-bolt	Polymer coating with PTFE contact liner	Damping polymer with PTFE contact liner	Low-friction axial sliding, liner adds damping
	#3		Lined U-bolt	Shrink coating	Thermoplastic half-round packer	Designed to prevent pipe corrosion
	#4		Flat bar clamp	Elastomeric damping liner with PTFE low-friction contact liner	Elastomeric damping liner with PTFE low-friction contact liner	Low-friction axial and lateral sliding, adds damping
	#5		Flat bar clamp CL-1-T-ST-4	PTFE low friction	PTFE low friction	Low-friction axial and lateral sliding
	#6		Flat bar clamp DCL-1-HT-T-ST-4"	Elastomeric damping liner with PTFE low-friction contact liner	Elastomeric damping liner with PTFE low-friction contact liner	Low-friction axial and lateral sliding, liner adds damping
10"	#7		Lined U-bolt	Shrink coating	Thermoplastic half-round packer	Designed to prevent pipe corrosion
	#8		Flat bar design CL-1-10"	None	Steel	
	#9		Flat bar clamp CL-1-T-ST-10"	PTFE low friction	PTFE low friction	Low-friction axial and lateral sliding
	#10		Flat bar clamp DCL1-T-ST-10	Elastomeric damping liner with PTFE low-friction contact liner	Elastomeric damping liner with PTFE low-friction contact liner	Low-friction axial and lateral sliding, liner adds damping

Stiffness calculation summary

The first step in the support categorization is the measurement and calculation of the support stiffness. The calculation summary for all supports is given in Table 5. The stiffnesses calculated are compared against the dynamic minimums for all three directions. For supports where all three stiffnesses exceed the dynamic minimum, the maximum frequency for which the support can maintain nodality is also reported.

Table 5: Categorization of common industrial pipe supports – summary

NPS	Support#	Direction	API 618 5th Ed. stiffness (lb/in)	Average measured participation	Corrected participation	% of API	Support stiffness (lb/in)	Stiffness > dynamic minimum?	F nodal
4"	#1	Vertical	9100	17.5%	14.9%	233%	21230	Y	N/A
		Lateral	9100	53.0%	51.5%	43%	3874	N	
		Axial	Pull test				2900	N	
	#2	Vertical	9100	12.0%	9.3%	403%	36665	Y	N/A
		Lateral	9100	52.0%	50.5%	44%	4038	N	
		Axial	Pull test				LOW	N	
	#3	Vertical	9100	7.5%	4.6%	922%	83863	Y	N/A
		Lateral	9100	13.0%	10.3%	357%	32449	Y	
		Axial	Pull test				4850	N	
	#4	Vertical	9100	14.0%	10.0%	369%	33598	Y	30.2
		Lateral	9100	18.5%	14.7%	238%	21617	Y	
		Axial	Pull test				29700	Y	
	#5	Vertical	9100	7.5%	3.2%	1455%	132416	Y	75.3
		Lateral	9100	10.0%	5.8%	700%	63724	Y	
		Axial	Pull test				22907	Y	
	#6	Vertical	9100	12.5%	8.4%	450%	40988	Y	34.5
		Lateral	9100	14.5%	10.5%	348%	31677	Y	
		Axial	pull test				16882	Y	
10"	#7	Vertical	204200	49.0%	47.4%	50%	102569	Y	N/A
		Lateral	204200	No MNF	N/A	N/A	LOW	N	
		Axial	Pull test				4500	N	
	#8	Vertical	204200	35.0%	26.9%	118%	240934	Y	35.3
		Lateral	204200	40.0%	32.5%	92%	188270	Y	
		Axial	Pull test				133950	Y	
	#9	Vertical	204200	34.5%	26.3%	121%	247287	Y	35.9
		Lateral	204200	47.0%	40.4%	67%	136192	Y	
		Axial	Pull test				96097	Y	
	#10	Vertical	204200	36.0%	28.0%	112%	228920	Y	34.1
		Lateral	204200	47.5%	40.9%	65%	133131	Y	
		Axial	Pull test				96000	Y	

Categorization summary

With the support stiffnesses available, and with the sliding force that the supports exhibit available from the raw data pull tests, support categorization can be carried out. Table 6 presents the results of such categorization for all the tested clamps. It follows the three decision points of the categorization flow chart given above.

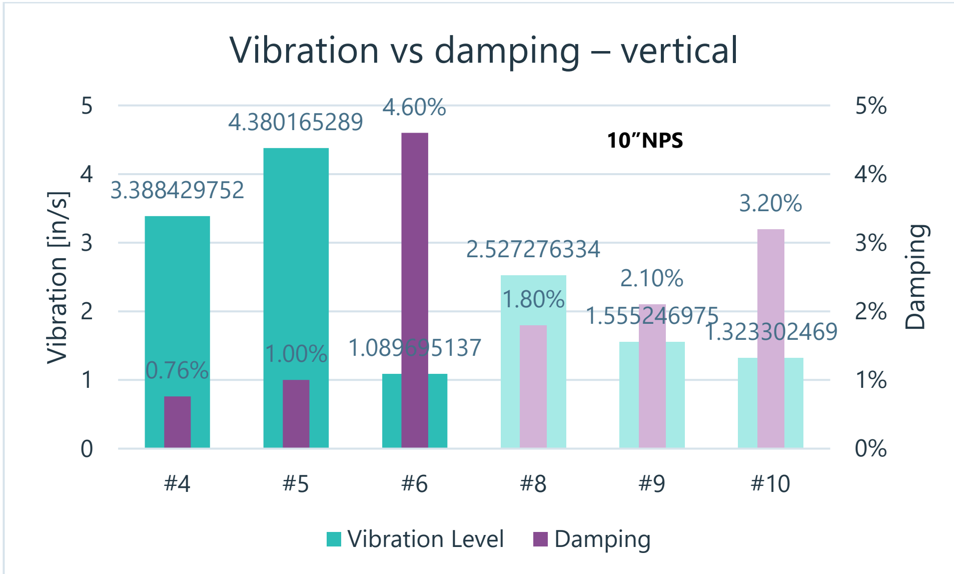
Table 6: Categorization process

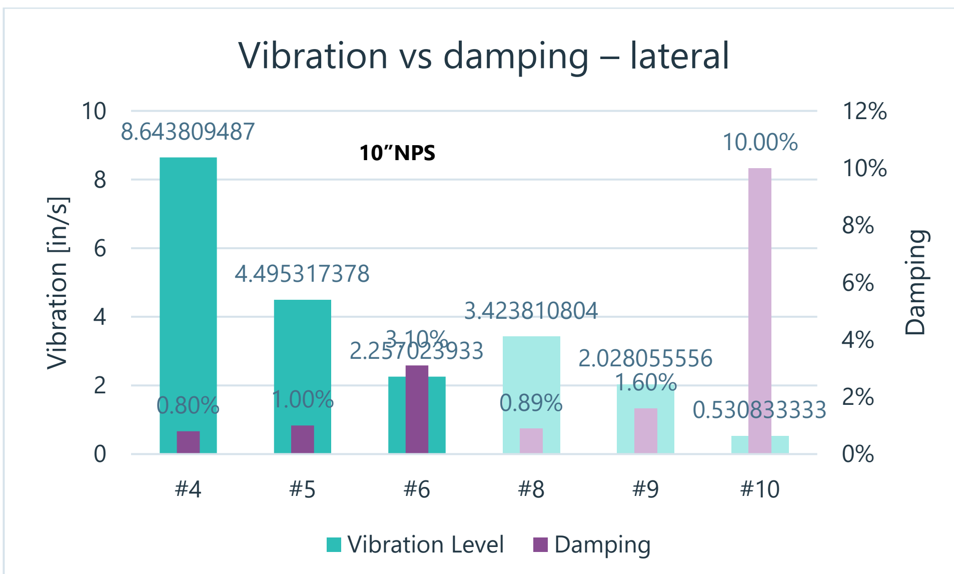
NPS	Support #	Description	Decision point 1: support stiffness > dynamic minimum in all directions?	Decision point 2: at least one direction allows sliding?	Decision point 3: breakaway friction force > minimum in all slide directions?	Category
4"	#1	Lined U-bolt	✗	NA	NA	Flexible
	#2	Lined U-bolt	✗	NA	NA	Flexible
	#3	Lined U-bolt	✗	NA	NA	Flexible
	#4	Flat bar clamp	✓	✓	✓	Dual purpose
	#5	Flat bar clamp CL-1-T-ST-4	✓	✓	✓	Dual purpose
	#6	Flat bar clamp DCL-1-HT-T-ST-4"	✓	✓	✓	Dual purpose
10"	#7	Lined U-bolt	✗	NA	NA	Flexible
	#8	Flat bar design CL-1-10"	✓	✗	NA	Rigid
	#9	Flat bar clamp CL-1-T-ST-10"	✓	✓	✓	Dual purpose
	#10	Flat bar clamp DCL1-T-ST-10	✓	✓	✓	Dual purpose

Results discussion

Vibration testing results are shown in Figure 16 below for the anti-vibration supports – those supports which qualify for use in vibratory service (categories 'rigid' or 'dual-purpose'). As the measurements show, the span damping ratio is a good predictor of vibration magnitude for the span – the higher the span damping, the lower the vibration response.

The procedure we proposed to qualify a support as 'anti-vibration' does not currently account for this result. Our procedure only considers the stiffness of the support, and questions whether it is high enough to generate a vibration node. Linings in supports will typically reduce the stiffness of the support and eat away at the maximum frequency at which the support can maintain nodality. However, this loss in stiffness might be offset by damping that the support adds to the piping span. Reduced stiffness is often a negative for an anti-vibration support as it hinders the support's ability to act as a vibratory node. However, the results above suggest the decrease of stiffness generally associated with linings might only in part affect support performance. With the increase in damping of a support, even though it acts less as a vibratory node, it can translate to an improved performance overall. The drawback in the current procedure is that it may disqualify a high-damping support due to stiffness considerations, whereas the damping that support provides should otherwise qualify it to serve the role of anti-vibration support. This emphasizes the need for some form of calibrated vibration testing benchmark to add or modify the methodology present herein.





*The 4" NPS supports vibration normalize to a frequency 30 Hz and the 8" NPS supports to a frequency of 70 Hz

Figure 16: Vibration performance for supports qualified for use in vibratory service

Recommendations

Manufacturer reporting on pipe support classifications

The goal of this initiative is to allow designers and engineers to make more informed decisions when selecting pipe supports. It is still common to see flexible supports installed on piping in vibratory service, and field level fixes are often required to deal with vibration problems that arise from inappropriate use of supports. It is thus recommended that support manufacturers begin to supply the information that piping designers need to both select the right support and to model the support accurately in pipe stress and vibration analyses.

The following presents the proposed minimum support classification data that must be reported:

- Flexible supports are relatively simple to model and require little information for accurate modelling. Typically, the performance of the support will be driven by the structure it interacts with, which is outside the manufacturer scope. As such, breakaway friction force or COF are not within manufacturer scope, unless these parameters are intrinsic to the support design. A support manufacturer should supply the following information for a typical flexible support:
    - Stiffness, in all three directions
    - Allowable load, in all three directions
    - Breakaway friction force, if intrinsic to support
    - Coefficient of friction, if intrinsic to support
    - Sliding surface material, if sliding is at the support/structural contact
    - Travel gap, if intrinsic to the support
- Rigid supports are also relatively simple to model and require little information for accurate modelling. Manufacturers should be able to supply all the information required in the list below, as all support parameters for a rigid support are intrinsic to the support. A support manufacturer should supply the following information for a typical rigid support:
    - Maximum frequency at which nodality can be maintained
    - Stiffness, in all three directions
    - Allowable load, in all three directions
- Dual purpose supports are more difficult to model and require more information to be modelled accurately. This information is currently missing from many supports available on the market and needs to be provided to allow better design decisions. A support manufacturer should supply the following information for a typical dual-purpose support:
    - Maximum frequency at which nodality can be maintained
    - Stiffness, in all three directions
    - Allowable load, in all three directions
    - Directions in which sliding can occur
    - Breakaway friction force for each direction in which sliding occurs
    - Coefficient of friction, if intrinsic to support
    - Sliding material, if sliding is at the support/structural contact
    - Travel gap, if intrinsic to the support

Conclusion

This paper provides a framework for industrial designers and end users of piping systems to better understand which pipe supports are suitable for vibration service, thermal service and combined service in their systems. It presents methodologies for categorizing pipe supports to clearly display what service functions they are suitable for. The categorization process involves empirical measurements of the supports to determine performance in the criteria of support stiffness, sliding ability and damping.

Pipe supports can generally be described in two broad categories:

1. **Thermal supports**: statically compliant, allowing pipe movement under thermal loads
2. **Anti-vibration supports**: dynamically fixed, preventing pipe movement under dynamic loads

However, it is discussed that these two categories are not mutually exclusive, and they can be integrated into a single support. This gives rise to three sub-categories of supports within the two broad categories of supports above. The table below summarizes as:

Support type	Function	Service
Flexible supports	Allow both static and dynamic pipe movement. Use where static loads must be accommodated and there is no significant dynamic (vibratory) load	Non-vibratory service only
Rigid supports	Prevent both static and dynamic pipe movement. Use where dynamic loads must be resisted and there is no significant static load	Both vibratory and non-vibratory service
Dual-purpose supports	Allow static movement but prevent dynamic pipe movement. Use where dynamic loads must be resisted *and* static loads must be accommodated	Both vibratory and non-vibratory service

A minimum set of information is recommended that should be published by support manufacturers so that piping designers and end users can select the appropriate pipe supports for their application and to model them accurately.

The provided testing methodologies were used to demonstrate the performance and categorization of 10 pipe supports commonly used in the industry for a 4” NPS and 10” NPS pipe. The results presented in this paper demonstrate that many common pipe supports can be categorized sufficiently to the benefit of designers and end users and can be used to validate claims of a support’s validity in vibration or thermal service. It also proves that supports can be designed to achieve the dual purposes of anti-vibration and thermal requirements.

The proposed procedures not only address the need for a general classification of supports but also the specific need for actual characterization data to allow more realistic modeling. These procedures can be used to help classify further supports and sizes not tested here.

This paper also proposes for industry guidelines to prompt support manufacturers to categorize their supports according to the scheme described herein and to provide information about the support that enables piping designers to make an informed decision on a support’s appropriate application.

Future work

A methodology to standardize the vibration performance to a benchmark is needed to account for (or discount) the categorization based upon actual vibration performance of a particular support. Although the stiffness methodology is useful from a pipe stress and vibration analysis prediction perspective, a grading system that can adjust the categorization based on vibration performance must be given to inform users of the practical vibration performance that can be expected.

For the indirect method of stiffness measurement, it was observed that the damping the span experiences can vary widely depending on the support. The range of damping varied from a low of around 0.5% to upwards of 10% damping. The categorization method prescribed in this paper does not account for the damping the support imbues to the pipe, but this turns out to be a highly important variable in regard of a support’s anti-vibration performance. A future version of this categorization method should account for damping and include it in some fashion as a qualification for anti-vibration supports. Indeed, a support with high damping will see its stiffness decrease despite potentially better vibration control performance. The reduction of stiffness may exclude high-damping supports as per the criteria used in this paper.

The pulling rig used for the ‘static support stiffness and breakaway force’ measurement was found to have difficulty in making static stiffness measurements. The pipe was not adequately restrained from rotating during the pulls, and we found that this exaggerated the displacements being measured. As such, the stiffnesses calculated from the direct pull method are likely lower than the actual stiffness. This also likely explains most of the difference in results we observed in the two calculation methods. The lateral and vertical stiffnesses calculated by the indirect method are thus preferred. The breakaway friction force may also have suffered because of this issue. An improved pulling rig was designed to eliminate this problem, but fabrication of the rig was not complete before publication. Future versions of this categorization method should check for parity between the two calculation methods. Additionally, the pipe used on the rig did not directly match that proposed for use in the indirect stiffness method. The difference in results due to using the actual test rig has not been evaluated at this time, and the actual stiffness may differ from the calculated results because of this.

The procedure prescribed for categorizing the supports did not account for the effect of multiple push/pull cycles for dual purpose supports. Ideally, a dual-purpose support would have the same breakaway friction force for each pull, but our limited testing in this area indicates that the breakaway friction force will converge at a final breakaway friction force. A future version of the categorization method should account for this phenomenon.

The procedure prescribed for categorizing the supports only allows for real-world testing. In the future, a version of categorization could include FEA modelling as a means to generate some or all of the data used to categorize the supports. Results would have to be validated by real-world results, and a validation method would need to be prescribed.

The procedure prescribed for categorizing the supports assumed the contents of the piping was empty. A pipe with liquid would be subject to different mechanical natural frequencies and different minimum stiffnesses. A future version of support categorization could include a procedure that deals with supports for use on pipes with liquid contents.

Free webinar

Watch our free, on-demand webinar for more information and examples:

References

API RP 688. (1st Edition). *Pulsation and Vibration Control in Positive Displacement Machinery Systems for Petroleum, Petrochemical, and Natural Gas Industry Services*.

API Std 618. (5th Edition). *Reciprocating Compressors for Petroleum, Chemical and Gas Industry Services*.

API Std 674. (3rd Edition). *Positive Displacement Pumps—Reciprocating*.

Chris Harper, Timothy Bootsveld. (2017, December 13). Wood Webinars. *Shake, Rattle, and Grow Pt. I*.

GMRC, Wood (formerly BETA Machinery Analysis). (2005). *Pipe Support Stiffness.* Dallas: GMRC.

Timothy Bootsveld, Jordan Grose. (2018, September 26). Wood Webinars. *Shake, Rattle, and Grow Pt. II*.

Appendix A – equipment, methodology and raw data

The following section presents the equipment used, the specific method and results for 10 pipe supports that were tested on both a 4”NPS and 10” NPS pipe.

Test rig

The test rig in its initial configuration for determining the pipe support data is shown in the figure below. The test setup is shared by all following tests presented in this paper and is essentially a pipe with pinned-pinned boundary conditions at the support locations. An A106B carbon steel pipe with NPS (nominal pipe size) of the support to be tested is laid down on two 8”x24 wide flange beams anchored to a concrete floor. The beams have end caps and a mid-gusset welded into the web to ensure the structure is as stiff as possible.

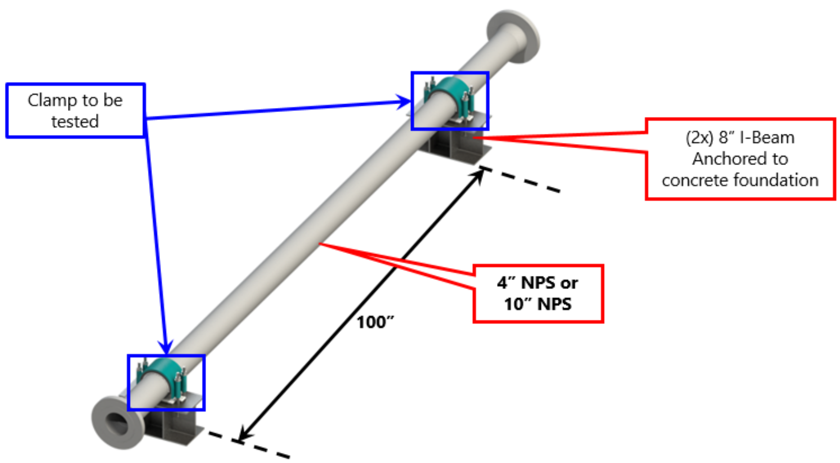
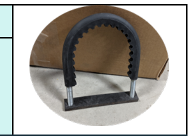


Figure 17: Basic setup

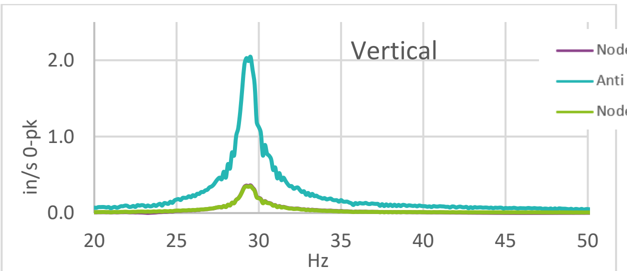
Equipment used

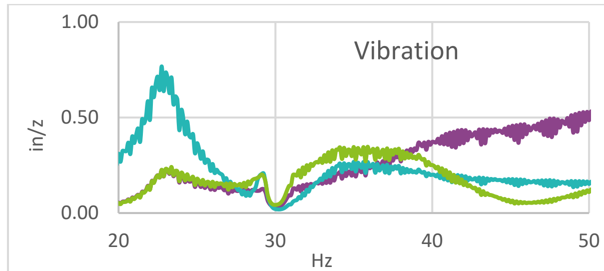
- A four-channel data acquisition analyzer; Data Physics Quattro
- Four calibrated velometers
- Linear displacement transducer
- Calibrated impact hammer
- Rotating weight shaker with consistent unbalance weight setting for each vibration test
- One variable frequency drive
- One digital torque wrench
- Two pulling straps
- One 4 inches sch std pipe x 120 inches long; flanged at both ends
- One 10 inches sch std pipe x 120 inches long; flanged at both ends
- Supporting beams 120 inches apart
- Two specimens of each pipe support tested

Support #1 test results

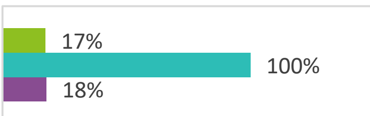
Description:	Coated u-bolts	
Key manufacturer claimed features	• Isolates pipe from the mounting bolts and u-bolt to prevent fretting and corrosion • Isolates dissimilar metals (eg, between pipe and u-bolt) to prevent electrolytic corrosion • Allows thermal expansion and contraction	

Vibration test:





Node participation



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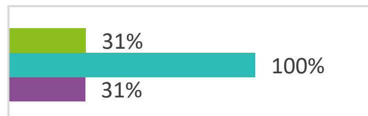
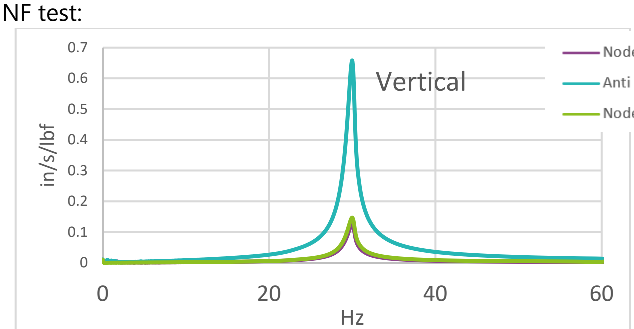
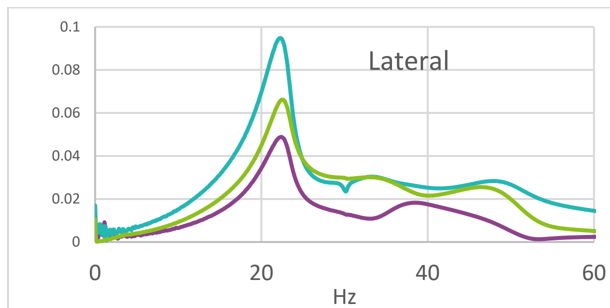


MNF test:

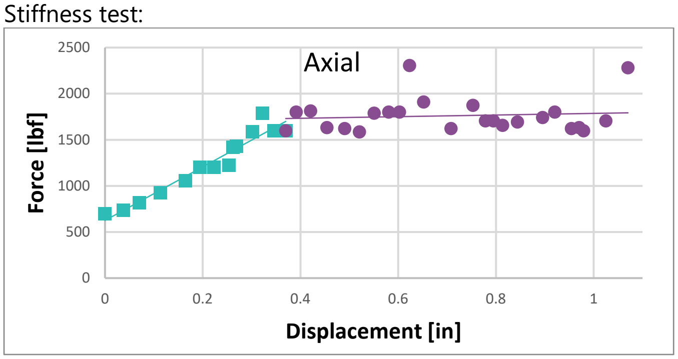


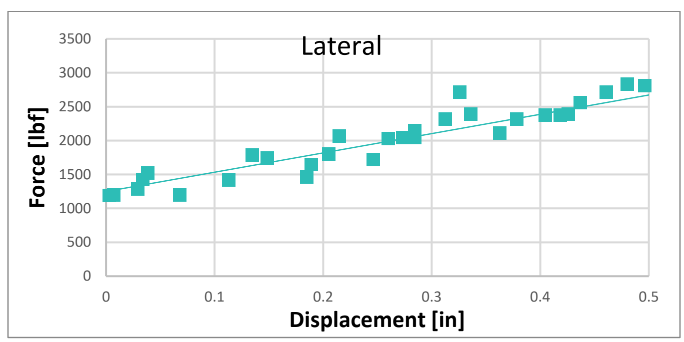


	Experimental	Theoretical	Ratio
MNF	30	31.9	0.94
Damping	1.5%		

	Experimental	Theoretical	Ratio
MNF	22.6 Hz	31.9	0.71
Damping	8.5%		

Stiffness test:





Stiffness type	Bilinear
Stiffness	2900 lbf/in
Breakaway Force	1700 lbf
Coefficient of friction	NA

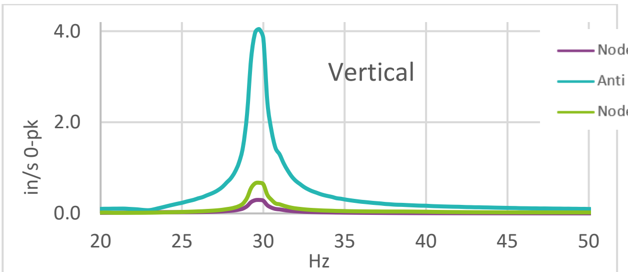
Stiffness type	Linear
Stiffness	2850 lbf/in
Breakaway Force	NA
Coefficient of friction	NA

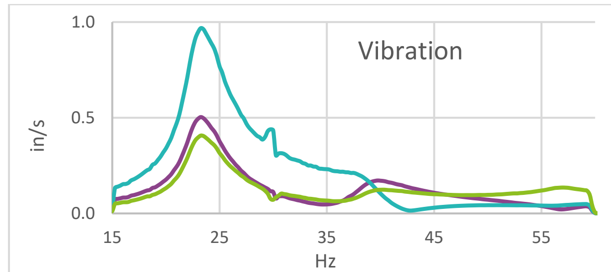
Results comments:	Flexible in lateral direction throughout the test frequency. Permanent distortion of the support is observed through the stiffness test. The bilinear axial stiffness curve is not caused by true sliding but rotation/distortion of the u-bolt liner. Damping measured did not have a significant effect on vibration levels.	Categorisation results: **Flexible**

Support #2 test results

Description:	Polymer coated u-bolts; Damping rest; PTFE-lined	
Key manufacturer claimed features	• Isolates the pipe from the mounting bolts and u-bolt to prevent fretting and corrosion. • Isolates dissimilar metals (eg, between pipe and u-bolt) to prevent electrolytic corrosion • Allows thermal expansion and contraction	

Vibration test:





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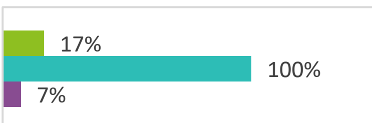

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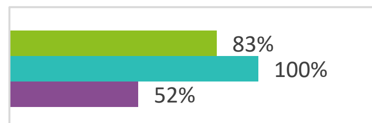
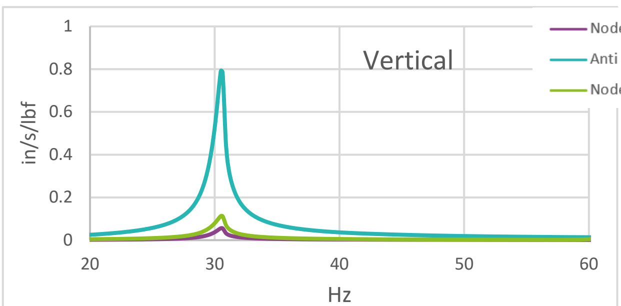
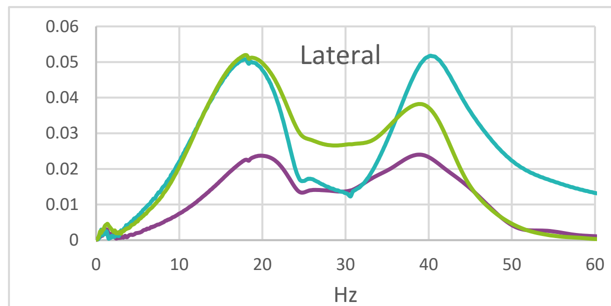


MNF test:



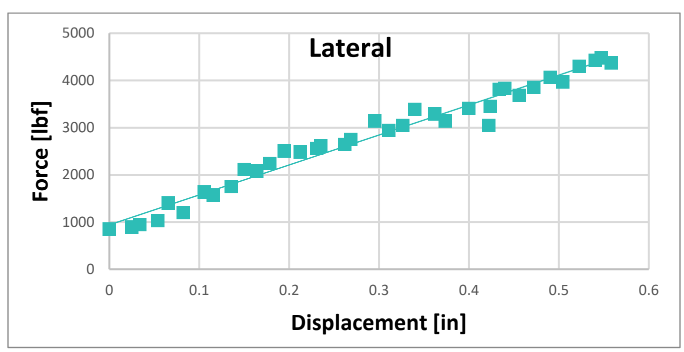


	Experimental	Theoretical	Ratio
MNF	30.5	31.9	0.96
Damping	1.3%		

	Experimental	Theoretical	Ratio
MNF	18.5	31.9	0.58
Damping	NA		

Stiffness test:

No Data



Stiffness type	
Stiffness	
Breakaway Force	
Coefficient of friction	

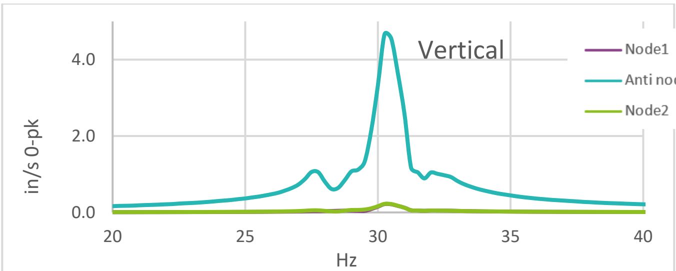
Stiffness type	Linear
Stiffness	6350 lbf/in
Breakaway Force	NA
Coefficient of friction	NA

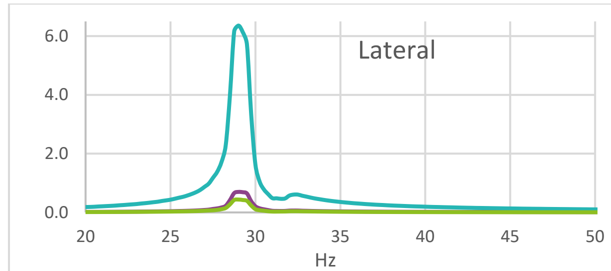
Results comments:	Very flexible in the lateral direction despite acceptable results in the vertical direction. The lateral mode shape at resonance does not exhibit pinned-pinned behaviour, it appears to be rigid body motion. Axial stiffness and breakaway force are too low to register through the used method of measurement. High vibration response.	Categorisation results: **Flexible**

Support #3 test results

Description:	Heat-shrink coated u-bolt; thermoplastic rest	
Key manufacturer claimed features	• Anti-corrosion • Electrical isolation	

Vibration test:





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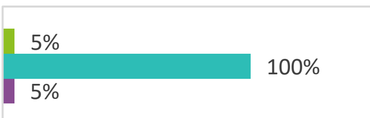

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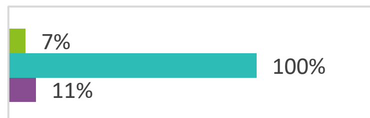
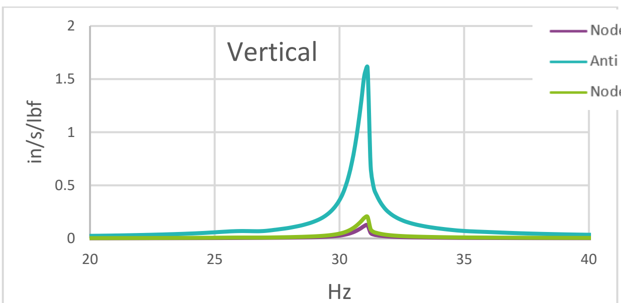
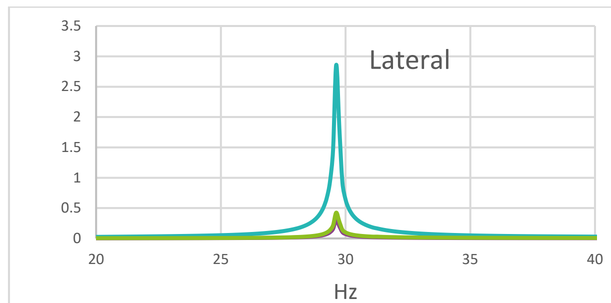


MNF test:

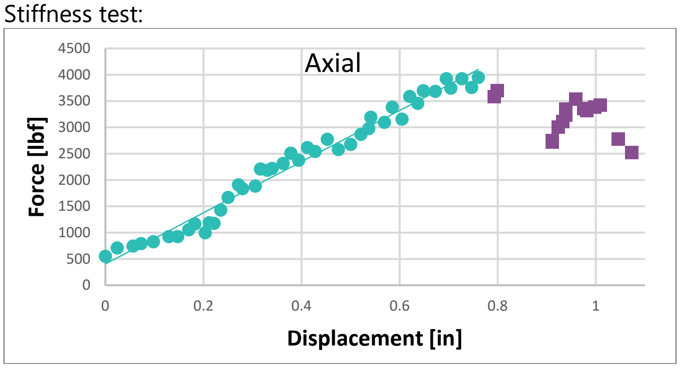


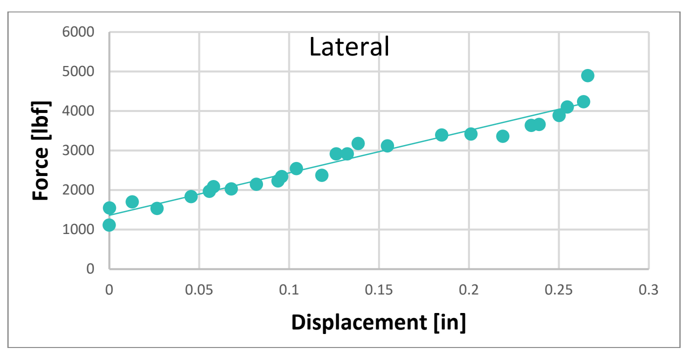


	Experimental	Theoretical	Ratio
MNF	31.1	31.9	0.97
Damping	0.8%		

	Experimental	Theoretical	Ratio
MNF	29.6	31.9	0.93
Damping	0.95%		

Stiffness test:



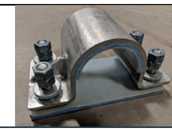


Stiffness type	Bilinear
Stiffness	4850 lbf/in
Breakaway Force	3500 lbf
Coefficient of friction	TBD

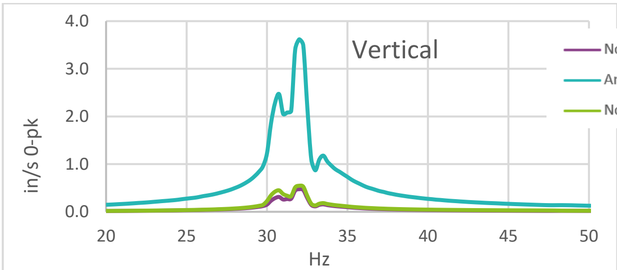
Stiffness type	Linear
Stiffness	10700 lbf/in
Breakaway Force	NA
Coefficient of friction	NA

Results comments:	U-bolt liner gets distorted through the stiffness test. The axial stiffness exhibits a breakaway force threshold which is accompanied with damage to bolt coating. Only good for small transverse displacement. High to very high vibration response.	Categorisation results: **Flexible**

Support #4 test results

Description:	Flat bar pipe clamp design; damping polymer and PTFE-lined	
Key manufacturer claimed features	• Damping material liner • PTFE contact layer for low-friction sliding	

Vibration test:



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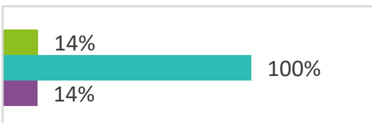

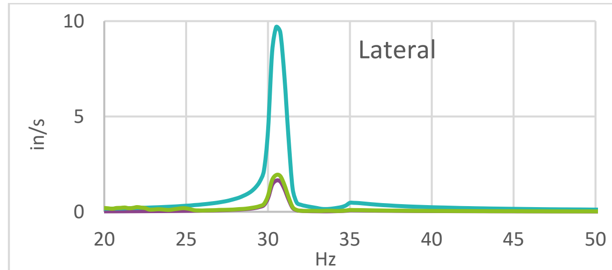

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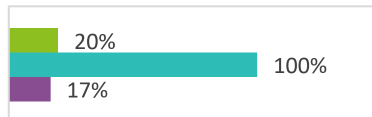
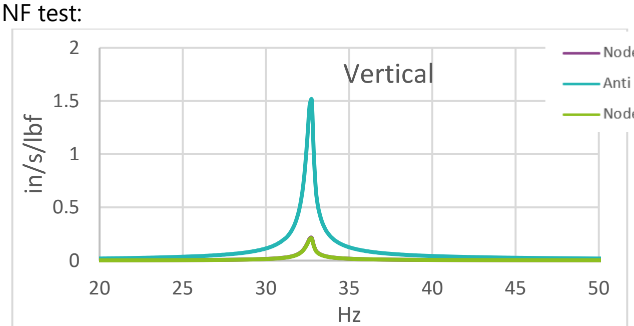
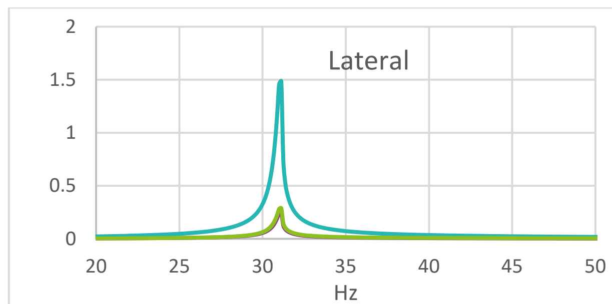


MNF test:

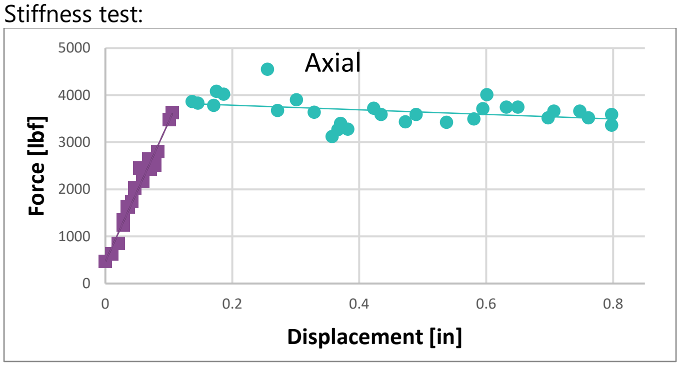


	Experimental	Theoretical	Ratio
MNF	32.8 Hz	31.9 Hz	1.03
Damping	0.76%		

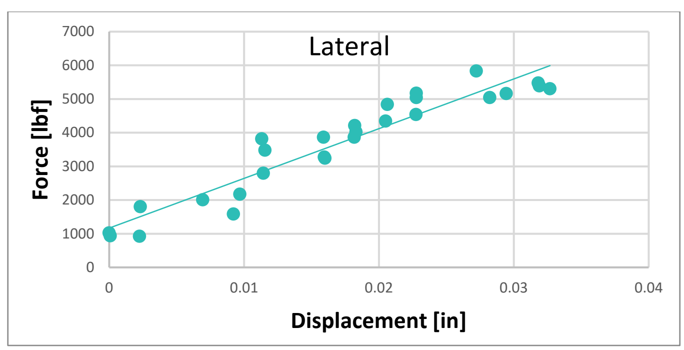


	Experimental	Theoretical	Ratio
MNF	31.1	31.9	0.97
Damping	0.8%		

Stiffness test:



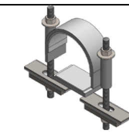
Stiffness type	Bilinear
Stiffness	29700 lbf/in
Breakaway Force	3700 lbf
Coefficient of friction	0.2



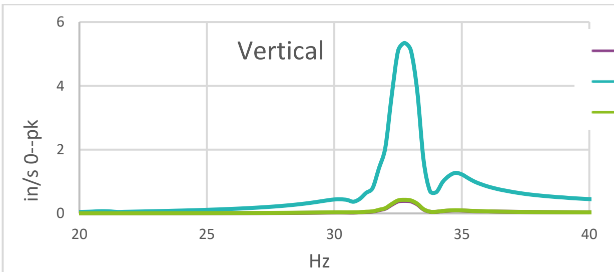
Stiffness type	Linear
Stiffness	147614 lbf/in
Breakaway Force	NA
Coefficient of friction	NA

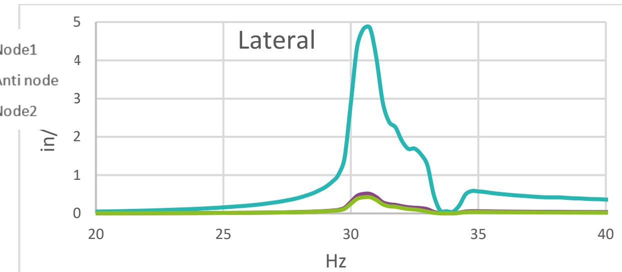
Results comments:	Noticeably higher vibration level in the lateral direction compared the other clamps tested. The damping is measured to be even less than the 1% damping with simple metal clamps. Extreme vibration levels observed.	Categorisation results: **Dual purpose**

Support #5 test results

Description:	CL-1-T-ST-4; flat bar pipe clamp design with PTFE liner, and lateral sliding hardware	
Key manufacturer claimed features	• Allows for thermal growth in axial and lateral direction	

Vibration test:





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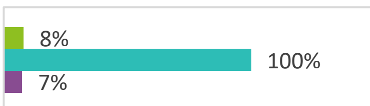

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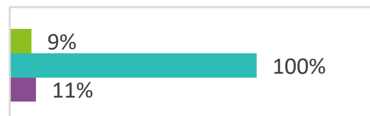
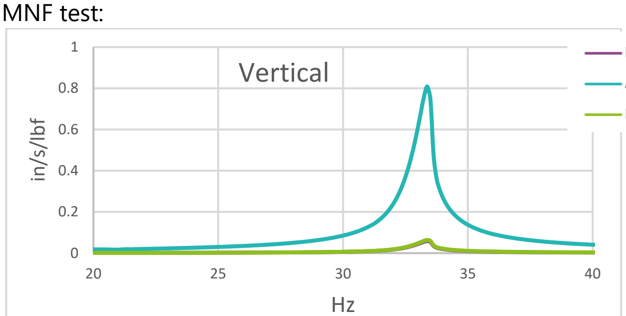
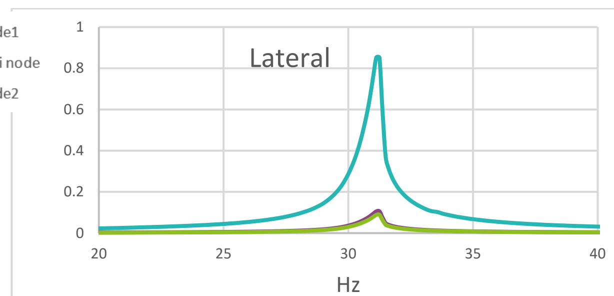


MNF test:

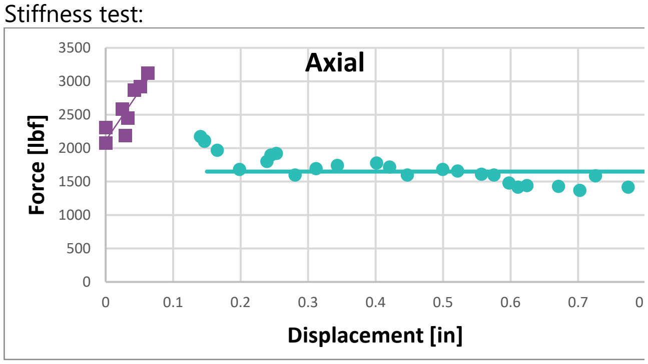


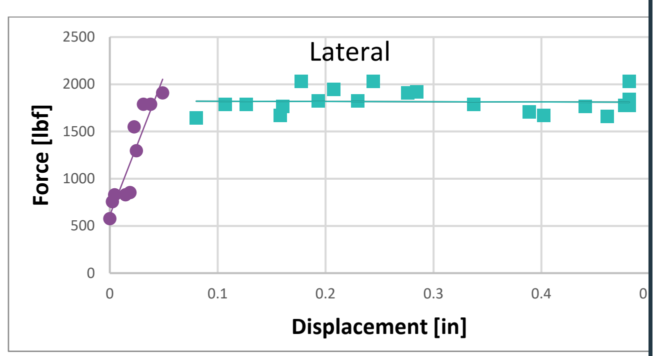


	Experimental	Theoretical	Ratio
MNF	33.4	31.9	0.97
Damping	1.01		

	Experimental	Theoretical	Ratio
MNF	31.3	31.9	0.98
Damping	1.0%		

Stiffness test:



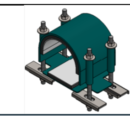


Stiffness type	Bilinear
Stiffness	22907 lbf/in
Breakaway Force	1600 lbf
Coefficient of friction	0.17

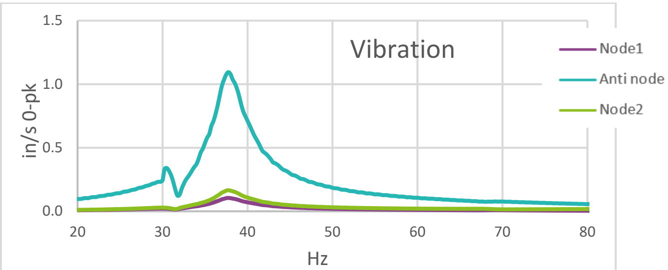
Stiffness type	Bilinear
Stiffness	29500 lbf/in
Breakaway Force	1700 lbf
Coefficient of friction	0.09

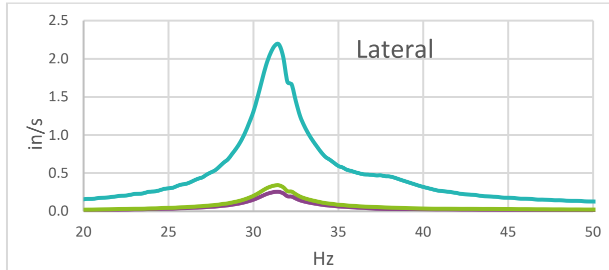
Results comments:	Axial stiffness is significantly offset from the zero point, possible related to rig issues. Performs well as anti-vibration clamp, exhibiting good nodality. Exhibits bilinear stiffness in both axial and lateral directions. Higher MNF than previous clamps. High vibration levels observed.	Categorisation results: **Dual purpose**

Support #6 test results

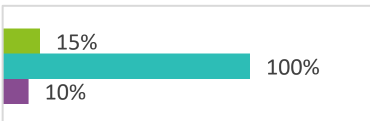
Description:	DCL1-HT-T-ST-4; Flat bar pipe clamp design with damping and lateral sliding hardware	
Key manufacturer claimed features	• Allows for thermal growth in axial and lateral direction • Damping liner with a PTFE contact layer for low-friction sliding	

Vibration test:





Node participation



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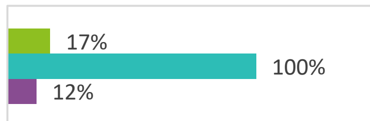
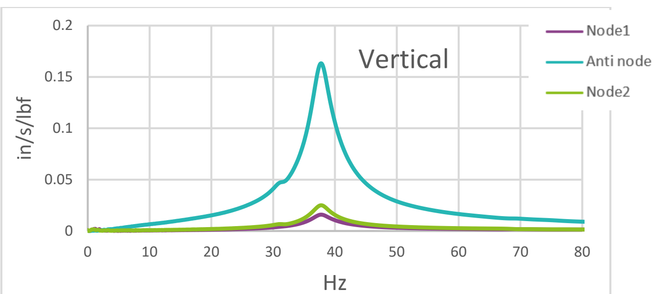
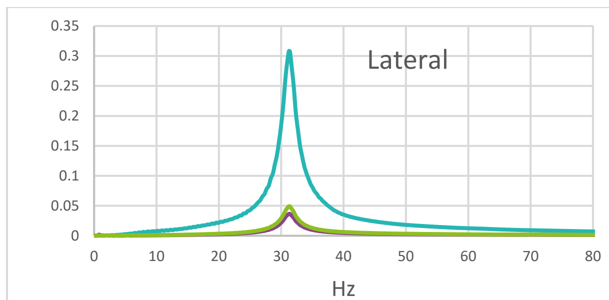


MNF test:

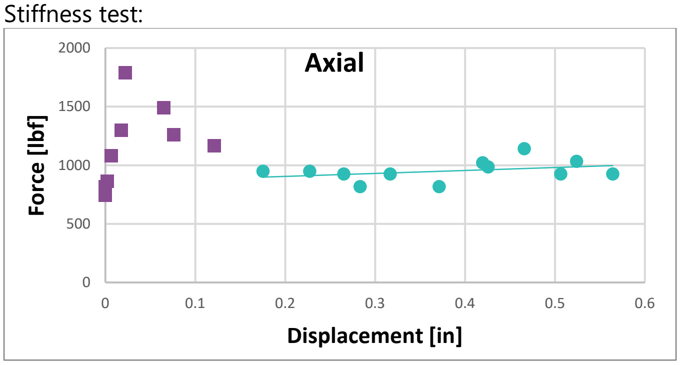


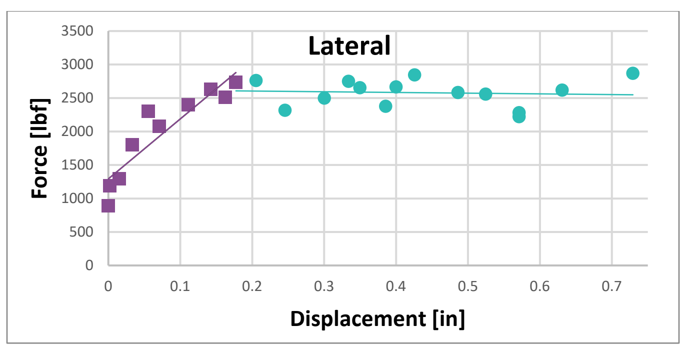


	Experimental	Theoretical	Ratio
MNF	37.8	31.9	1.18
Damping	4.6 %		

	Experimental	Theoretical	Ratio
MNF	31.3	31.9	0.93
Damping	3.1 %		

Stiffness test:





Stiffness type	Bilinear
Stiffness	??? lbf/in
Breakaway Force	950 lbf
Coefficient of friction	0.05

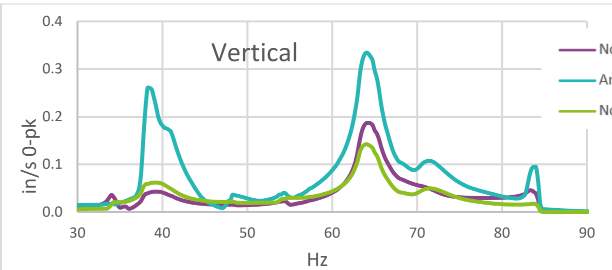
Stiffness type	Bilinear
Stiffness	9000 lbf/in
Breakaway Force	2500 lbf
Coefficient of friction	0.13

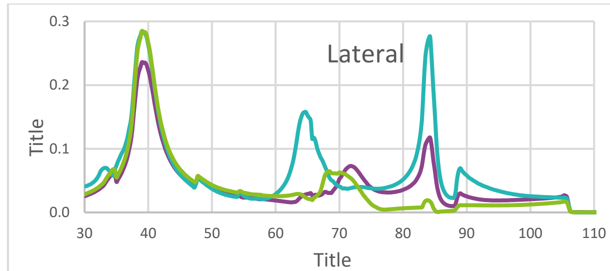
Results comments:	Static stiffness in axial direction could not be determined. Exhibits the lowest vibration level of all 4" supports tested. Damping measured upwards of 4.6%.	Categorisation results: **Dual purpose**

Support #7 test results

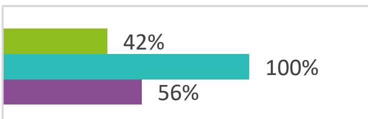
Description:	Heat shrink u-bolt coated; Thermoplastic sleeper; **10” NPS**	
Key manufacturer claimed features	• Anti-corrosion • Electrical Isolation	

Vibration test:

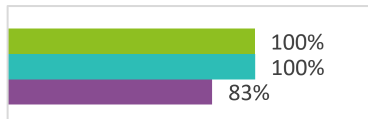




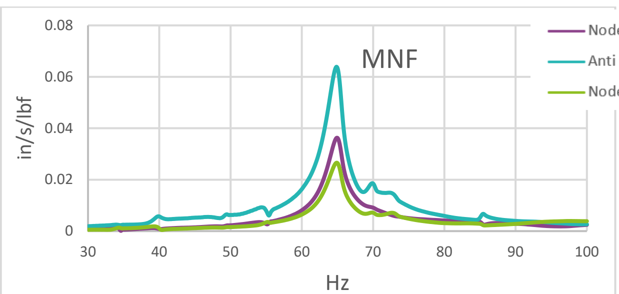
Node participation

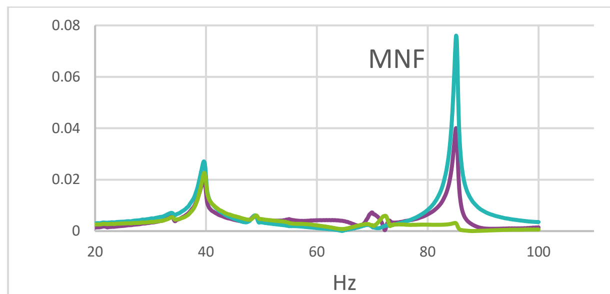


Node participation



MNF test:

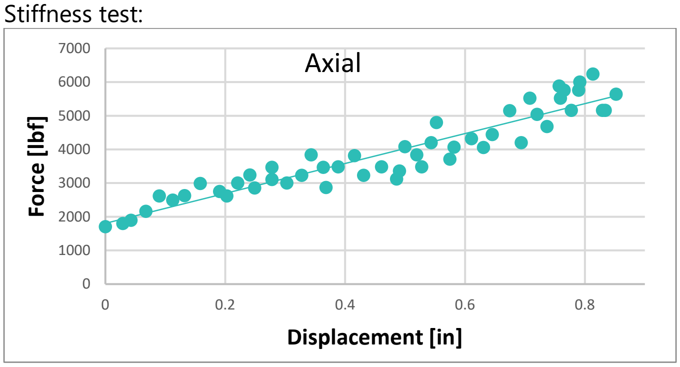


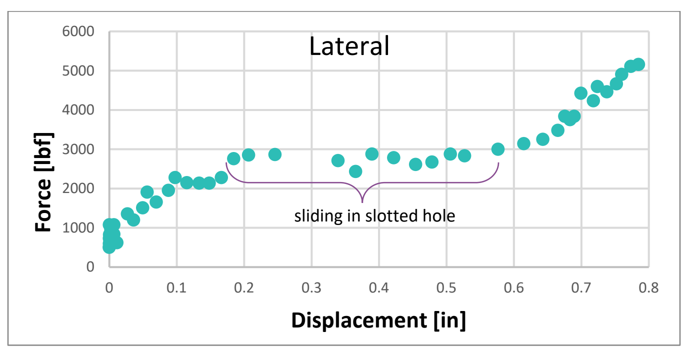


	Experimental	Theoretical	Ratio
MNF	65	77.7 Hz	0.84
Damping	0.8%		

	Experimental	Theoretical	Ratio
MNF	40 Hz	77.7 Hz	0.45
Damping	0.95%		

Stiffness test:



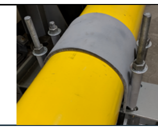


Stiffness type	Linear
Stiffness	4500 lbf/in
Breakaway Force	NA
Coefficient of friction	NA

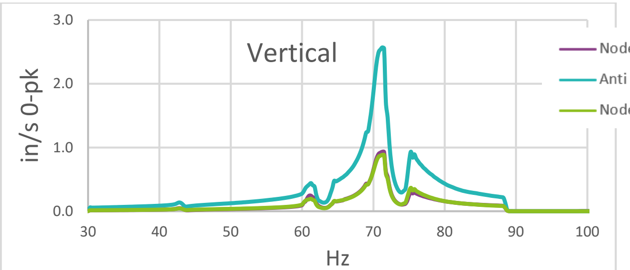
Stiffness type	Bilinear
Stiffness	13500 lbf/in
Breakaway Force	2800 lbf*
Coefficient of friction	TBD

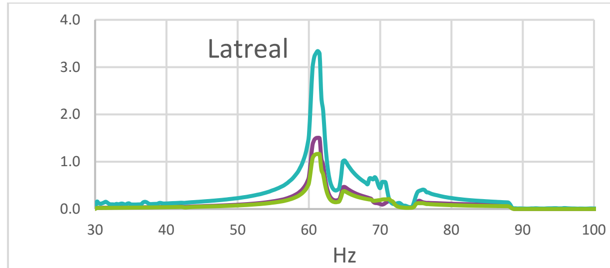
Results comments:	No clear pinned-pinned mode shape is found in the lateral direction. The stiffness test showed some breakaway force in lateral direction due to the test configuration, but this was due to a slotted hole in the structure (unrelated to the support design). The 83Hz vibration is due to the second mode of vibration and not applicable to this analysis.	Categorisation results: **Flexible**

Support #8 test results

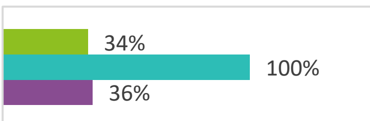
Description:	CL-1–10”; Flat bar pipe clamp design; **10” NPS**	
Key manufacturer claimed features	• Flat bar clamp, unlined	

Vibration test:

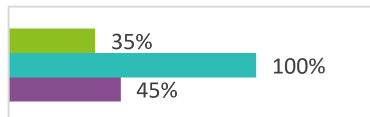




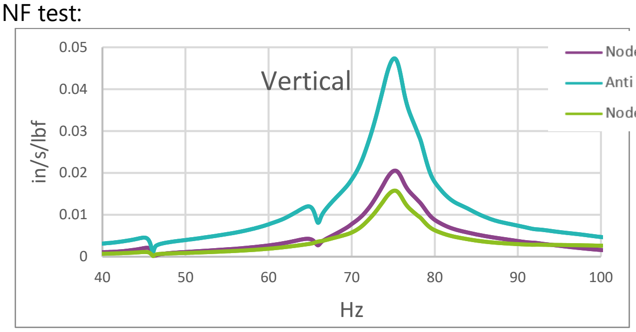
Node participation

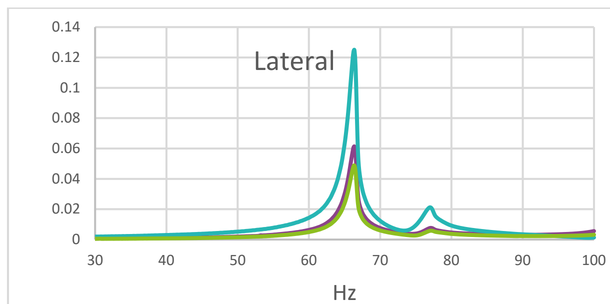


Node participation



MNF test:

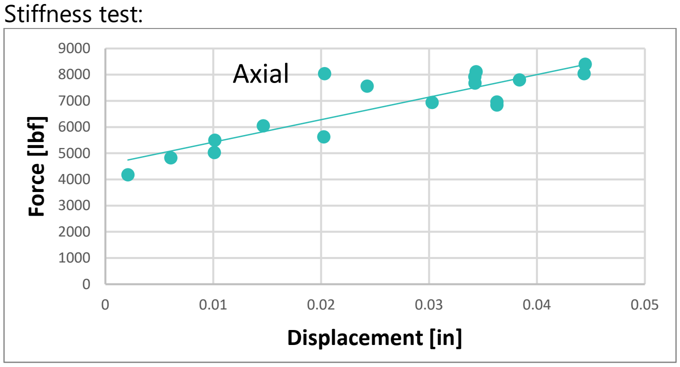


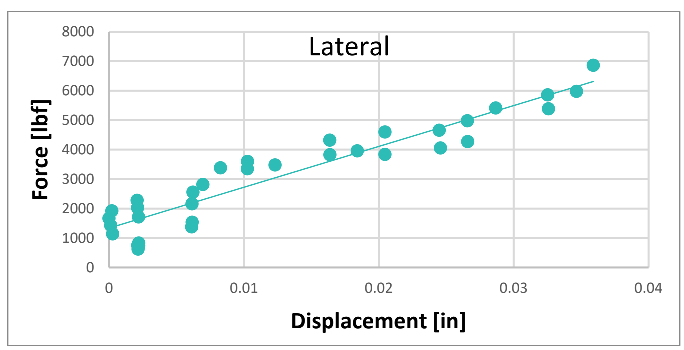


	Experimental	Theoretical	Ratio
MNF	71.3 Hz	77.7 Hz	0.92
Damping	1.8 %		

	Experimental	Theoretical	Ratio
MNF	67 Hz	77.7 Hz	0.86
Damping	0.89%		

Stiffness test:



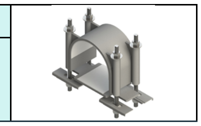


Stiffness type	Linear
Stiffness	133950 lbf/in
Breakaway Force	NA
Coefficient of friction	NA

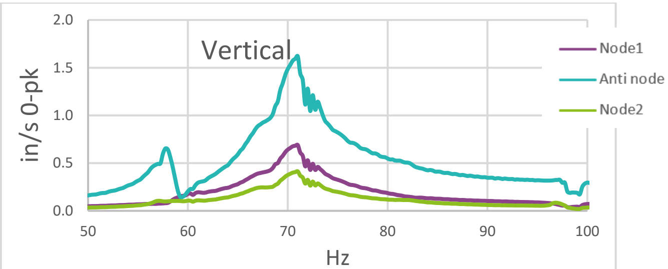
Stiffness type	Linear
Stiffness	140000 lbf/in
Breakaway Force	NA
Coefficient of friction	NA

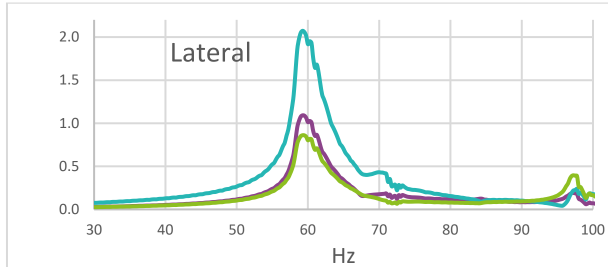
Results comments:	MNF data shows a clear pinned-pinned beam mode shape for both axial and vertical directions.	Categorisation results: **Rigid**

Support #9 test results

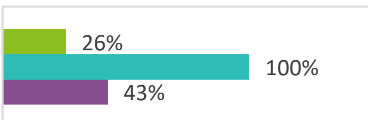
Description:	CL1-T-ST-10”; Flat bar design with sliding plane; **10” NPS**	
Key manufacturer claimed features	• Sliding plane for axial and lateral	

Vibration test:

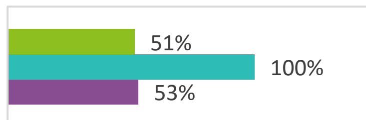




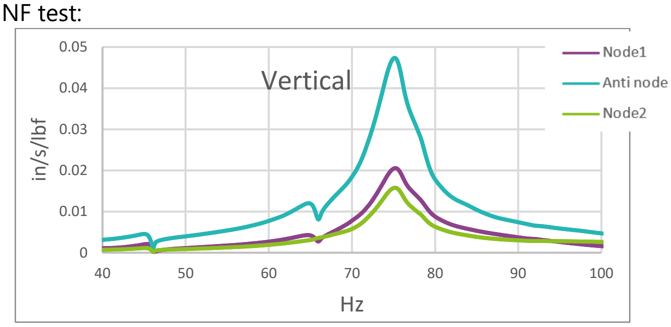
Node participation

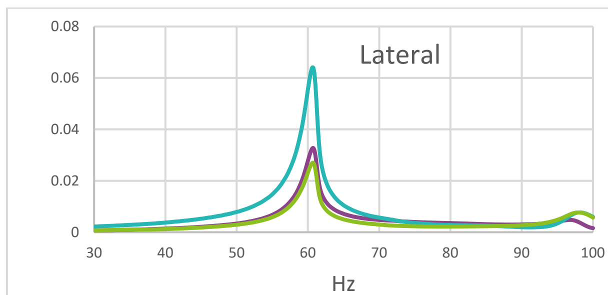


Node participation



MNF test:

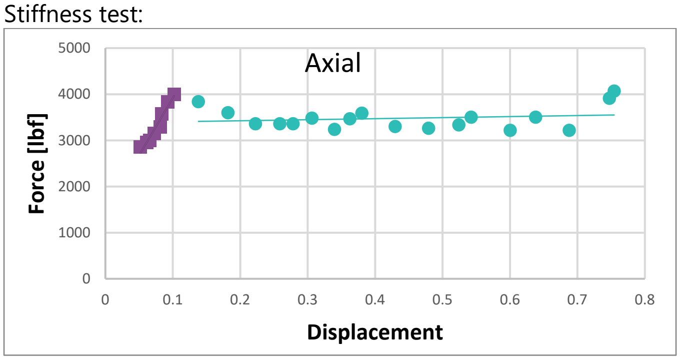


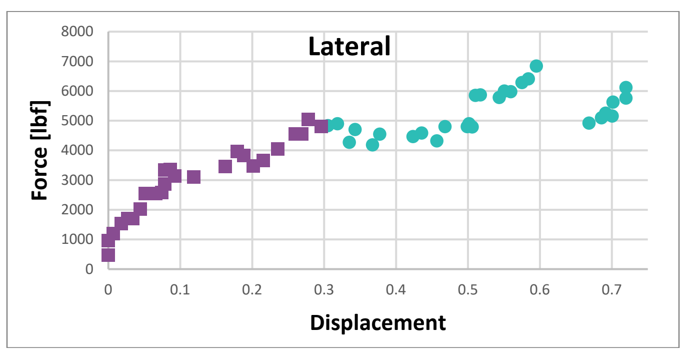


	Experimental	Theoretical	Ratio
MNF	71.6 Hz	77.7 Hz	0.92
Damping	2.1 %		

	Experimental	Theoretical	Ratio
MNF	66.4	77.7 Hz	0.85
Damping	1.6%		

Stiffness test:



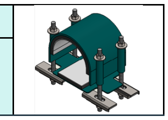


Stiffness type	Bilinear
Stiffness	96097 lbf/in
Breakaway Force	3400 lbf
Coefficient of friction	0.1

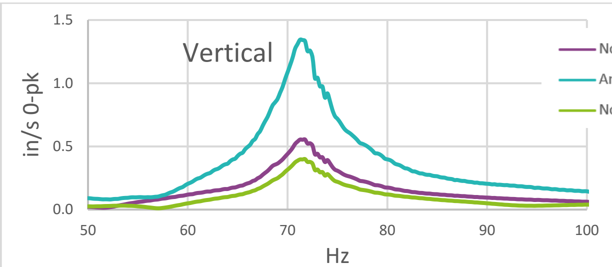
Stiffness type	Bilinear
Stiffness	12000 lbf/in
Breakaway Force	5000-6000 lbf
Coefficient of friction	0.14-0.17

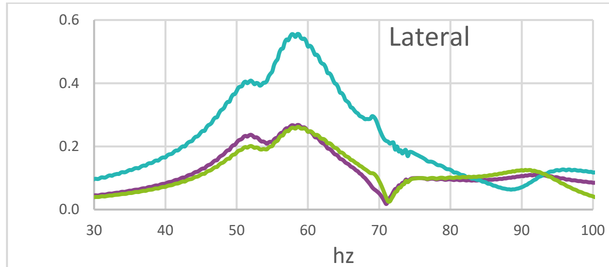
Results comments:	Slightly more participation, but higher damping than the non-thermal version of the clamp. Lower vibration level due to higher damping. The increase in damping is more noticeable in the lateral direction.	Categorisation results: **Dual purpose**

Support #10 test results

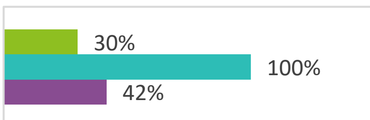
Description:	DCL-1-ST-10"; Flat bar pipe clamp design with damping and lateral sliding hardware	
Key manufacturer claimed features	• Allows for thermal growth in axial and lateral direction • Damping liner with PTFE contact layer for low-friction sliding	

Vibration test:

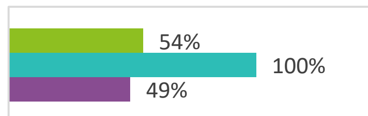




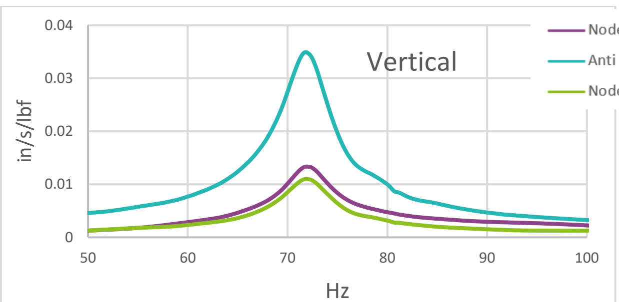
Node participation

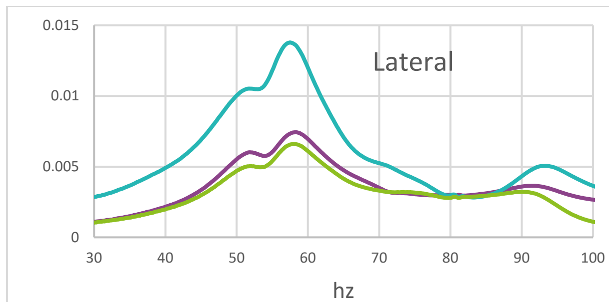


Node participation



MNF test:

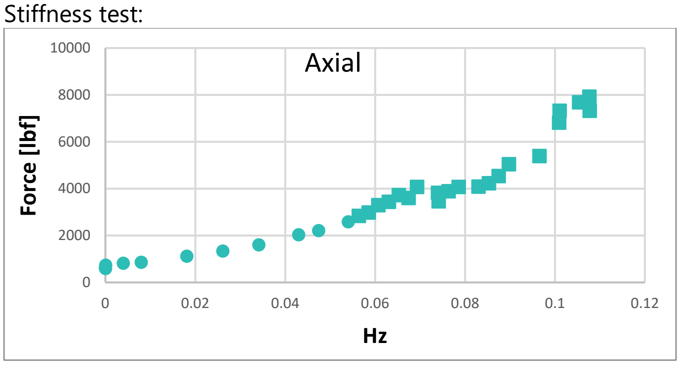


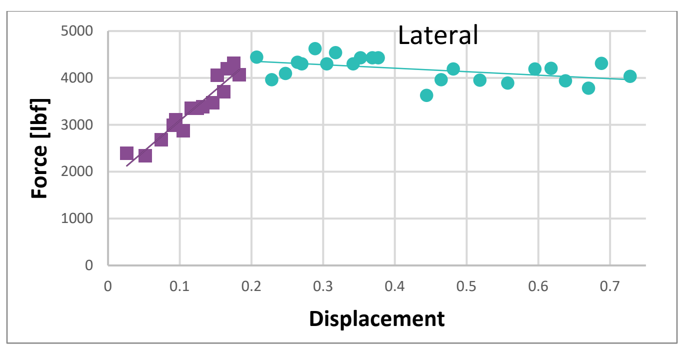


	Experimental	Theoretical	Ratio
MNF	72 Hz	77.7 Hz	0.93
Damping	3.2 %		

	Experimental	Theoretical	Ratio
MNF	57.5	77.7 Hz	0.71
Damping	10.0%		

Stiffness test:





Stiffness type	Linear
Stiffness	96000 lbf/in
Breakaway Force	NA
Coefficient of friction	NA

Stiffness type	Bilinear
Stiffness	13000 lbf/in
Breakaway Force	4200 lbf
Coefficient of friction	0.12

Results comments:	Significant reduction of lateral vibration with damping as high as 10%. The vibration was reduced to the level of the testing rig resonance.	Categorisation results: **Dual purpose**