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Friction Reduction for Microhole CT Drilling

FINAL TECHNICAL REPORT

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ABSTRACT

The objective of this 24 month project focused on improving microhole coiled tubing drilling bottom hole assembly (BHA) reliability and performance, while reducing the drilling cost and complexity associated with inclined/horizontal well sections. This was to be accomplished by eliminating the need for a downhole drilling tractor or other downhole coiled tubing (CT) friction mitigation techniques when drilling long (>2,000 ft.) of inclined/horizontal wellbore. The technical solution to be developed and evaluated in this project was based on vibrating the coiled tubing at surface to reduce the friction along the length of the downhole CT drillstring.

The Phase 1 objective of this project centered on determining the optimum surface-applied vibration system design for downhole CT friction mitigation. Design of the system would be based on numerical modeling and laboratory testing of the CT friction mitigation achieved with various types of surface-applied vibration. A numerical model was developed to predict how far downhole the surface-applied vibration would travel. A vibration test fixture, simulating microhole CT drilling in a horizontal wellbore, was constructed and used to refine and validate the numerical model.

Numerous tests, with varying surface-applied vibration parameters were evaluated in the vibration test fixture. The data indicated that as long as the axial force on the CT was less than the helical buckling load, axial vibration of the CT was effective at mitigating friction. However, surface-applied vibration only provided a small amount of friction mitigation as the helical buckling load on the CT was reached or exceeded. Since it would be impractical to assume that routine field operations be conducted at less than the helical buckling load of the CT, it was determined that this technical approach did not warrant the additional cost and maintenance issues that would be associated with the surface vibration equipment. As such, the project was concluded following completion of Phase 1, and Phase 2 (design, fabrication, and testing of a prototype surface vibration system) was not pursued.

TABLE OF CONTENTS

FINAL REPORT
FRICTION REDUCTION FOR MICROHOLE COILED TUBING DRILLING

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TABLE OF FIGURES

1. EXECUTIVE SUMMARY

The objective of this project was to improve microhole coiled tubing drilling (CTD) bottom hole assemble (BHA) reliability and performance, while reducing the drilling cost and complexity by eliminating the need for a downhole tractor or vibrator. As such, a predictive software vibration attenuation model was developed, a test fixture was built, and testing was conducted to determine if vibrating coiled tubing (CT) at surface, below the injector, would be a viable means of reducing friction along the length of the CT in inclined or horizontal well sections.

Highlights of key results and conclusions documented as a result of the work conducted under this project include the following:

- Predictive software modeling results and testing demonstrated that axial vibration does decrease friction when applying an axial force to CT in horizontal sections (simulating application of weight on bit), up until the helical buckling load (HBL) is reached in the CT.
- At loads above the HBL, vibration provided a limited amount of friction mitigation, but the reduction was not as significant as was hoped. The wall contact forces caused by the helical buckling attenuated the vibration before it could adequately mitigate the friction.
- Of the 3 vibration modes examined, axial vibration was best at mitigating friction. Torsional vibration was less effective. Lateral vibration resulted in mechanical failure of the CT and additional work with this vibration mode was abandoned.
- Some improvement in force transfer was noted when axial or torsional vibration energy was applied, but this improvement was not significant enough to warrant further development of the surface vibration concept.
- The additional wall contact forces caused by helical buckling of the CT (under a compressive axial load) were too significant to be completely mitigated by vibration.
- When the axial force was less than the helical buckling load, axial vibration was effective at mitigating friction. If CTD field operations can be performed without exceeding the HBL of the CT, axial vibration will allow significant incremental WOB.

- For the testing conducted in this project, the friction mitigation due to vibration was best modeled as a fixed increase in the amount of force that could be transmitted to the simulated ‘downhole’ end of the CT.

Thus Phase 1 of this effort proved that vibrating CT from surface would not sufficiently mitigate downhole friction to justify the additional cost and complexity of the required surface vibration equipment. As such, this project was concluded at the end of Phase 1, and did not proceed with Phase 2, which was focused on developing and field testing a conceptual design of a surface CT vibration system.

2. INTRODUCTION

The objective of this project was to improve microhole CT drilling BHA reliability and performance, while reducing the drilling cost and complexity associated with drilling inclined or horizontal well sections with CT. This was be accomplished by eliminating the need for a downhole tractor or vibrator. The project objective was to be met by vibrating the coiled tubing from surface to reduce the friction along the length of the CT drill string. It was intended that this new technology would enable Operators to economically develop additional hydrocarbon resources by utilizing CT drilling techniques and existing bottomhole assemblies to drill shallow wells with long (3,000 feet) horizontal well sections.

The microhole coiled tubing drilling friction reduction system to be developed under this project focused on a new technology to be applied at the surface, to reduce CTD costs and extend the performance of existing BHA equipment. It was hoped that the friction reduction system would provide significant benefits as a result of:

- Extending the maximum safe range for CT directional drilling with existing BHA equipment. This was to be accomplished without the use of an expensive downhole drilling tractor or some other device to overcome friction effects (mitigate downhole friction.
- Reduced BHA operating costs by extending downhole mud motor life (reduced motor stalling).
- Reduced wellbore construction costs (less costs associate with motor replacement and unproductive trip time to replace failed motors).

An overview of several problems that plague existing BHA equipment used in CTD operations for inclined/horizontal wells are described below.

CTD is challenged by the inability to rotate the CT string, low initial weight-on-bit (WOB), and rapidly diminishing downhole weight transfer (due to friction effects between the CT and wellbore) as the well is drilled deeper in a directional or horizontal fashion. Downhole friction limits the amount of directional displacement that a BHA can drill in a given well, as the downhole CT string will reach the “lockup” stage, preventing the CT from any further downhole movement. Additional CTD is effectively halted at this point, as a result of the inability to physically move the BHA deeper in the well. At this juncture, a downhole drilling tractor is required to help “pull” the BHA to deeper depths, or the friction forces between the CT string and the wellbore wall must be reduced.

Current CTD operations utilize downhole mud motors to enable directional drilling with low WOB, but this approach also comes at a price. Mud motors are expensive to operate and prone to early failure if the motor is repeatedly stalled while drilling. Stalling occurs when the torque applied to the bit exceeds the available downhole motor torque.

Unfortunately, the CT friction effects experienced during drilling of inclined/directional holes cause irregular transfer of weight to the bit. These weight spikes exacerbate the normal "slip/stick" cutting action of the bit, ultimately causing the motor to stall and lead to early downhole motor failure. Stalled motors fail prematurely when fluid blow-by in the motor cause excessive stresses on the rubber motor components. At this point, the BHA assembly must be tripped out of the hole (resulting in additional rig time costs) to replace the expensive downhole motor.

3. PROJECT OBJECTIVE

The focus of this project was create a robust microhole CTD friction reduction system that will enable the drilling of wellbores with 3,000 ft or more of horizontal displacement in a 3 1/2" wellbore without the use of any other downhole CT friction mitigation device. Surface applied vibration energy would be modulated such that it attenuates 1,000 ft above the BHA, to avoid any potential concerns with downhole BHA vibration. The system would be integrated with existing CTD equipment and operated via the use of hydraulic energy provided by the power pack of existing CTD units currently in use. Total daily cost of the commercial service would be $1,000 per day.

3.1. How the Proposed Work Would Solve the Problem

The microhole CTD friction reduction system to be developed under this project would utilize vibration energy applied at the surface to mitigate downhole friction. This would reduce the cost of drilling inclined/horizontal wells with CT, as it would eliminate the need for a downhole tractor or other friction mitigation device.

The surface-applied vibration energy would be transmitted downhole via the CT string, mitigating friction along the way. The amount of surface-applied vibration energy would be controlled such that the vibration energy will attenuate to zero at a point 1,000 ft above the bit. Attenuating the vibration energy at this point would avoid any potential concerns associated with downhole BHA vibration (i.e. bit whirl, etc.). See Figure 1 at the end of this report.

4. PHASE 1 TASKS

The following tasks are summarized as contained in the original project proposal.

4.1. TASK 1 – DEVELOP NUMERICAL MODEL

A model is needed which is capable of determining how far down a well a surface induced vibration will travel. This model is needed to conduct this project, and also will be needed when applying this technology in the field. CTES have developed the leading CT software package on the market for performing CT forces analysis. This software package (Cerberus™) actually contains two CT forces models, a well-proven soft-string model and a recently developed full 3D finite-element stiff-string model. One or both of these models would be modified to perform this vibration propagation calculation. Once proven, this capability will be available to all the users of the Cerberus software.

4.2. TASK 2 – DESIGN AND BUILD VIBRATION TEST FIXTURE

Testing is required to verify the results from the numerical vibration model. A test fixture will be designed and built. A long length (between 100 and 500 ft) of 2” or 2 3/8” pipe will be used so simulate the wellbore. It will be laid out horizontally and buried to dampen vibration that will be transmitted to it. Smaller CT strings (probably 1 1/4” and 1 1/2”) will be inserted into the longer string. A sensing mechanism at the “bottom” will measure the force and torque on the end (WOB and TOB). The “surface” end will be vibrated with both rotational and axial vibration, with varying amplitude, frequency and applied axial load. Measurements from both ends of the simulated horizontal CT string will be gathered in a data acquisition system. These measurements will be analyzed to determine the CT friction mitigation effects provided by vibration of the CT string.

4.3. TASK 3 – TESTING AND MODEL VALIDATION

Testing will be performed with two CT sizes inside the vibration test fixture. Results from this testing will be compared to the numerical vibration model results. The model will be modified until it accurately predicts the test fixture results.

4.4. TASK 4 – CONCEPTUAL DESIGN AND OPTIMIZATION

Several concepts for surface equipment design will be studied to determine the most practical and cost effective means of vibrating the CT at surface. The power requirements, capital cost, longevity and maintenance requirements of the equipment will be considered. This analysis will be combined with the results of the vibration propagation analysis and testing to determine the most practical and cost effective equipment concept which will perform this vibration function. A specification for this equipment will be written, for use in Phase 2.

4.5. TASK 5 – PHASE 1 TECHNOLOGY TRANSFER AND REPORT

The technology transfer efforts for this phase of the product will include creation of:

- Technology overview flyer (750 copies)
- 1 Trade journal article
- 2 Technical presentations
- 1 Industry workshop
- Exposure at 2 industry trade shows
- PowerPoint slides containing a project overview
- Dedicated technology page on CTES website

The Phase 1 report will include:

- The equations used in the numerical vibration model, results of the model validation tests, and any critical values such as friction coefficient needed to obtain agreement between the model and test fixture results.
- Surface equipment conceptual design and optimization results. This will include a specification for the surface vibration equipment.

5. RESULTS BY TASK – PHASE 1

5.1. TASK 1 RESULTS – DEVELOP NUMERICAL MODEL

5.1.1. Tubing Forces Model

Modeling of CT in a horizontal wellbore is done by summing the forces acting on the CT from one end to the other. A predictive software model was created for this case which divided the CT up into 1 ft sections. For each section, the friction due to the wall contact force (WCF) for that section is added. The additional friction force is equal to the WCF multiplied by a friction coefficient, μ. Thus:

$$F_f = WCF\mu \tag{1.1}$$

If the CT is simply lying on the low side of an inclined or horizontal wellbore, the WCF is caused by the weight of the pipe. The weight per foot of the 1" and 1.5" CT are show as horizontal dashed lines in Figure 4. If the pipe is loaded in compression and buckled into a helix, there is a WCF due to the helix. The WCF due to helical buckling is given by the following equation:

$$WCF_{HB} = \frac{\left(ID_{hole} - OD_{CT}\right)L}{8EI} F_a^2 \tag{1.2}$$

where:

ID_{hole} = Internal diameter of the wellbore

OD_{CT} = Outside diameter of the CT

L = Length of the section (in this case 12 inches)

E = Modulus of Elasticity of the CT

I = Moment of inertia of the CT

F_a = Axial force in the CT at this section

Note that the axial force, F_a, is needed to calculate the WCF_{HB}, which is used to calculate the friction force, F_f, which is then used to calculate the axial force, F_a. For this model, the axial force F_a, from the previous section was used in this equation to avoid an iterative solution.

Figure 4 illustrates the resulting WCF from equation (1.2) as solid lines. At low axial loads the WCF due to helical buckling is less than the WCF due to weight, but since the WCF due to helical buckling increases as the square of the compressive axial force, they quickly exceed the WCF due to weight. The helical buckling load (HBL) is also shown. Theoretically the WCF is caused solely by the weight up until the HBL is reached. After the HBL is reached, the WCF will be only the WCF_{HB}. It is not intuitive, but the WCF due to the weight is no longer applied.

Figure 2 contains a sketch which illustrates how the force-in was applied and the force-out was measured for this test apparatus. The model simulates this situation by summing the forces from the applied force-in and calculating the force-out. Figure 5 **Error! Reference source not found.** provides the results from this model for the case of 1.0” CT. As the input force increases, the output force also increases. However, the WCF_{HB} increases as the square of the applied axial force, causing the friction to increase rapidly with increasing axial force. The “% Force Transfer” is calculated at any point by increasing the input force by 100 lbs, and determining the corresponding amount of increased output force. When the “% Force Transfer” becomes 1% or less, the CT is assumed to be “locked” in the wellbore. This phenomenon is referred to as “Helical Lockup”.

5.1.2. Vibration Modeling

During testing in the vibration test fixture, three modes of vibration for friction mitigation were considered:

1. Lateral Vibration: Linear vibration, orthogonal to the CT axis to create a side-to-side motion.
2. Axial Vibration: Linear vibration applied parallel to the CT axis to cause the CT to ‘slide’ back and forth within the well bore.
3. Torsional Vibration: Circular vibration applied about the center line of the CT axis. This applied vibration creates a small twisting motion which propagates down the CT axis.

All of the above modes of vibration were created with two rotational vibrator motors (operating at identical speed) configured through careful motor placement and mechanical feedback.

To sufficiently describe the forces and torques on the CT string due to vibration, three significant energy components were considered:

1. Energy applied by vibrator motor:

When operated in tandem, the centrifugal force of the two vibrator motors cancels in at least one direction to produce a vibration of the same frequency, 90 degrees out of phase (lag) with the motor force. The 'centrifugal force' produced by these vibrator motors is proportional to the square of the operating frequency:

$$F_c = \frac{U \cdot (\omega \cdot r_w)^2}{r_w \cdot g} = \frac{U \cdot \omega^2 \cdot r_w}{g} \tag{1.3}$$

Where:

U = vibrator's unbalance weight [lb]

r_w = vibrator's effective unbalance radius [ft]

ω = motor frequency $\cdot 2\pi$

g = gravitational constant

Frequency (Hz)	Small Motor F_c (lbf)	Mid Sized Motor F_c (lbf)
40	139	693
60	313	1,560

2. Energy required to vibrate the exposed tubing and fixtures:

The force, or torque consumed due to motion of a lumped mass during vibration is also proportional to the square of the vibration frequency. This element always opposes the force applied by the vibrator motors. Due to the complexity of this function, we do not have a precise description of the energy consumed during this process. Rough estimates show this energy to be near the same magnitude as the vibration energy.

3. Vibrational energy applied to the CT string in the region of interest:

This energy is the actual energy applied to the CT string within the casing. With some simplifications, this energy can be described as the difference between items 1 and 2 (listed above). This force is frequency dependent; however, due to the uncertainty associated with item 2 (above), an analytical expression describing the energy input cannot be attained within the scope of this project. Testing shall be performed to determine the actual energy applied to the region of interest.

Several attempts were made to use this information to model the effect of the vibration on the tubing forces. Less sophisticated methods, utilizing a fixed increase in output force due to the application of vibration, proved to match the measured data more closely than the complicated energy methods. These results are discussed later in this report.

5.2. TASK 2 RESULTS - DESIGN AND BUILD TEST FIXTURE

5.2.1. Vibration Test Fixture Description

A horizontal wellbore vibration test fixture (shown in Figure 2 and Figure 3) was developed to simulate the effects of applied vibration ‘above’ the point of helical buckling during microhole CT drilling. This fixture includes two 2 7/8” CT strings simulating a ‘straight’ and a ‘deviated’ horizontal wellbore casing, respectively. Each simulated wellbore was held in place by concrete pillars placed at 10 ft increments. These pillars insured consistent geometry of the wellbore and dampened vibration transmission through the axis of the simulated horizontal ‘wellbore casing’.

The CT string being tested passed through the wellbore casing (as shown in Figure 2) to simulate WOB during field CT drilling operations. The WOB value that would be observed during actual field operations is equivalent to the “force-out” data recorded during tests conducted in the vibration test fixture. The CT string extended 2 ft from both ends of the simulated horizontal wellbores to permit direct connection of instrumentation, the vibration motors used to apply vibration energy, and the device used to apply axial force to the CT. Two different diameters of CT (1.5” and 1.0”) were evaluated in the vibration test fixture during this project.

The vibration test fixture simulated downhole CT drilling conditions by forcing the CT string into helical buckling mode. This was accomplished by holding the downhole ‘drilling end’ of the CT in a fixed position, while the CT string’s ‘surface end’ was forced further into the simulated wellbore, effectively increasing the WOB. During this process, force-in and force-out at each end of the CT were digitally acquired and recorded for analysis.

Performance of this simulation under varying applied axial load and vibration conditions at the ‘surface end’ provided sufficient data to review and determine the downhole effect (friction mitigation) associated with surface-applied vibration.

The design of the vibrating CT test facility includes the following equipment:

1. 558 ft of 2 7/8” OD CT for the ‘straight’ simulated wellbore casing
2. 558 ft of 2 7/8” OD CT for the’ deviated’ simulated wellbore casing
3. 570 ft of 1.5” OD CT, to be used as a simulated CT drillstring
4. 570 ft of 1.0” OD CT, to be used as a simulated CT drillstring
5. 1 x 30 klbf 48” stroke piston
6. 2 x industrial air springs mounted on opposing ends of the CT
7. 2 x 30 klbf load cells mounted on opposing ends of the CT
8. 2 x Accelerometers mounted on opposing ends of the CT
9. 2 x Small electric vibrator motors (360 lbf @ 60 Hz)
10. 2 x Mid-sized electric vibrator motors (1,800 lbf @ 60 Hz)
11. 1 x National Instruments data acquisition system

5.2.2. Vibration Modes

The three vibration modes considered for this project were created as follows:

1. Lateral Vibration Configuration

Motors were mounted opposing one another across the pipe center and aligned with the pipe axis. This configuration caused the two unbalanced shafts to configure such that their respective centrifugal forces oppose one another in one of the directions away from the CT center and add to one another in the one remaining direction orthogonal to the CT axis. This configuration produces a linear force with sinusoidal amplitudes (frequency dependent) directed perpendicular to the CT axis.

2. Axial Vibration Configuration

Motors were mounted opposing one another across the axis of the CT. These motor shafts were run orthogonal to the CT axis and turned 180 degrees from one another. This configuration caused the two unbalanced shafts to configure such that their respective centrifugal forces oppose one another in all directions away from the CT center and add to one another in the axial direction. This configuration produced a linear force with sinusoidal amplitude directed along the axis of the CT. In axial vibration mode, the torque applied was negligible and the vibration force applied along the axis of the CT was frequency dependent.

3. Torsional Vibration Configuration

Motors were aligned with one another across the CT center in line with the CT axis. This configuration caused the two unbalanced shafts to configure such that their respective centrifugal forces opposed one another in all linear directions. However; with the motors offset from the CT center, there was an applied torque about the CT axis. In torsional vibration mode, the linear force applied was negligible and the vibrational torque applied about the axis of the CT was frequency dependent.

5.2.3. Data Acquisition

The primary data of interest (force-in and force-out) to determine friction mitigation as a result of CT vibration was acquired from the load cells attached to each end of the CT. These load cells passed a 4-20 milliamp signal output to an analog low pass filter with a 3 decibel cutoff at 500 Hz which was then sampled at > 500 Hz. This data was then scaled in pounds to represent the force-in and force-out on the CT. Load cell signals were affected by noise generated by the motor controller, calibration drift, and off-axis loading; accordingly, we expect maximum force-in error to be less than ±50 lbs without motor operation and ±150 lbs with motors operating, and ±50 lbs of error for the force-out signal under all conditions.

Signals of secondary importance were:

- Accelerometer outputs (0-10 volts @ 1 g / 100 millivolts , where g = acceleration due to gravity)
- Motor controller current (0-5 volts @ 0.15 amperes / 100 millivolts)
- Motor frequency (Computer controlled Hz)

To accommodate the acquisition of these digital signals, an National Instruments LabView program was created to acquire, display, and record all the above signals into an ASCII text file. The interface created included a force-in vs. force-out plot, instant load readings, frequency control for the vibrator motors and digital signal filtering controls.

5.2.4. Test Procedure

For each CT diameter, the testing procedure consisted of the following steps:

1. Determine the helical buckling load and maximum yield load for the diameter of CT being tested.
2. Configure the vibrator motors for the desired vibration mode (discussed in section 5.2.2).
3. Begin data acquisition utilizing the LabView program.
4. Move the hydraulic piston forward at the 'surface' end of the CT (~1 inch per minute), imparting a compression load on the CT and simulating WOB, until the load input is several times the HBL of the CT and yet still well below the CT yield point.
5. Release the axial load applied to the 'surface' end of the CT and allow the CT to relax.
6. Start the vibrator motors to impart vibration at the 'surface' end of the CT and perform steps 3 through 5 for frequencies 25-60 Hz in increments of 5 Hz.

5.3. TASK 3 RESULTS - TESTING AND MODEL VALIDATION

5.3.1. Vibration Mode and Energy

Testing of the three vibrational modes began with the 1.0" CT string (within the 'straight horizontal wellbore') using two vibrator motors with limited energy output. Initial vibration tests were focused on lateral vibration. Unfortunately, lateral vibration at the frequencies utilized during testing (25-60 Hz) quickly caused fatigue-related CT failure. Due to this failure, lateral vibration was eliminated as a viable mode of vibration, and no additional lateral vibration testing was performed.

Further testing of the 1.0" CT string with the axial and torsional vibration modes using the initial low-energy vibrator motors yielded little or no friction mitigation vs. the non-vibrational case. After observing that the vibration energy level initially applied to the CT had no significant effect, the vibrator motors were upgraded to apply significantly higher centrifugal energy/force (from 313 to 1,516 lbf).

5.3.2. Testing Results

Figure 6 and Figure 7 contain results for the 1" and 1.5" CT test cases respectively. The light blue dashed line shows the ideal situation (i.e. zero friction) where force-out is equal to the force-in. The right side of this line illustrates the data for force-in being applied, which is the data of interest. The left side of this line contains the data for the force-in being released, which is not really of interest for this project. The red, "No Vibration" curve plots the data as the force-in is applied and then released. The dark blue line illustrates the results obtained from application of axial vibration, and the green line provides the results obtained with torsional vibration energy.

In both cases, the axial vibration followed the ideal (force-in = force-out) curve further than the torsional vibration. From this it was concluded that axial vibration performs better at mitigating friction than torsional vibration. However, after the CT is loaded with a certain amount of compressive axial force (force-in = 1200 lbs for the 1" CT and 4,000 lbs for the 1.5" CT) the axial vibration no longer mitigates all of the friction, and the dark blue line tends to run parallel to the "No Vibration" curve. Thus the ability to mitigate CT friction as a result of applying vibration was not as significant as hoped.

The somewhat jagged shape observed in the measured data from the vibration test fixture is due to the "slip-stick" nature of the motion of the CT.

Figure 8 and Figure 9 contain torsional vibration results for various vibration motor frequencies. As the frequency increases, more vibration energy is being added, and thus there is some improvement in the output force for a given input force.

Similarly, Figure 10 and Figure 11 illustrate torsional and axial vibration results at various vibration motor frequencies. Again, it is evident that axial vibration tends to be better at mitigating friction than torsional vibration, and that the higher frequency results are more effective at mitigating friction than the lower frequency results.

5.3.3. Comparison of Model to Test Results

Figure 6 and Figure 7 contain the vibration energy attenuation model results vs. the measured results from the vibration test fixture. The yellow line for model data with no vibration closely follows the red line of measured data from the test fixture. For this yellow line, it was assumed that the CT was always buckled. If the CT did not buckle until the HBL was reached, the brown "knee" would have been followed for that portion of the modeled line. Note that there is no indication of this "knee" in the measured data. There was some snapping motions of the CT as it was compressed (due to application of a compressive axial load), but no evidence of the onset of helical buckling was observed in the measured data from the vibration test fixture.

For the modeled data to accurately match the test fixture measured data, a friction coefficient of 0.20 was used for the 1" CT case and 0.27 was used for the 1.5" CT case. Theoretically, the fiction coefficient should be the same for both sizes of CT. This difference could be due to several variables, including residual bend of the CT, calibration differences in the force measurement gauges, and variations in the amount of lubricant between the CT and the casing.

For modeling the predicted friction mitigation results with vibration (shown as a black line titled "Model with Vibration") a fixed calibration offset in the modeled output force was added to obtain the values as shown. For the 1" CT case this increase was 200 lbs. For the 1.5" CT case it was 500 lbs.

5.4. Task 4 Results - Conceptual Design and Optimization

As discussed in the conclusions, the friction mitigation results recorded during Phase 1 testing were not what we had expected. The data showed that developing a system to vibrate CT at surface was not a commercially-viable approach to solving the downhole friction mitigation challenge. Thus, the project was concluded following completion of Phase 1, and Phase 2 was not attempted.

5.5. Task 5 Results - Technology Transfer and Final Report

This report is the final project report for this effort, even though it only contains results from Phase 1 of the project. Phase 2 of the project (design, fabrication, and field test of prototype surface vibration equipment for CT) was not pursued, as a result of the limited friction mitigation results that were recorded in Phase 1 testing. While the results from Phase 1 were different than anticipated, they have documented some very interesting findings with regard to vibration attenuation and the ability to mitigate downhole friction in inclined or horizontal wellbores.

The results from this project have been publicly disseminated through multiple technology transfer channels, including publication of this final report. Project progress updates and test results were presented at three DOE Microhole Technology Integration meetings in the Houston, TX area. These meetings were well-attended by interested parties. Powerpoint slides of these presentations were subsequently posted on the DOE Microhole Technologies website.

Project results were also included in a Society of Petroleum Engineers technical paper (SPE #106979, "*Vibration and Rotation Considerations in Extending Coiled-Tubing Reach"*), and this paper was presented at the 2007 SPE Intervention and Coiled Tubing Association annual conference. A summary of this SPE paper is scheduled for publication in a 2007 issue of *Journal of Petroleum Technology (JPT)*. CTES has posted information regarding this project on our website, and has also represented the project findings at numerous industry trade shows. PowerPoint slide presentations containing a summary of the project results have also been made publicly available, and will continue to be provided to interested industry groups.

6. CONCLUSIONS

The following points summarize the primary conclusions from this project:

- Of the 3 vibration modes examined, axial vibration was most effective at mitigating friction in an inclined or horizontal wellbore. Torsion vibration was less effective. Lateral vibration resulted in mechanical failure of the CT and additional work with this vibration mode was abandoned.
- There was some friction mitigation achieved as a result of application of axial and torsional vibration, but this friction reduction was not significant enough to warrant further development of the surface CT vibration concept.
- The additional wall contact forces caused by helical buckling of the CT were too significant to be completely mitigated by vibration.
- When the axial force was less than the helical buckling load, axial vibration was effective at mitigating friction. If CTD field operations can be performed without exceeding the HBL of the CT, axial vibration will allow significant incremental WOB.
- For the testing conducted in this project, the friction mitigation due to vibration was best modeled as a fixed increase in the amount of force that could be transmitted to the simulated 'downhole' end of the CT.

This project has demonstrated that vibration can be used to mitigate friction. The data observed during project tests in the vibration test fixture also provided evidence that vibration is attenuated by wall contact forces created by helical buckling of the CT. The results from the project are useful in the design of drilling operations utilizing downhole vibrators.

It was decided not to pursue Phase 2 of this project (development and field testing of the surface-applied vibration concept), due to the vibration attenuation (friction mitigation decrease) that was recorded when the pipe was operating in a buckled mode. Industry is currently considering other technical solutions to mitigate downhole friction, including surface-applied rotation of CT. While the potential benefits associated with rotating CT are interesting, there are numerous technical questions with this approach that remain to be answered.

7. LIST OF ACRONYMS AND ABBREVIATIONS

Acronym	Meaning
BHA	Bottom Hole Assembly
CT	Coiled Tubing
CTD	Coiled Tubing Drilling
DOE	Department of Energy
ft	feet
HBL	Helical Buckling Load
Hz	Hertz
ICoTA	Intervention and Coiled Tubing Association
klbf	thousand pounds-force
lbf	pounds-force
SPE	Society of Petroleum Engineers
TOB	Torque on Bit
WCF	Wall Contact Force
WOB	Weight on Bit

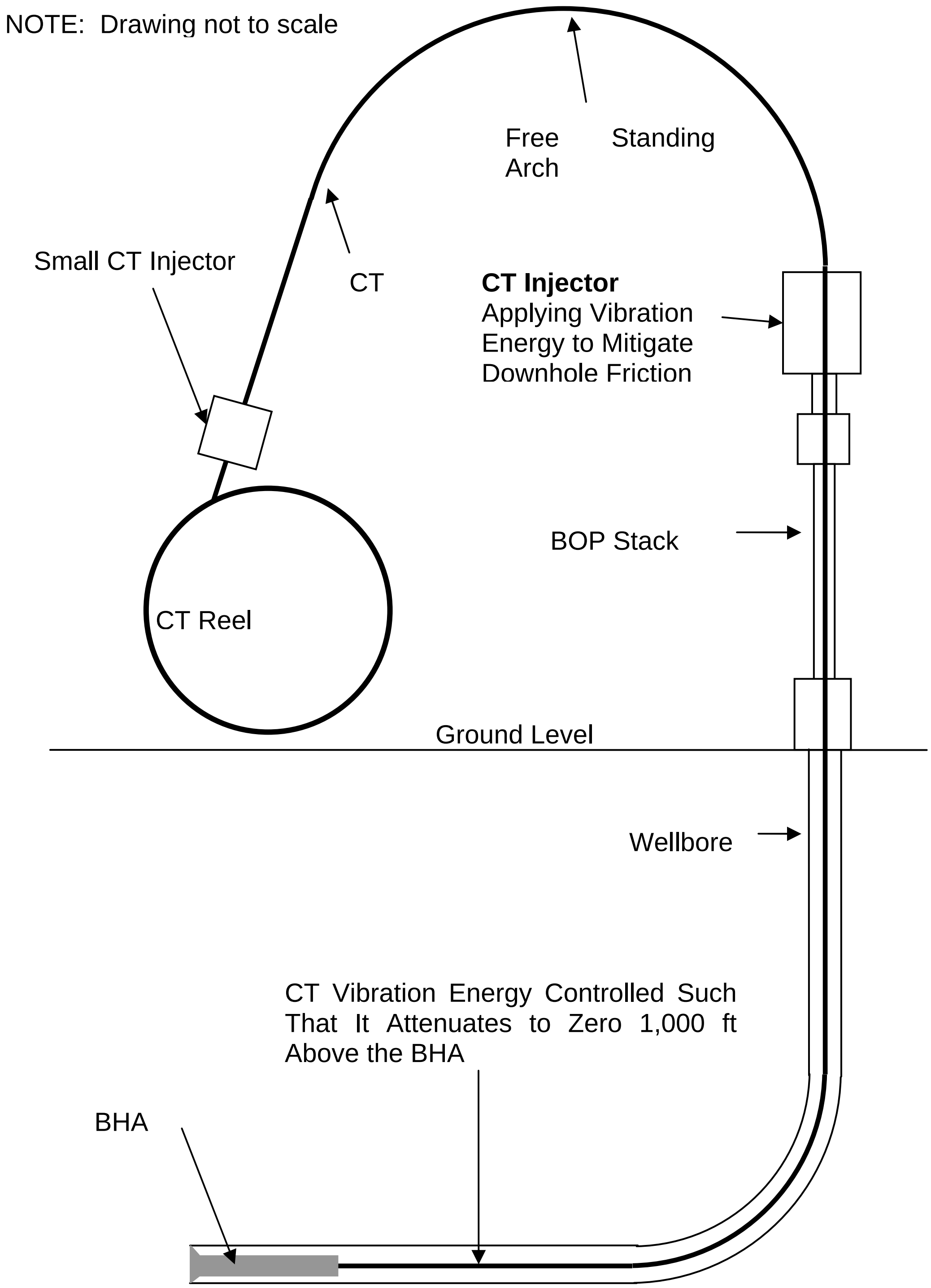
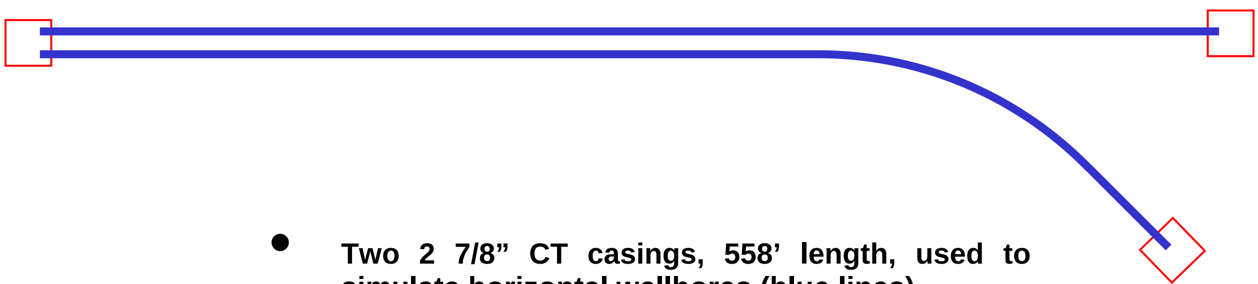


Figure 1 Microhole CTD Friction Reduction in Horizontal Wellbores



- **Two 2 7/8" CT casings, 558' length, used to simulate horizontal wellbores (blue lines)**
- **Build Up Radius of 30 deg/100 ft to 45 deg in one simulated horizontal wellbore**
- **1" or 1.5" OD CT drilling test strings are inserted into the simulated horizontal wellbores**
- **CT drilling strings are tested by applying an axial load, with/without vibration to test friction mitigation as a result of vibration energy application**
- **Friction mitigation effects quantified by comparing applied force-in vs. measured force-out at the end of the CT**

Figure 2 – Vibration Test Fixture Schematic

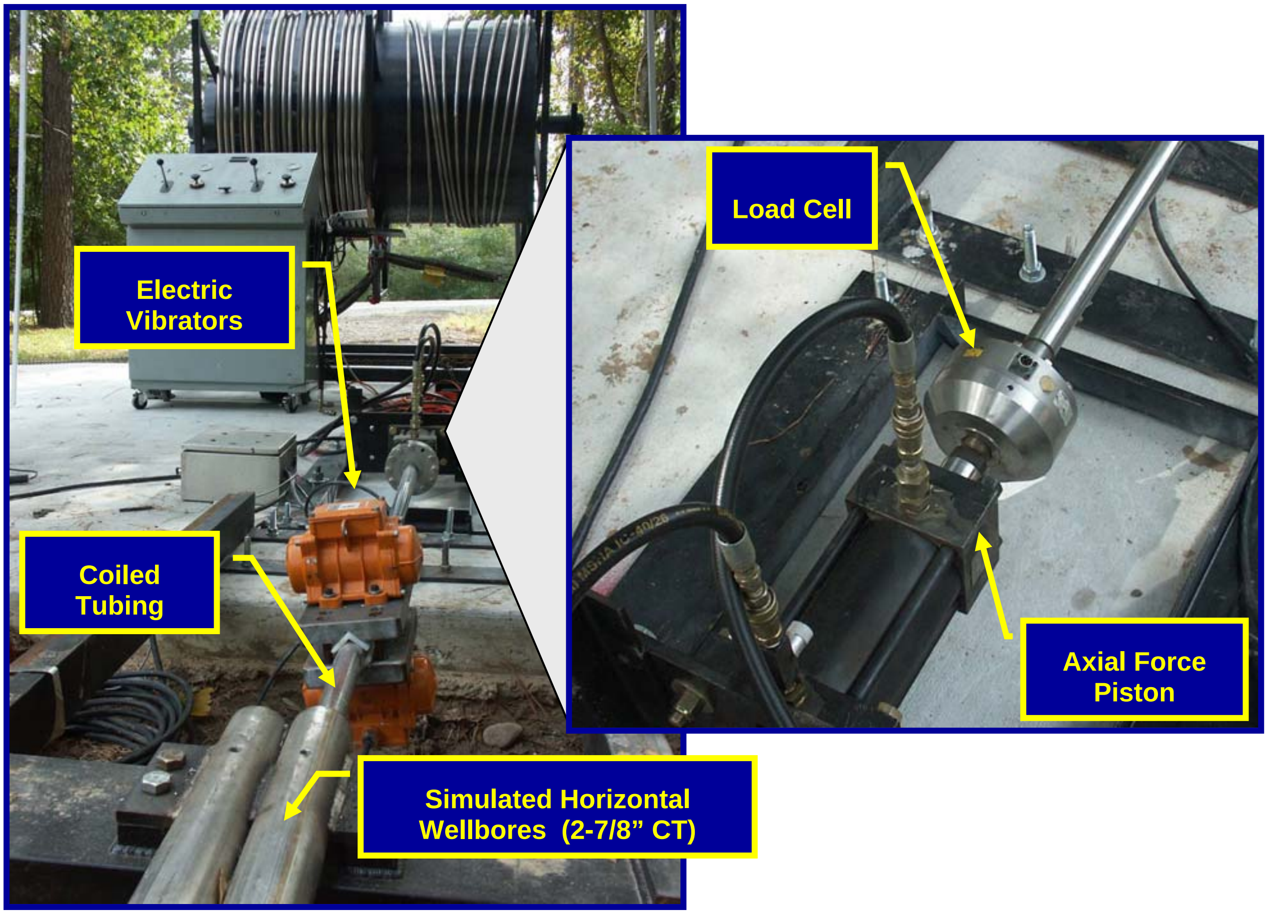


Figure 3 – Photo of Key Components - Vibration Test Fixture

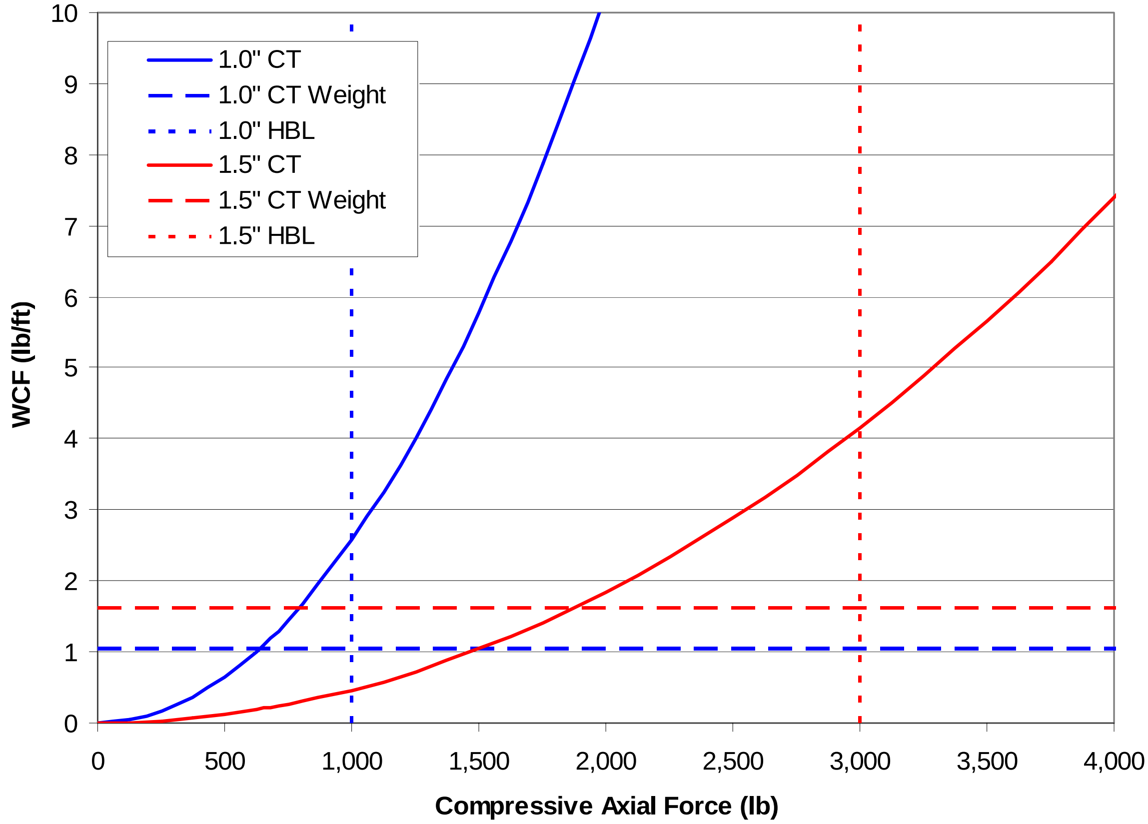


Figure 4 – Wall Contact Force vs. Compressive Axial Force

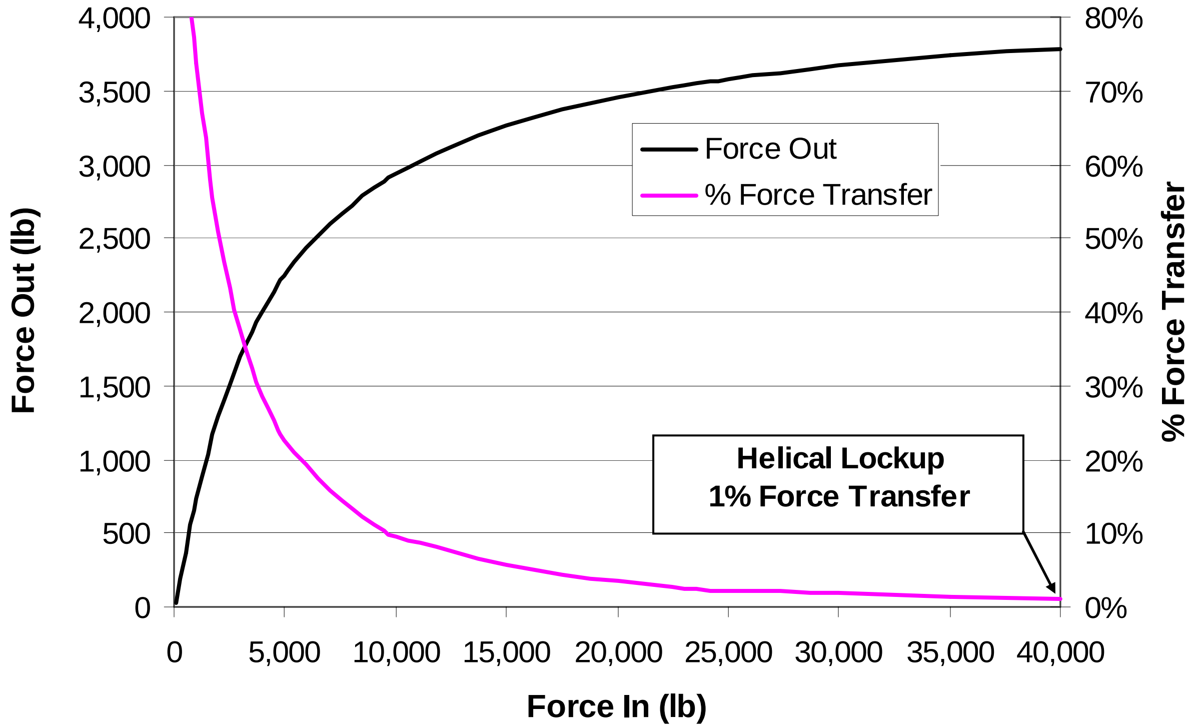


Figure 5 – Theoretical Force-in vs. Force-out Results (1.0" CT in Straight Fixture)

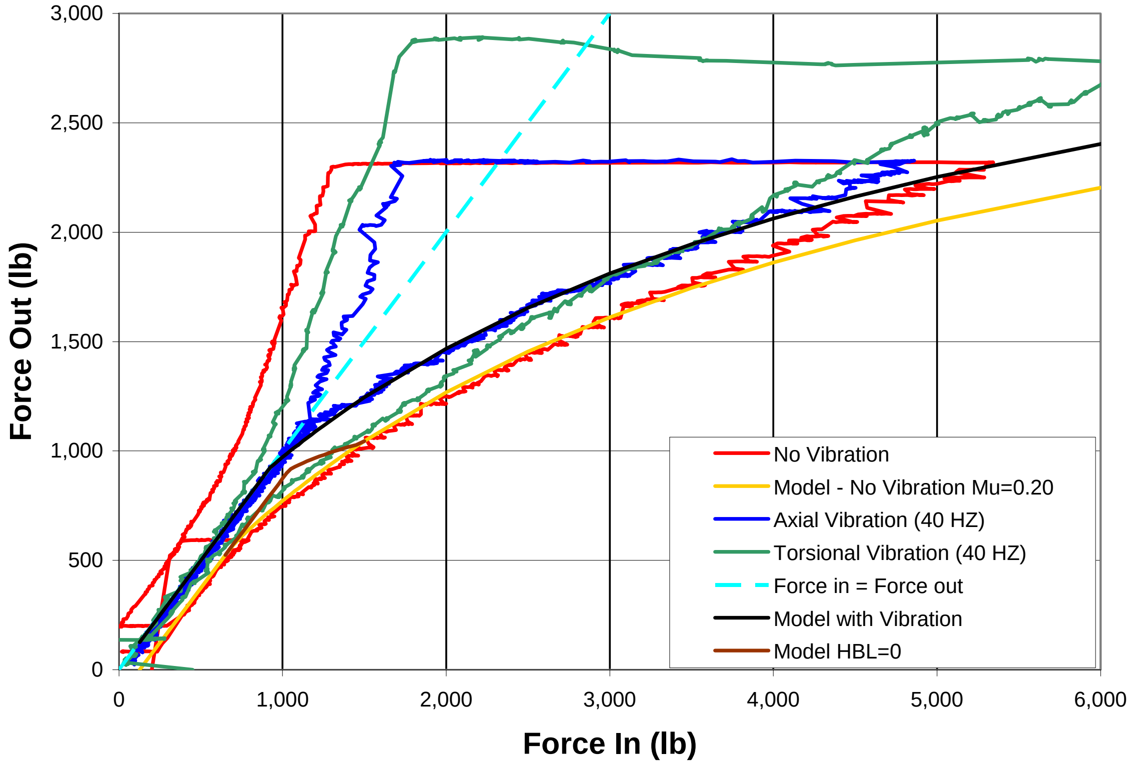


Figure 6 – Axial and Torsional Vibration Results vs. Model Results, 1.0" CT

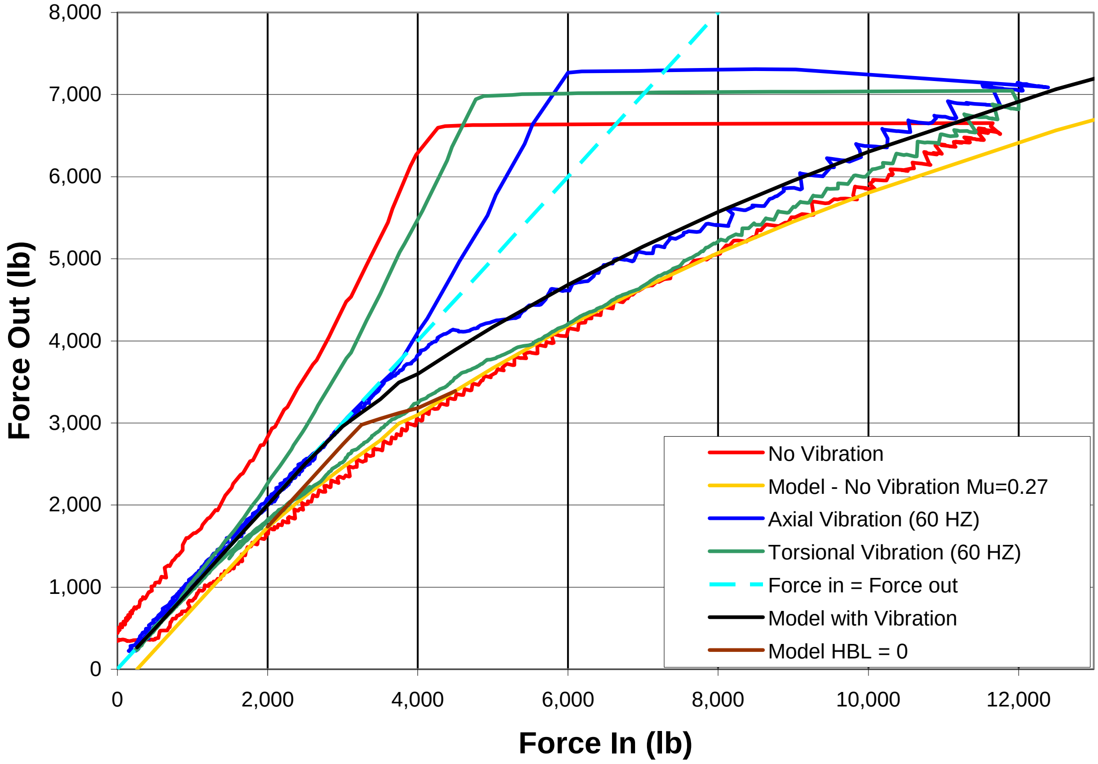


Figure 7 – Axial and Torsional Vibration Results vs. Model Results, 1.5" CT

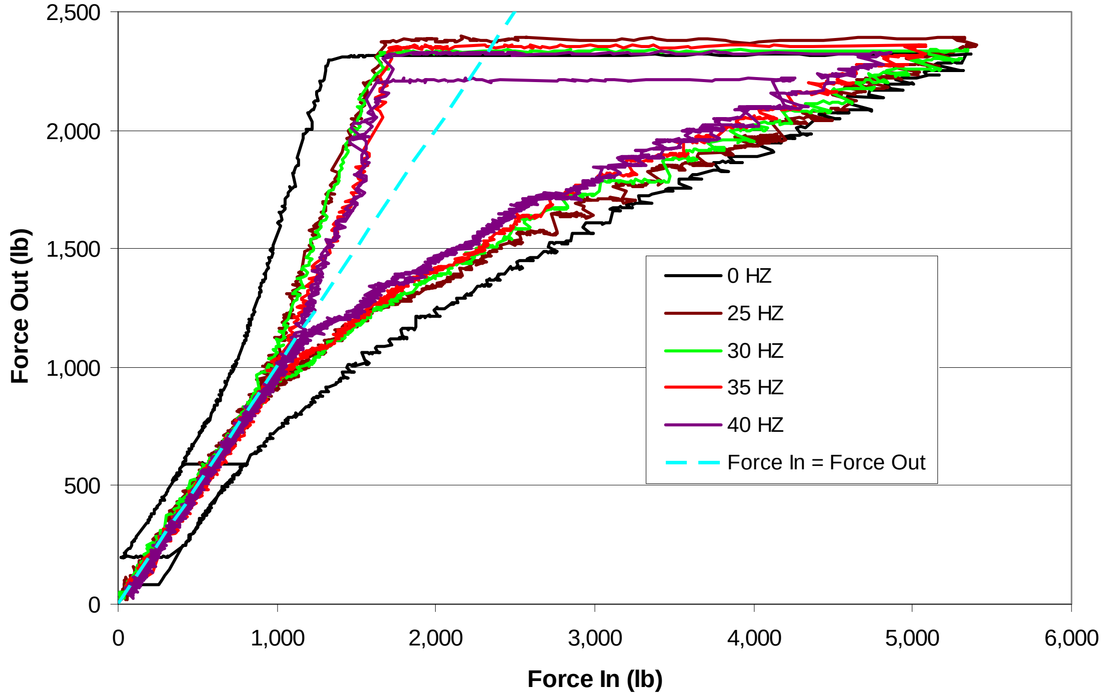


Figure 8 - Torsional Vibration Results, 1" CT

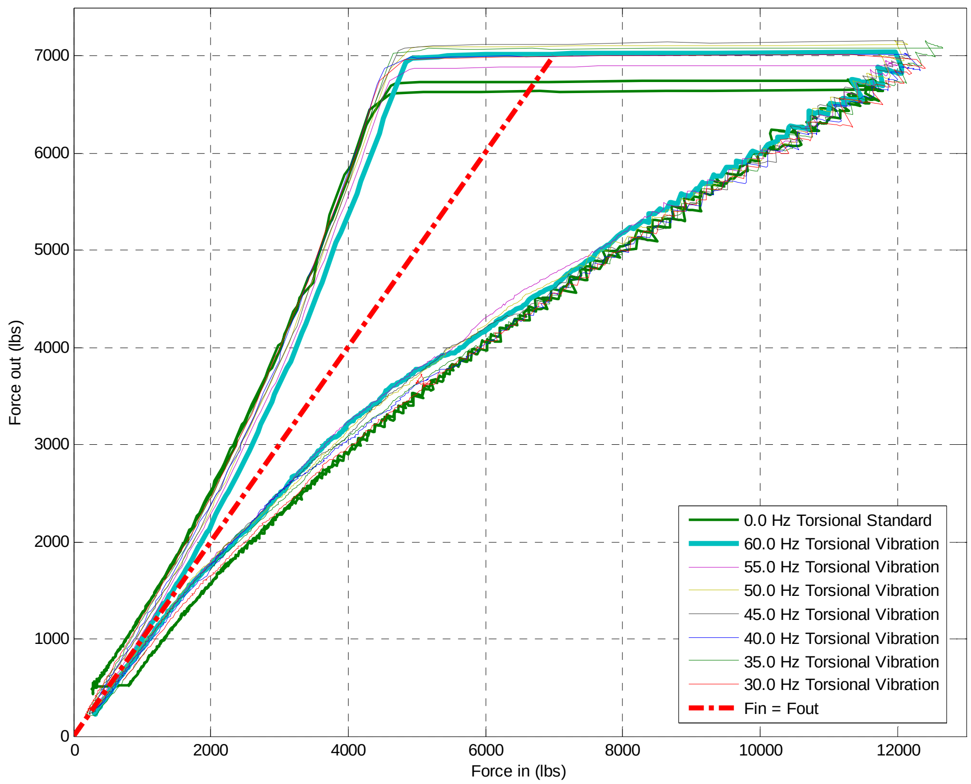


Figure 9 - Torsional Vibration Results, 1.5” CT

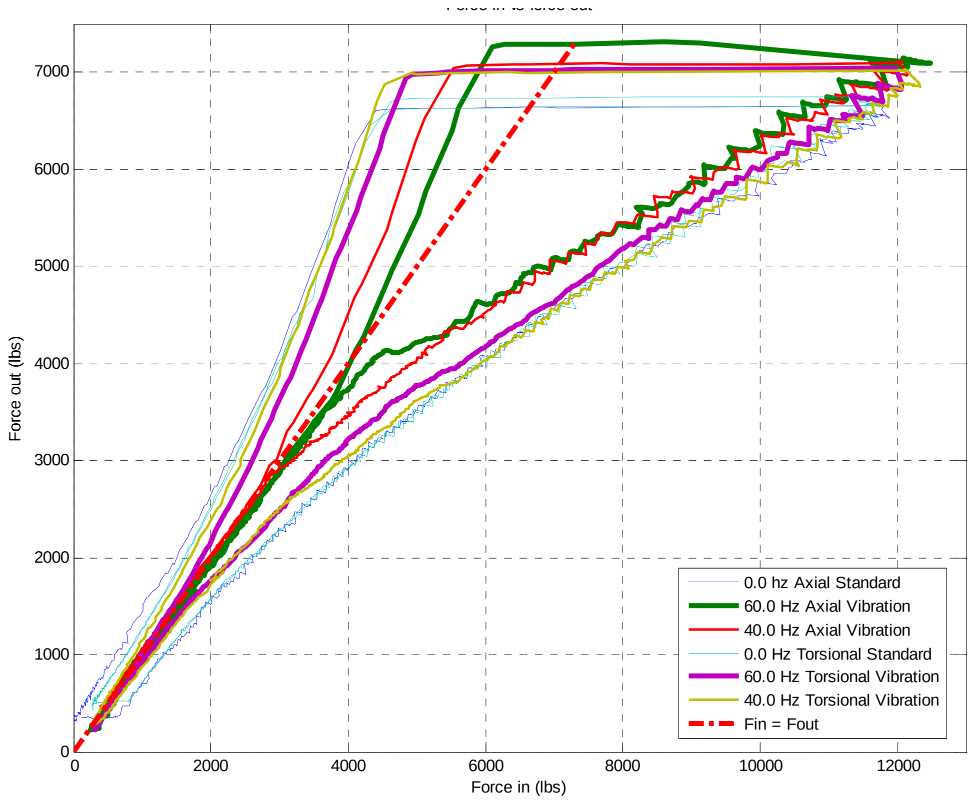


Figure 10 - 1.5”CT Torsional and Axial Vibration Comparison

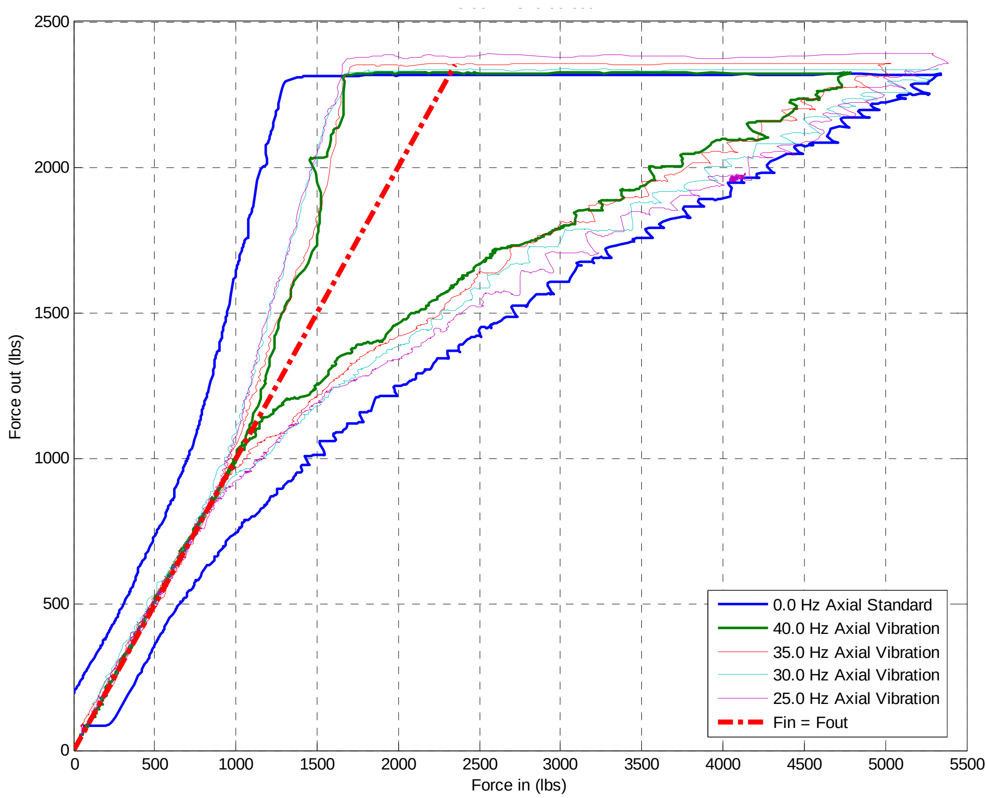


Figure 11 - 1.0"CT Axial Vibration Comparison