THE EXTRACTION STUCK OIL FIELD TUBULARS USING SURFACE RESONANT VIBRATORY TECHNIQUES

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ABSTRACT

Stuck pipe has been identified as the largest single contributor to non-productive drilling time. The use of resonant vibration as a means of freeing stuck tubulars from a well bore has been demonstrated to be effective in both Drilling and Workover environments and has the potential to provide almost immediate results in many day-to-day applications. The challenge for the future is to further explore both proven and potential applications of this technology in order to evaluate the benefits and reduce the unknown associated with the technology. The long term industry benefit will be a different approach to stuck tubular recovery available in the form of superior technology that addresses real needs while substantially reducing costs. The technology offers the benefits of being quick and easy to apply, operations are conducted from surface with no downhole intervention, and results may be achieved very quickly. Demonstrated successes in both cased and open hole applications has prompted the industry to embrace the technology as a viable and often preferred means of stuck pipe recovery.

THE EVOLUTION OF AXIAL VIBRATION OF PIPE AT RESONANT FREQUENCIES IN OIL FIELD APPLICATIONS

The concept of using vibration to free stuck objects from a wellbore originated in the 1940's, and probably stemmed from the 1930's use of vibration to drive piling in the former Soviet Union. The early use of vibration for driving and extracting piles was confined to low frequency operation; that is, frequencies less than the fundamental resonant frequency of the system and consequently, although effective, the process was only an improvement on conventional hammer equipment.

Early patents and teaching attempted to explain the process and mechanism involved, but lacked a certain degree of sophistication. In 1961, A. G. Bodine obtained United States Patent 2,972,380[1] that was to become the "mother patent" for oil field tubular extraction. Mr. Bodine introduced the concept of resonant vibration that effectively eliminated the reactance portion of mechanical impedance, thus leading to the means of efficient sonic power transmission. Subsequently, Mr. Bodine obtained additional patents directed to more focused applications of the technology.

A 1987 Society of Petroleum Engineers (SPE) paper[2] detailed the nature of the work and the operational results that Resotek achieved. Resotek's work involving liner, tubing, and drill pipe extraction and was very successful, as was Baker Oil Tool's subsequent work[6] on continuing the work began by Resotek.

NON-RESONANT VIBRATORY SYSTEMS - JARRING OPERATIONS

Stuck tubular extraction tools or systems have been available to the oil industry almost since the first well was drilled. Drilling or fishing jars are routinely run with the bottom hole assembly. Workover operations can run fishing tools on tubing, coil tubing or even wireline; as such, all fishing operations require downhole tool intervention such as spears, overshots, taper taps, washover pipes, etc.

Jarring operations may require anywhere from a few to sometimes thousands of impacts to release a fish. The time required to set the jar and trip it may be on the order of 2 to 3 minutes per impact and the total time involved for a successful jarring operation can reach over 50 hours of continuous impacts. Therefore, operations involving jarring usually last days, sometimes weeks, resulting in a considerable loss of productive rig time.

Another consideration when using jars is their placement relative to the stuck point. When run on the drill string, the assumption is made that the stuck point will be below the jar, otherwise jars would not serve any useful purpose. During a workover or completion operation, jars will always be placed above the stuck point but can suddenly find themselves below the point of usefulness should the pipe get constricted further up the hole due to sand deposition, mud solid buildup, casing collapse, junk being deposited in the hole or excessive friction due to irregular hole geometries.

RESONANT VIBRATORY SYSTEM – ECCENTRIC WEIGHT OSCILLATOR

The vibration equipment used to extract stuck downhole tubular is called an eccentric weight oscillator, schematically depicted in Figure 1. This particular type of oscillator uses a pair of eccentric weights rotated in opposite directions by geared shafts so that the weights cancel each other for sideways forces but are added together during vertical oscillation. This gives a pure, simple harmonic vertical-force component that is transmitted down the pipe column as a series of alternate tension and compression waves as shown in Figure 2. This causes a series of rapid percussive forces at the stuck point. This entire assembly hangs from elevators on the traveling block and attaches to the exposed tubular above the rig floor.

The wave pattern shown on the left of Figure 2 is the conventionalized form with a lateral pattern to illustrate alternate compression and tension being transmitted longitudinally down the pipe. The node is a point of maximum dynamic stress on the pipe and the anti-node, or rarefaction, is a point of maximum dynamic movement of the pipe body. If you placed a 'free point' indicator on a nodal point you would register maximum strain. If you placed an accelerometer (a device for measuring motion) on an anti-node location, you would measure maximum movement. The inverse is true, that is, a free point tool would not measure strain at an antinode, and an accelerometer would not register motion at a node.

There are many dynamics involved in the use of Resonant Vibratory Energy, the most important being the resonant frequency itself. Every structure, or system, has a resonant frequency that when excited at that frequency by an external force tends to maintain its motion indefinitely, in the absence of friction, damping or other retarding forces. When an object or structure is vibrating at its fundamental resonant frequency, or one of its harmonics, its resistance to motion, otherwise known as its Mechanical Impedance, is at a minimum and is defined in the equation of Figure 3.

When $\omega m = k/\omega$, a resonant condition exists and the effective mechanical impedance, Z, is at a minimum and equal only to the external resistance, R_m, acting on the system. The reactive components ωm and k/ω essentially cancel each other out. 'm' is defined as the total mass, k is the elasticity or the spring constant, and ω is the angular frequency of vibration (measured in radians/sec).

The Mechanical Impedance concept is most important in resonant vibratory systems and clearly explains why systems undergoing resonant vibration are more efficient than non-resonant systems. In the non-resonant system, the oscillator force must cyclically accelerate, stop and reverse the entire load mass.

In resonant systems the elastic forces, i.e. the elastic compliance k/ω in the system, performs the cyclic operations which must be done by brute force in non-resonant systems, such as in oilfield jarring. The resonant vibrator system can now devote itself to the task of overcoming the external resistance, R_m, in the equation.

As an analogy (see Figure 4) electrical systems work on the same principal, i.e. if current and voltage are in phase (a resonant condition) the total power delivered to a motor is known as the Apparent Power and is the product of the voltage and current. If the current and voltage are out of phase, some power is circulating in the load but is not doing work. This power is called the Reactive Power and is analogous to the (ωm-k/ω) part of the equation in Figure 3.

In summary, the mechanically resonant system (consisting of the oscillator, stuck pipe and retaining media) virtually eliminates the effect of the mass reactance, ωm, by matching it with the elastic or capacitive reactance, k/ω. Hence, all of the oscillator generated energy now goes to overcoming the external resistance R_m.

To conclude this section, we must mention two other factors at work here, and that is Dilation and Contraction of the pipe body and Fluidization of the retaining media.

Technically, Poisson's Ratio is defined as the ratio of lateral strain to axial strain in a body. This implies that when an elastic body is subjected to axial strain such as when a length of pipe is stretched, its diameter will contract. Similarly, when the length of pipe is compressed, its diameter will expand. Since a length of pipe undergoing vibration experiences alternate tensile and compressive forces (see Figure 2) as waves along its longitudinal axis (and therefore longitudinal strains), its diameter will expand and contract in unison with the applied tensile and compressive waves. This means that for alternate moments during a vibration cycle the pipe may actually be physically free of its bond.

The term fluidization is used to describe the remarkable action of soil particles when excited by a vibrational source of proper frequency. Under this condition, granular material is transformed into a fluidic state that offers little resistance to movement of bodies through the media. In effect, it takes on the characteristics and properties of a liquid.

ENERGY DELIVERED DOWNHOLE TO A STUCK POINT

The energy output of an eccentric weight oscillator is a function of the force and velocity of its rotating weights. Knowing the stroke or amplitude of the vibrating pipe as well as the frequency of vibration and the work string's weight per foot, one can calculate the energy delivered to the stuck point. The resulting instantaneous peak energy demand integrated over time yields the curves of Figure 5 and 6.

We've made many generous assumptions with regard to the size of the actual pipe mass that is vibrated at any one time for delivery of the energy to the retaining medium. Our scenario assumes that only 1/4 of the wavelength of the frequency of vibration is the associated mass of pipe that is in motion at any one time (this comes from Den Hartog's discussion on wave shapes covered by Figure 8 below). Plus, we've assumed that due to the wave shape of the vibration that only 1/3 of that mass is the actual mass having any velocity. The amplitude of vibration considered here is 1/2".

Even with all of those conservative assumptions, the amount of energy delivered is quite substantial. The energy delivered to the stuck point increases with pipe mass, amplitude, frequency of vibration as well as the time duration of the resonant oscillatory motion.

A quick review of the graph in Figure 5 indicates that, for example, 4-1/2" 12.75 Lb/Ft Tubing, the maximum energy delivered to the stuck point ranges from 60 Million Ft-Lbs for 1 Hour of vibration at 10 Hz to 180 Million Ft-Lbs at 20 Hz for 3 Hours of vibration. This duration can be continuous or intermittent depending on what other activities are ongoing at the time of the pipe extraction operation.

Figure 6 shows how much the energy delivered to the stuck point increases with increasing pipe mass. The delivered energy increases to 92 Million Ft-Lbs after 1 hour of resonant vibration at 10 Hz for 5" 19.5 Lb/Ft Drillpipe to 1.1 Billion Ft-Lbs of energy after 3 hours of operation at 20 Hz. It goes up even higher for 20" 94 Lb/Ft casing (graph not shown) to about 5.3 Billion Ft-Lbs of energy after 3 hours. It should be noted that this infusion of energy to the stuck point may occur within the first 3 hours of oscillator operation.

Jars would create a rather large instantaneous energy input in the form of an impact some distance away from the stuck point (depending on where the jars are placed) but it dissipates quickly due to the decaying impulse. A jar may be tripped 30 times per hour; the total energy input to the stuck point based on using 5" drillpipe with drill collars with an Impact Force of 1,000,000 lbs. and a decaying Impulse of 60 milliseconds amounts to 23.2 Million Ft-Lbs of energy generation after 3 hours (See Figure 7).
Contrast this with the energy delivered by a resonant vibratory oscillator using 5" 19.5 Lb/Ft drillpipe with an energy input at 20 Hz of over 1.1 Billion Ft-Lbs using resonant vibration (See Figure 6) after 3 hours. It would require 129 hours or 5 days of jarring to equal the output energy of a resonant vibrator operating for just 3 hours under the conditions just stated.

It should be noted that when the jarring crew shows up, you typically have an approximate 12 hour round trip time to get the jars into the hole, depending on the depth of the free point. Assuming a 1 hour setup time for the resonant oscillator, as much as 5.3×10^9 Ft-Lbs of energy could have been input to the stuck point when using 6-5/8" 25.2 lb/ft drillpipe while operating at 20 Hz before the Jar would have been tripped even once. Time is of the essence here....according to Reference 3, there is an 85% success rate in extracting stuck pipe within the 1st 24 hours of getting stuck. It decreases to approximately 20% after 72 Hours.

THE MECHANISM OF FREEING STUCK DRILLPIPE THROUGH APPLICATION OF RESONANT AXIAL PIPE VIBRATION

Vogen[9] has put together a concise narrative of the process of freeing a stuck liner that is probably appropriate for any stuck tubular.

"As the liner is subjected to cyclic loading applied at its top, resistance to movement takes the form of shear stresses developed along the contact between the liner and the oil bearing sands. The developed shear stresses at any depth are a function of the displacement of the liner and increase in a roughly linear fashion up to the shear strength of the interface. Because the load is applied at the top of the liner the load carried by the liner will be greatest at its top and it must decrease to essentially zero at the bottom of the liner. The displacements of the liner due to elastic stretching will therefore be greatest at the top, and will diminish with depth. Thus the greatest shear stresses resisting movement of the liner will initially be developed at the top, but as shear strength is reached the liner will move relative to the surrounding sands and the full development of shear resistance will gradually move down the pipe. However, because the frictional resistance provided by soils tends to decrease with vibration the shear strength will tend to degrade, first at the top of the liner where the cyclic displacements are greatest, thus transferring the center of resistance to movement further down the pipe, and substantially at greater depths."

STUCK TUBULAR RECOVERY PROCEDURE

The literature is peppered with procedures when the first indicators of being stuck appear. One of these includes regaining circulation via standpipe pressure and pipe manipulation. If the pipe is not free once full circulation is established, resonant vibration operations are commenced while either pulling or setting down weight in the opposite direction to the last pipe movement. Once the pipe is free, it is rotated and the hole cleaned prior to continuing pipe tripping.

On some modes of sticking, there are preliminary procedures that can be put in place before a resonant vibration unit arrives on location. These can include spotting fresh water pills when stuck in mobile salt formations, or spotting a lubricant pill when differentially stuck. Sometimes a naturally over pressured shale or claystone collapse causes a negative pressure differential which, if possible, should be rectified for well control reasons prior to axial pipe vibration operations. This can be done by increasing the mud weight so that a condition of positive pressure differential exists. Vibrating the tubular with both up and down static pipe weight biases will assist in breaking up splintery shales.

The general procedure for the recovery of stuck tubulars is to work the pipe with the rig, usually in tension but sometimes also with torque typically applied with a top drive unit if one is available, or by rotary table means. It should be noted that the utilization of torque for this purpose usually requires the application of high torsional stresses to the string and connections wherein the connections may be damaged, particularly when 8 rd casing connections are involved. If the physical condition of the stuck pipe is suspect due to corrosion or otherwise deteriorated, it is not advisable to apply substantial amounts of torque.

The vibration procedure may be as follows:

- Rig up the vibration unit (similar to rig up of a power swivel) and make-up to the stuck tubular.
- Pick-up off slips and operate to vibrate the pipe string. The output of the vibrator is axial vibration with amplitude of approximately one-half inch. Vary the tensile pull on the pipe string while operating the vibrator to determine the appropriate level of tension for best results. Several things will be going on while the operation is conducted and one of the most evident is the stimulation of a lateral response in the pipe string. The lateral response is generally not an effective means of working the pipe free and may be controlled or minimized by varying frequency and tensile pull on the pipe.
- The key to success is inducing a resonant longitudinal standing wave pattern in the pipe string and maintaining that pattern. Take careful measurements of applied tension and pipe elevation to monitor results. In most cases results will soon become apparent.

- Continue to operate until no incremental stretch is achieved. Use patience during the process; it is not unusual to see a variation of recovery rate and the first instant that recovery seems to stop is too soon to abandon the process since experience has shown that it may begin again in a reasonable amount of time. Vibration personnel are experienced in this type of work and will know when it is time to apply alternative procedures.

Multiple data readings are sometimes taken and may be displayed in a three dimensional waterfall plot as shown in Figure 8. The figure illustrates the readings of a particular job with acceleration amplitude on the vertical axis, frequency of vibration on the horizontal axis and time of day on the Z or depth axis. The measurements are from 0 Hz to 50 Hz which covers the frequency compliance of most oil field systems.
A Spectrum Analyzer is very well suited for gathering and displaying accelerometer data and can be used to display changes in the downhole vibration 'system' that would sometimes not be readily apparent at surface. From the waterfall graph, one can notice the excitation or driving frequency of the oscillator as large peaks toward the left of the frequency axis, and multiple harmonics of that frequency more towards the right side of the frequency axis. This information indicates the status of the system impedance and indicates when it transitions from a fixed-free system to a free-free suspended tubular as shown by Den Hartog[4] calculations on the resonant frequencies for various suspended tubulars (see Figure 9). In essence, pipes that are constrained or free at both ends exhibit harmonic frequencies (multiples of the fundamental) in 'consecutive' fashion, that is, multiples of 1, 2, 3, 4,.....etc. If the pipe is constrained at one end and free at the other, the various harmonics or overtones will be 'odd' multiples of the fundamental frequency, i.e. 1, 3, 5, 7, ... etc.

Below are three slices in the Z axis of Figure 8 showing the status of the vibration patterns at particular times of the pipe extraction operation. Figure 8a shows the startup of the vibrator in that it is not tuned to any resonant frequency harmonic. Figure 8b shows a subsequent lock-in to a resonant pattern and the odd harmonic multiple of that resonant frequency, indicating a fixed-free condition, i.e. the pipe is stuck. Figure 8c finally shows the pipe coming free whereby it exhibits a free-free resonant pattern by exciting the consecutive multiples of the resonant frequency.

Let us review several types of stuck pipe scenarios and describe the actual procedure taken to retrieve the fish.

Case History #1 ... Keyseated Drillpipe

Details:
Keyseat Stuck 8-3/4" BHA at 9,504 ft.
Well Depth: 10,000'; Casing: 9-5/8" to 1,705 ft
Work String: 4-1/2", 16.6#/ft DP; String Wt: 177,000k; Indicated. Wt: 210,000k

The rig had jarred for two and one half days, moving the pipe one foot. They then decided to back off at 9,504 ft leaving 15 joints of 6-1/2", 98#/ft DC's and 8-3/4" bit in the hole. After pulling out of the hole and running in with 16.6#/ft DP, they screwed onto the fish. The surface resonant vibrator was rigged up and the work string vibrated at resonance with 180,000 lbs indicated weight (while varying the rig pull to a maximum of 235,000 lbs.) making a total of 4" on a surface stretch measurement or greater than 330' in stuck point movement downhole, in less than one hour. Continued vibration at 240,000 lbs to 260,000 lbs tension resulted in no additional progress. At this point, the vibration procedure called for vibration at 150,000 lbs indicated, i.e. 27,000 lb downward bias at the stuck point, with an associated change in resonant frequency, for 6 minutes and resulted in an overall two feet downward movement at the surface.

With this progress being made, it was decided to dynamically vary the indicated weight from 150,000 lbs to 325,000 lbs while simultaneously conducting resonant vibration; this resulted in pulling the 1st joint of drillpipe above the rotary after 1 ½ hours of operation. Next, an additional 16 joints of drillpipe was recovered using intermittent vibration. This was necessary since the pipe would get stuck every 30 feet or so and the vibrator would be turned on momentarily to allow unsticking the pipe. The vibrator was subsequently rigged down and the rig pulled the remaining drilling assembly out of the hole.

Case History #2 ... Formation Stuck Liner

Details:
5,079 ft of 7-5/8", 39#/ft Liner Mechanically Stuck in Swelling Shale 7-5/8" Liner shoe at 8,878 ft.~ 3,820 ft, 5", 19.5#/ft DP; T.I.W., S.J. running tool; E.J.I.B. tandem liner hanger; string weight = 194,000 lbs. in 14.9#/gal mud.

The liner was stuck for 48 hrs in a shale section @ 8,878 ft prior to resonant vibration operations. A 2 deg. deviation existed at shoe, built to 5-½ deg. at stuck point, and was 1 deg. at TD. Prior to resonant pipe vibration, diesel was spotted as a lubricant and the drillpipe worked from 250,000 to 400,000 lbs. The surface resonant vibrator was rigged up and vibrated in resonance while working the pipe up to 400,000 lbs and down to 275,000 lbs for 26 minutes until an apparent 2” upward stretch movement was observed on the 400,000 lb pipe mark at the surface. The rig subsequently pulled to 420,000 lbs and vibrated at resonance for 1 additional minute until the pipe freely moved upward with 15K lb drag. At this point, the vibrator was rigged down and the liner run to bottom and cemented.

Case History #3 ... Differentially Stuck Casing

Details:

9-⅞” 62.8# Casing at 7,138 ft. differentially stuck 3,264 ft. from bottom. in 12 ¼” Open Hole; 128 centralizers, one per joint from bottom of casing. String weight with top drive was 405,000 lbs. Mud weight = 12.5 ppg water base. Wellbore geometry: Dev. 30 deg. @ 13- 3/8” shoe (3,166 ft); Dev. 41.5 deg. @ side track point. (5,885 ft); Dev. 31 deg. @ stuck point; Dev. 3 deg. @ TD.

Casing was stuck for 51 hrs prior to the surface resonant vibrator arrival onsite. The operator had spotted Black Magic™ at the stuck interval and had worked the casing to no avail. The vibrator was rigged up and resonant vibration operations commenced with 405K lbs indicated.weight while being varied down to 250K lbs (putting the stuck point into a downward load bias). The resonant vibration and pulling combination was worked in this manner for 54 minutes and resulted in 2” extra stretch relative to a 450K lb mark on pipe at the surface, or over 450’ downward movement of the stuck point. At this point the rig pulled up to 500K lb indicated and vibrated for 4 minutes resulting in a loss of 15K lbs on the weight indicator while continuing to walk the pipe out of the hole. The surface resonant vibrator was rigged down and the casing was run to 9,700’ where it was cemented in place.

Cost, Risks, and Probability Considerations

An analysis of conventional fishing and pipe vibration daily service costs indicates that they are approximately equal to each other when wireline services are included as an essential part of the conventional fishing approach. Furthermore, these service costs may be approximately equal to the daily operations spread costs for land based operations in the United States at locations where stuck pipe services are conveniently available. However, as shown in Figure 10, pipe vibration may end the stuck pipe event in less than two days at a total cost of 4 times the spread cost. By comparison, conventional methods could take eight days (by this example) at a total cost of 16 times the spread cost; a 4:1 cost advantage.

This leads to the conclusion that, regardless of the means used to address a stuck pipe event, the service costs will be essentially the same and equal to the spread cost on a daily basis. The differentiators between the two approaches then become:

- Relative risk associated with the procedure.
- Probability of the selected procedure being successful.
- Time required to apply the procedure and reach a conclusion

The subject of well intervention risk assessment and mitigation is widely documented in the industry. An abundance of articles and papers describe the elements of various risks and some of the consequences:

“Intervention jobs often get into difficulty because of a lack of accurate downhole information, despite surface indications to the contrary. For example, milling assemblies are sometimes retrieved with little to no mill wear, and overshots and spears have been pulled empty despite positive surface indications. A recent job planned for 14 runs and 30 days of rig time to recover a gravel-pack assembly from 25,000 ft, but lack of quality downhole information forced an additional 10 trips and consumed an additional 28 rig days.”[7]

"Well intervention operations are specialized, often critical, and bring with them an inherent element of risk in the form of unseen subsurface conditions and events that can manifest themselves as unplanned non-productive time (NPT) with potentially severe fiscal consequences. Well intervention operations are traditionally performed using surface acquired parameter measurements such as revolutions per minute (RPM) and hook load and complemented by a tool expert’s sense of feel and anticipation. The industry is entering a period where this type of personal expertise is becoming scarce."[8]

It is not uncommon to find that conventional open hole fishing procedures will require several days for completion if they are not immediately successful within the first day of application. Pipe vibration operations are almost always completed in one day in open or cased hole, and have established a historical success rate that exceeds 45%. Pipe vibration generally does not require downhole intervention and thus a substantial amount of procedural risk is eliminated and time to completion is minimal. By referring to Figure 9, the advantages offered by these attributes become readily apparent.

Figure 11 illustrates the proportion and scale of costs associated with resolving a stuck pipe event as well as the potential for cost savings.

CONCLUSIONS

Resonant Vibration techniques have been used to extract oil field tubulars since the early 1980's with very good success. The technology offers the benefits of being quick and easy to apply, operations are conducted from surface with no downhole intervention, and results may be achieved almost instantly. The science behind the technology has been documented[2,10], measured and proven with field results. The uses of acoustic energy for enhancing primary cement have been proven via Reference 5 whereby casing is vibrated from the surface to prevent annular gas flow during the curing time of well bore cement.

Tremendous amounts of energy can be input to the stuck point within two hours upon commencement of vibration operations. Heavy weight tubing or drill pipe is always the preferred conduit of acoustic energy since energy is a function of pipe mass. As compared with non-resonant systems, the speed of attaining results is in the order of several magnitudes. Although jars are acoustic energy absorbers, many a fish with downhole jars attached have been retrieved. It is highly suggested that resonant vibratory techniques are used before any conventional methods are employed since sometimes the situation becomes exacerbated by further packing the retaining material from extraneous operations.

Stuck pipe intervention costs can be approximated as equal to the spread costs for land based rigs in the U.S. In offshore scenarios with higher spread costs, the financial advantages of pipe vibration become more pronounced. However, the caveat for pipe vibration procedures is the capture of valuable rig time since, for example, a 10 job scenario requiring over 40 days of conventional fishing techniques to complete would only require 10 days via resonant vibration procedures. That means that there are 30 fewer days where a personnel accident can happen, or from further complications due to extended and complex fishing procedures.

ACKNOWLEDGEMENT

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REFERENCES

1. Patent number: 2972380, Filing date: Feb 20, 1956, Issue date: Feb 1961, Inventor: Albert G. Bodine Title: "Acoustic Method and Apparatus For Moving Objects Held Tight Within a Surrounding Medium"

2. O. Gonzalez, "Retrieving Stuck Liners, Tubing, Casing And Drillpipe With Vibratory Resonant Techniques" SPE # 14759

3. T. R. Scholfield, O. P. Whelehan, A. Baruya, "A New Fishing Equation" Paper SPE 22380 presented at the SPE International Meeting on Petroleum Engineering held in Beijing, China, 24-27 March 1992.

4. Den Hartog, J.P. "Mechanical Vibrations", fourth edition, McGraw Hill Book Co. Inc. New York City, (1956) 429-32

5. C.E. Cooke, O.J. Gonzalez, D.J. Broussard, "Primary Cement Improvement by Casing Vibration During Cement Curing Time" SPE # 14199

6. Baker Oil Tools, “Resonant Systems Product No. 140-52”, Product Report number PR/FS/94002/2M/4-94, April, 1994

7. Journal of Petroleum Technology, Vol. 58, No. 8, August 2006, Technology Update

8. Jim McNicol, Baker Oil Tools, Drilling Contractor, May/June 2007, Well Intervention, P.114

9. Vogen, Wayne V., “Method and Apparatus for Removing Stuck Portions of a Drill String”, United States Patent 4,574,888, March 11, 1986.

10. O. Gonzalez, B. Bernat, "Stuck Coiled-Tubing Recovery Utilizing Surface Equipment and Methods" SPE # 130342

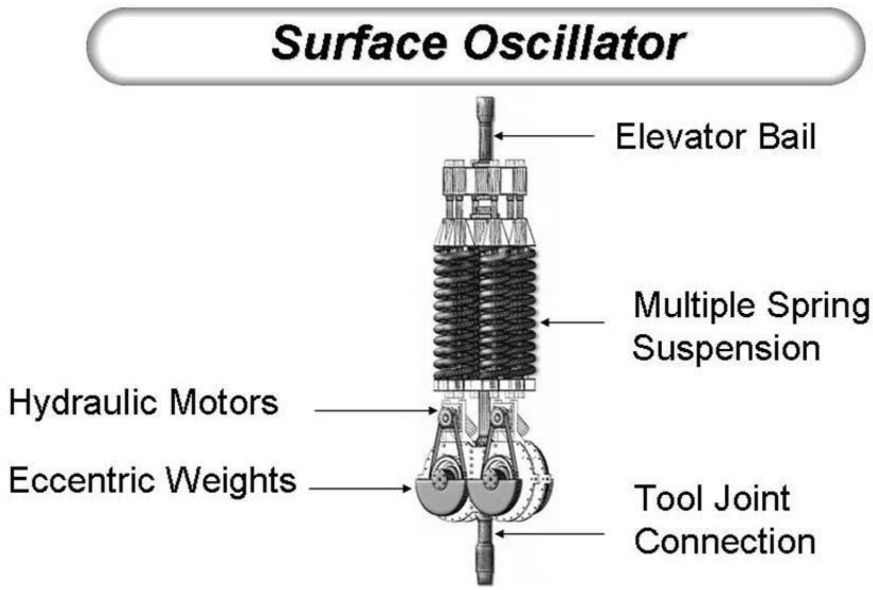
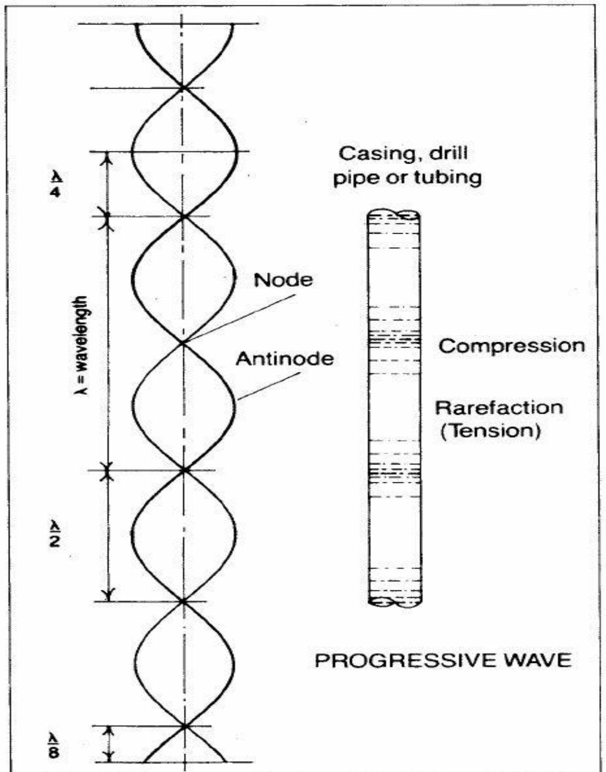


Figure 1



—Idealized representation of longitudinal standing-wave pattern.

Figure 2

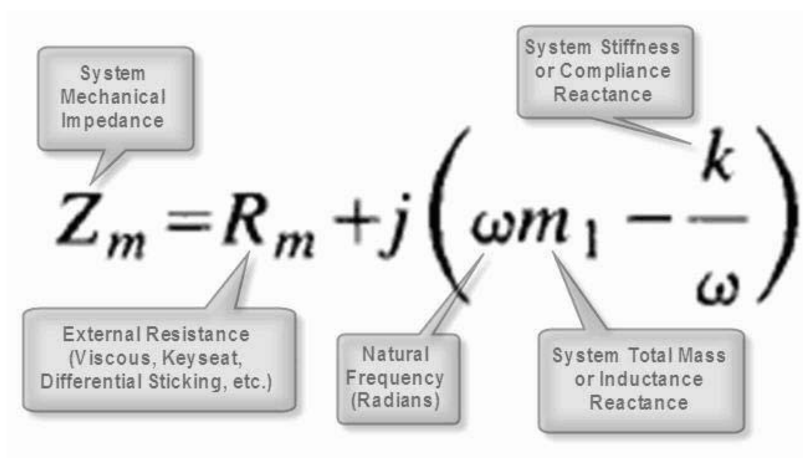


Figure 3

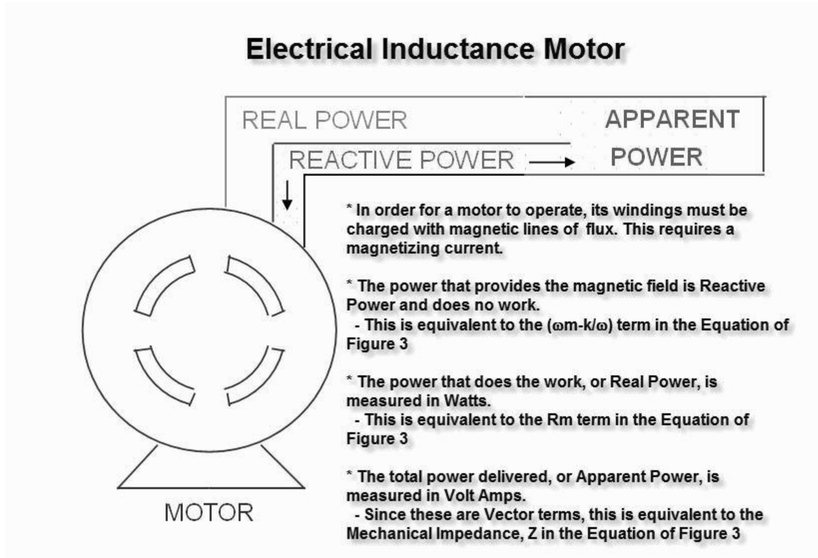


Figure 4

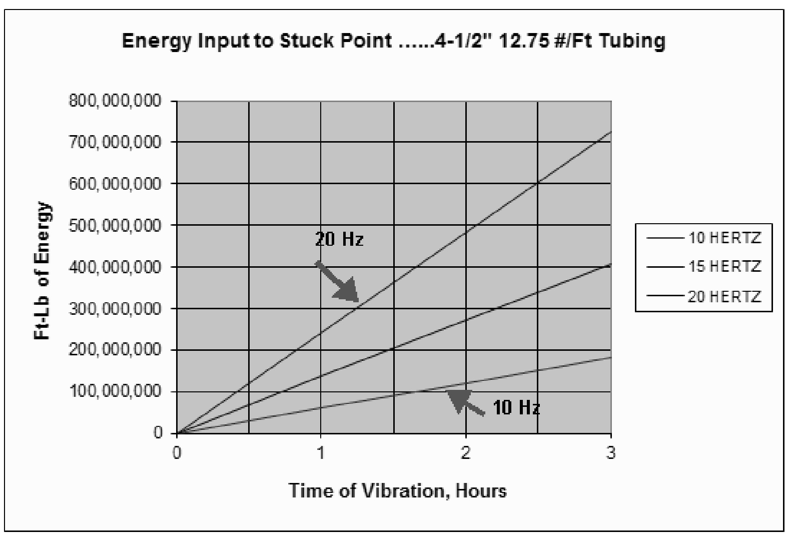


Figure 5

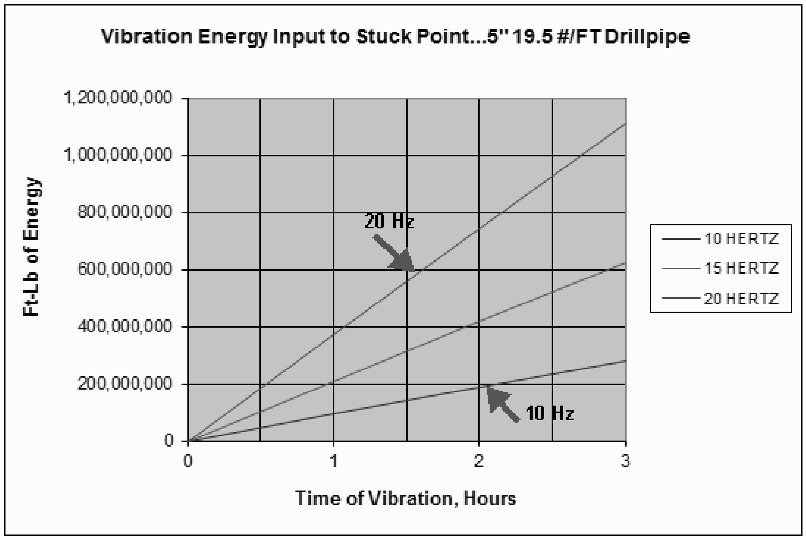


Figure 6

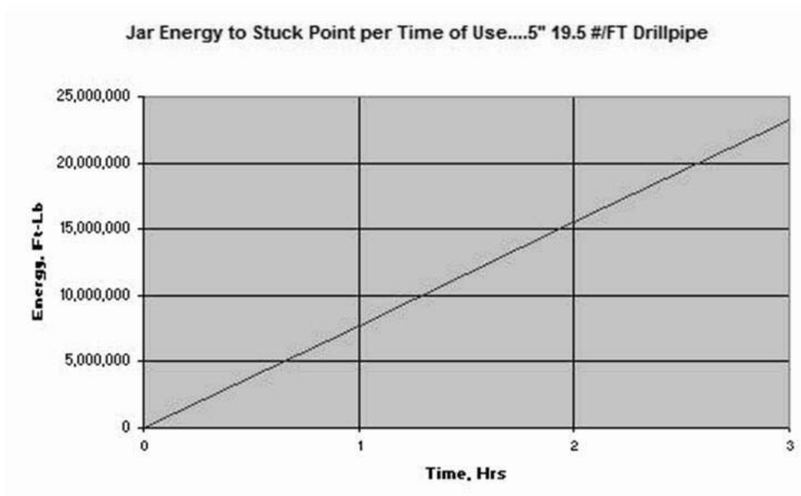


Figure 7

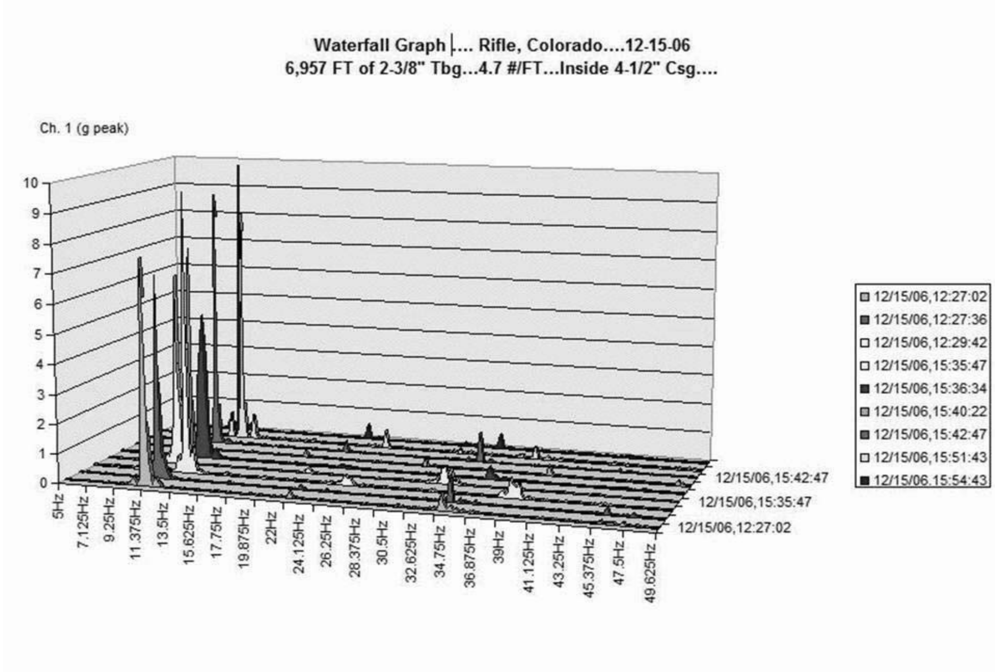


Figure 8

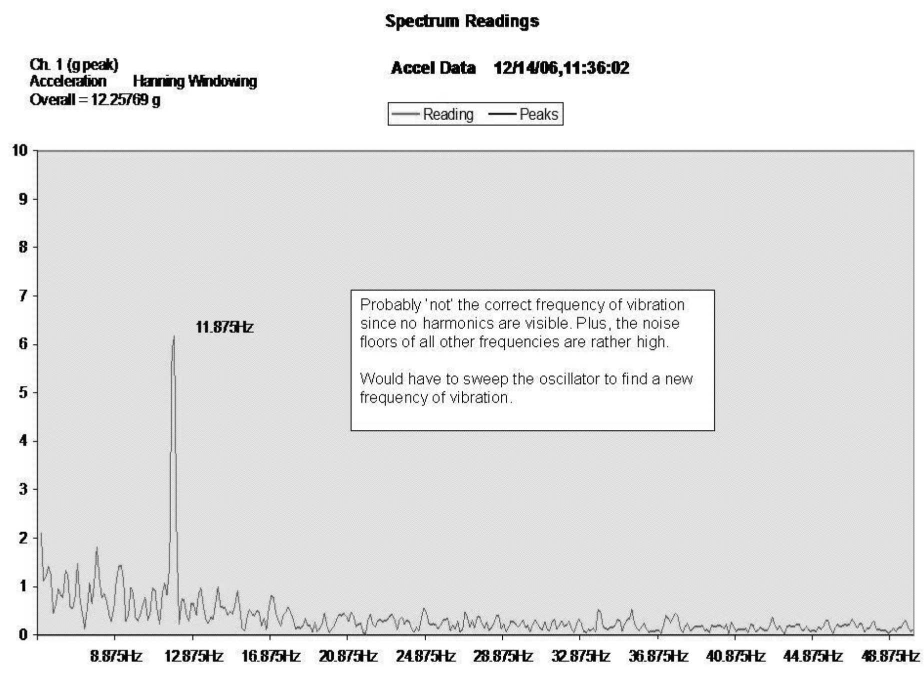


Figure 8a

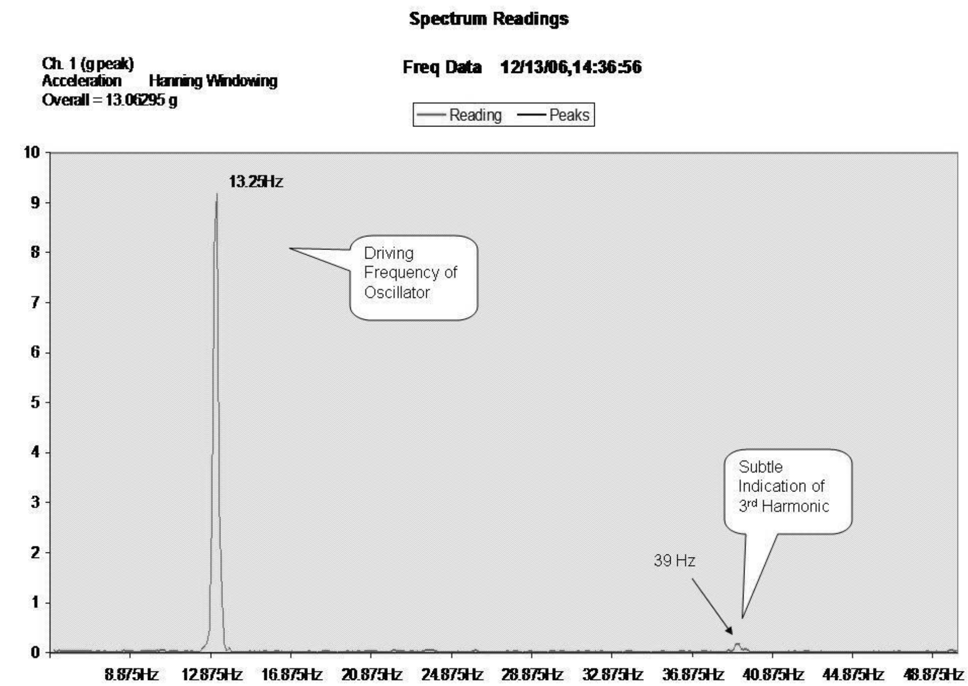


Figure 8b

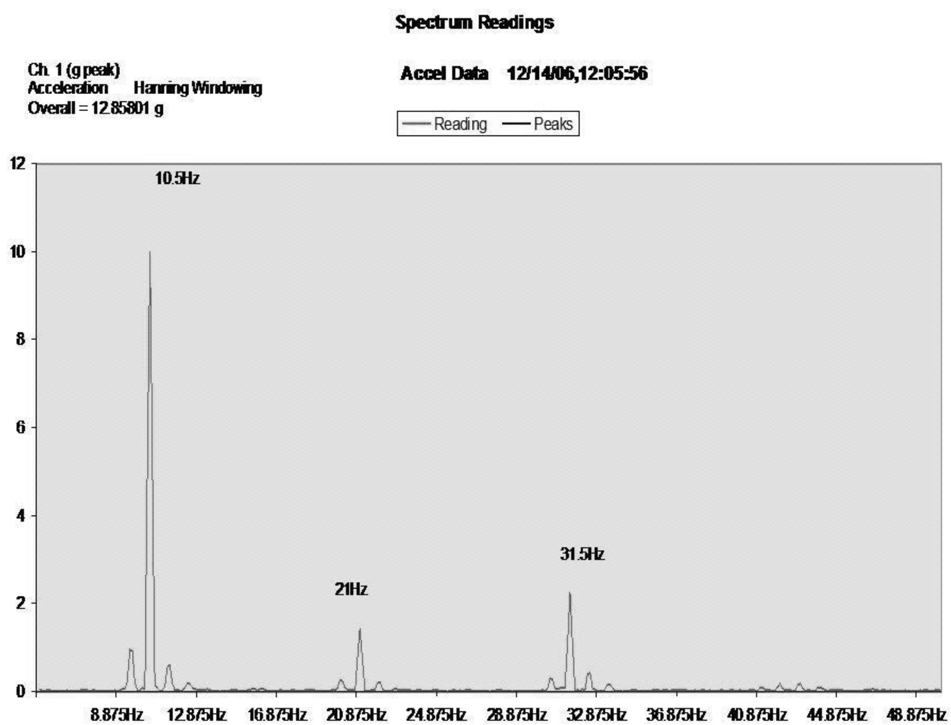
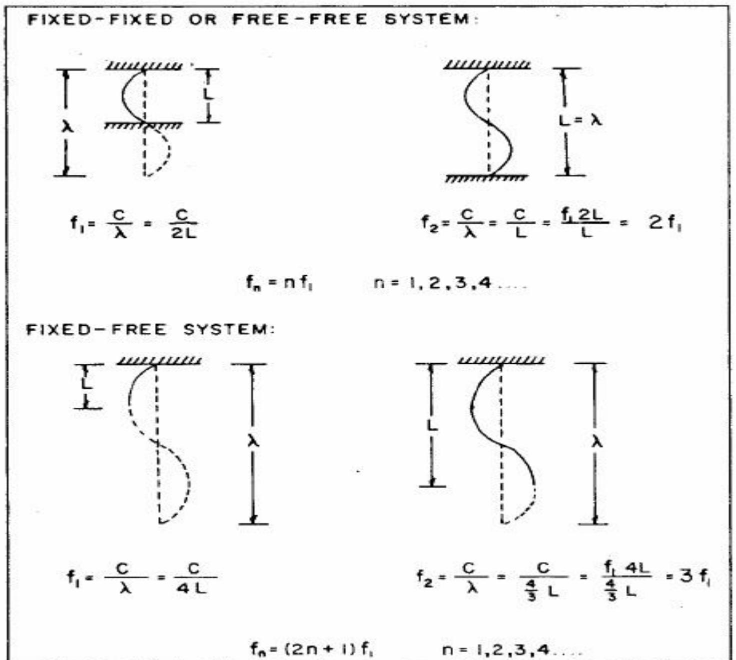


Figure 8c



—Idealized relationships of free/free or fixed/free systems consisting of freely suspended tubulars.

Figure 9

Comparison of Fishing Costs

- Costs are Essentially Equal between Surface Resonant Vibration Techniques vs. Conventional Fishing
- Costs Approximate Rig Spread Costs for Land Based Rigs
- Pipe Vibration Usually takes only 1 day for Completion vs. Multiple Days for Conventional Techniques

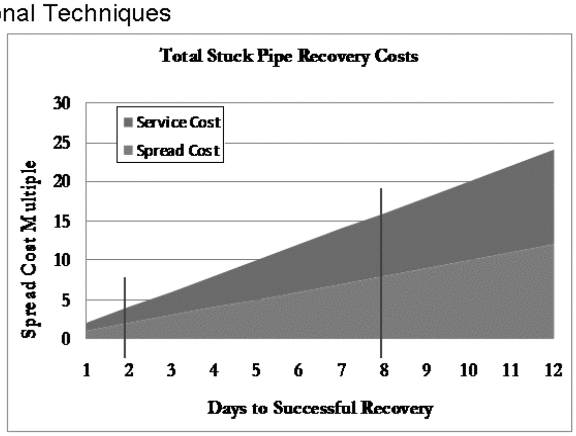


Figure 10

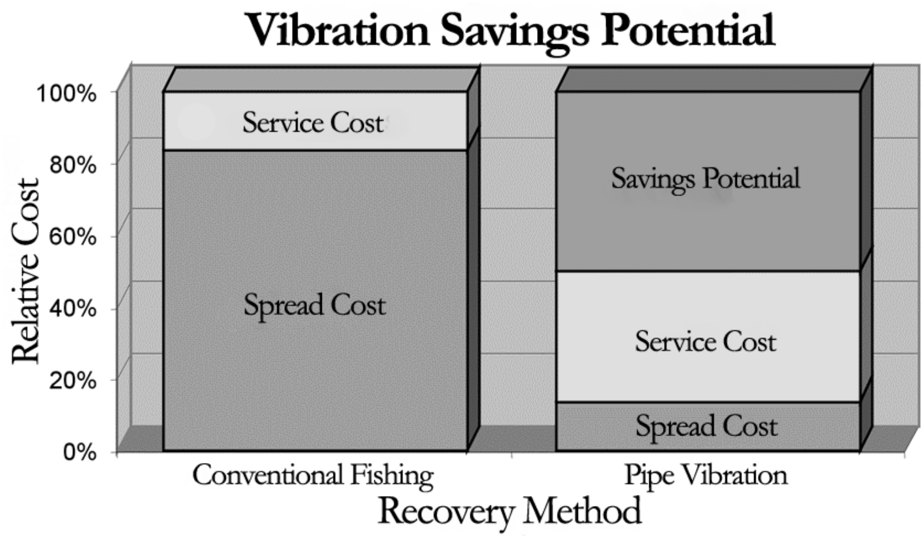

Vibration Savings Potential
100%
80%
60%
40%
20%
0%
Relative Cost
Service Cost
Spread Cost
Savings Potential
Service Cost
Spread Cost
Conventional Fishing
Pipe Vibration
Recovery Method

Figure 11