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Design of a Testing Facility for Investigation of Drill Pipes Fatigue Failure

J. Abdo[a*], E. Hassan[a], A. Al-Shabibi[a] and J. Kwak[b]

[a] *Department of Mechanical and Industrial Engineering, College of Engineering, Sultan Qaboos University, Muscat, Oman.*
[b] *Qatar University, Doha, Qatar.*

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Abstract: Drillstring and down-hole tool failure usually results from failing to control one or more of the vibration mechanisms. The solution starts with the ability to measure different modes of vibration, hence identifying different vibration mechanisms. Lateral, torsion and axial are vibration modes that take place when drill pipes run into problems downhole. Due to the three modes of vibration mechanisms such as bit bounce, stick-slip, lateral shocks, bit and bottom hole assembly (BHA) whirl, parametric and torsional resonance occur. Understanding the causes of the destructive loads is the main step towards developing approaches to prevent or reduce their effects, hence improving drilling performance. Vibration modes and mechanisms lead to failure of the drill pipes, BHA and drill bits. Drill pipes fatigue failure is very common due to capability of producing all vibration modes and mechanisms. Drill pipe and downhole tool assembly failure usually result from failing to have power over one or more of these vibration mechanisms. A novel in house experimental setup has been developed to mimic downhole axial, lateral and torsional vibration modes and mechanisms in drilling operations. In this paper, we focus on the design and construction of the testing facility. A number of tests were conducted to validate the capability and performance of the test setup. Drill pipe fatigue failure due to lateral cyclic stresses induced in the drill pipe has also been investigated and presented in this paper. The results show that operating on a rotation speed higher than 90% of the drillstring critical speed leads to yielding in the drillstring.

Keywords: Drillstring experiment setup; Fatigue failure; Vibration modes.

تصميم مرفق اختبار للتحقق من الاخفاق الناتج عن اجهاد أنابيب الحفر

جميل عبدو[أ]*، ادريس حسن[أ]، عبدالله الشبيبي[أ]، جان كواك[ب]

الملخص: عادة ما ينتج الاخفاق في جهاز الحفر و أداة حفر أسفل البئر عن الاخفاق في السيطرة على واحد أو أكثر من آليات الاهتزاز.و يبدأ الحل بالقدرة على قياس انماط اهتزازات مختلفة وبالتالي يتم تحديد آليات الاهتزازا المختلفة. تعد الاهتزازات الجانبية و الالتوائية والمحورية أنماطا من الاهتزازات التي تحدث عندما تصادف أنابيب الحفر مشاكل أسفل البئر. و يحدث الرنين الالتوائي الحدودي نتيجة ثلاثة أنماط من اليات اهتزاز ارتداد المثقاب وهي : انزلاق القضيب و الصدمات الجانبية و تجمع الاجزاء أسفل الحفرة. ان فهم أسباب أحمال الهدم هو الخطوة الرئيسية نحو تطوير اساليب لمنع أو الحد من آثارها وبالتالي تحسين أداء الحفر. كما أن اشكال وآليات الاهتزاز تؤدي إلى اخفاق في أداء أنابيب ومثقاب الحفر. و يعد الاخفاق الناتج عن اجهاد أنابيب الحفر من الامور الشائعة جدا بسبب امكانية قيامه بجميع انواع والآليات الاهتزاز. فعادة ما ينتج اخفاق أنبوب الحفر و ادوات أجزاء البئر عن الاخفاق في القدرة على التحكم في واحد أو أكثر من آليات الاهتزاز هذه. وقد تم تطوير جهاز تجريبي محليا (في المختبر) لمحاكاة انواع الاهتزازات المحورية و الأفقية والالتوائية والآليات المستخدمة في عمليات الحفر. نحن نركز في هذه الورقة على تصميم وبناء مرفق الحفر. وقمنا بإجراء عدد من الاختبارات للتحقق من مدى قدرة وكفاءة أداء الجهاز. وقمنا أيضا بالتحقق من سبب اخفاق أنبوب الحفر بسبب الإجهاد الدوري الجانبي الناجم عن أنبوب الحفر وقدمناه في هذه الورقة البحثية. وتظهر النتائج أن التشغيل على سرعة دوران أعلى من ٩٠٪ في منطقة الحفر و السرعة الحرجة تؤدي إلى مرونة في جهاز الحفر.

الكلمات المفتاحية: جهاز الحفر، الجهاز التجريبي، الاخفاق الناتج عن اجهاد جهاز الحفر

* Corresponding author's e-mail: jdabdo@squ.edu.om

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1. Introduction

Drillstring consists of a drill pipe and Bottom Hole Assembly (BHA). The drill pipe is a long hollow shaft that drives a bit at the bottom of the wellbore. Drillstring failure occurs in approximately one out of seven drilling rigs in low to moderate well depth and three out of seven in deep drilling wells. The cost of each failure ranges from $100,000 to $200,000 depending on well depth. Due to the frequent and high cost of drillstring failure, investigations have focused on raising awareness of the factors causing drillstring failure, and eliminating or reducing the occurrence of such failure incidents.

During drilling operations, drillstring interacts continuously with the rock formation, which results in severe shock and vibrations. Drillstring shock and vibrations are identified as the principal sources of performance deterioration in oil and gas drilling operations (Macdonald and Bjune 2007; Moradi and Ranjbar 2009; Reid and Rabja 1995). Drill pipe, BHA and drill bit are affected by the vibration induced as a result of high input impact energy. This energy introduces different states of stresses, which translate into excess vibrations that may lead to failure. The severity of shock and vibrations depends on three parameters: shock magnitude, duration or length of time and frequency or number of shocks. The main causes of these vibrations include: contact and friction at the borehole/drillstring and bit/rock formation interfaces, eccentricity, imbalance, initial curvature in the drill collar sections, and various linear or nonlinear resonances. Severe shock and vibration may subsequently produce fatigue and abrasive wear in drill pipes, drill bit damage and reduction of penetration rate ROP (Jardine *et al*. 1994; Spanos *et al.* 2003; Khulief and Al-Naser 2005). As a consequence, the drilling process becomes inefficient and costly. In a drilling operation, drillstring exhibits one or more of three common modes of vibrations: axial, torsion and lateral. Preventing drill pipe failure calls for addressing all possible factors that can cause failure. Sometimes this is as simple as managing loads and load capacities, and having a good inception of the drilling operation. However, with complex causes, much more is involved in order to prevent failure (Jardine *et al.* 1994). Regardless of vibration mechanisms, drill pipes happen to deteriorate as a result of flaws in one or more of the following areas: design, inspection, operation and characteristics of drilling operation. The mechanical and chemical environments surrounding the drillstring can have a major effect on whether or not failure may take place. Vibration, mud type, dissolved gas content, salinity, and other factors play key roles in many drill pipes failure.

Lateral vibrations are recognized as a leading cause of drillstring and BHA failures. Lateral vibration also damages the well when BHA large shocks impact the wellbore. Several attempts have been made to theoretically study drill pipe lateral vibration in order to overcome the difficulties encountered during drilling process (Berlioz *et al.* 1996; Yigit and Christofourou 1996). Most of the mathematical models report slight progress in order to determine causes of drill pipe failure. However, not much has been reported about the procedures to accurately account for the effects of induced lateral vibration in drillstrings during drilling operations. Very few modeling attempts have been undertaken in order to address the effects of lateral vibration on drill pipes, drill bit, and BHA. It suffices to say that nearly all models are very much simplified and far away from addressing the real problem. One should note that modeling of such a long rotating element is non-linear and complex due to the fact that drillstring dynamics involve broad vibration profile, which includes axial, lateral and torsional modes (Baryshnikov *et al*. 1997; Wang *at al*. 2016). In addition, drilling process is very complex as many influencing parameters are not under drilling engineers' control (Abdo and Al-Sharji 2015). Some attempts have been made to study the non-linear dynamics of the drilling string. Non-linear treatments were proposed in (Al-Hiddabi *et al*. 2003, Abdo 2006, Abdo *et al.* 2015, Farhang and Lim 2007). The authors undertook such a procedure to suppress torsional vibrations and reduce lateral vibrations of drilling sting non-linear modes.

This paper aims at gaining a deeper understanding of drill pipe complex behavior under vibrations and its detrimental effect on drilling operation. The present work focuses on the design and development of an in-house testing facility. The developed facility is proposed to be capable of generating various vibration modes that a drillstring experiences when it runs into hard rock formation during drilling operations. The facility intends to provide further expansion for more comprehensive drillstring testing. It can readily accommodate other relevant effects such as wellbore and drillstring contact, drillstring interaction and stick-slip phenomenon. The controlled testing facility also aims to offer oil and gas industries with satisfactory answers and justifications on the drillstring performance under various loading and operating conditions. The investigations are expected to lead to better understanding of drill pipe behaviors. It also accounts for the number of cycles to fatigue failure due to induced lateral vibration in the drill pipe under various loading conditions.

2. Drillstring Testing Facility

Drilling processes are complex as many of their influencing parameters are not in control of drilling engineers. In many situations, mathematical formulations do not necessary lead to accurate explanations of failure causes. Drill pipe fatigue failure is one of the most frequent failures that occur due to rapid and continuous cyclic stresses induced by vibration and high shock loads. Mathematical and computational models have important roles in the investigation of vibrations in drillstrings. Such models enable configuration of drillstring behaviour under range of loading, physical and boundary conditions. However, a combination of the drillstring geometry (long thin-walled rotating object) as well as forces and torques acting on it during drilling operations lead to complications in drillstring dynamic response and broad vibration profile that includes axial, lateral and torsional patterns. Hence, there is a need to develop an in-house testing facility that is capable of imitating drilling process and has the potential of generating the three different types of vibrations. The testing facility is also utilized to investigate drillstring connections behavior under all modes of vibrations.

In the current setup, a braking mechanism was developed and assembled to the lower side of the facility in order to introduce torsional vibration in the drill pipe. The braking mechanism is employed to induce torsional vibration of various amplitudes in the drill pipe. Lateral vibration is created due to the eccentric rotation of the drill pipe. The frequency and amplitude of the lateral vibration are controlled by varying the drillstring rotational speed. The following sections briefly discuss the testing facility design and construction. In subsequent sections, the effect of inducing lateral vibration of the drill pipe on its lifetime fatigue failure is experimentally investigated utilizing the developed testing facility.

2.1 Experimental Setup

The experimental setup shown in Fig.1 consists of the following: a testing pipe that represents the drillstring; support system that includes supporting plates fixed to the ground to provide stability for the facility, C-Channels beams to connect the supporting tables; loading and rotation mechanism which includes motor, pulleys, belts, chucks, pillow bearings, connections, flanges and housing pipes; mild steel cylinders representing the wellbore and also used as stabilizers for the drillstring; a control unit and speed controller; sensing mechanism, that includes load cells and sensors for measuring top and bottom torques, rotation speed, number of cycles, and vibration amplitude; braking mechanism and pressure mechanism utilized for inducing torsional vibration in the drill pipe at various frequencies and amplitudes; and a data acquisition system which includes twelve channels data logger and computer. Figure 1a shows an image of the facility while Fig. 1b shows a schematic of the facility and its individual components and systems. The representations for the numbers indicated on Fig. 1b are listed in Table 1.

The facility structural support consists of two 16 mm thick mild steel tables, two ring shape stabilizers and four C-channel beams connecting the tables to the stabilizers and providing stability to the facility. The C-channels are fixed to a concrete floor. The structural support is responsible for providing safe working environment and holding other mechanisms such as rotation and braking mechanisms. The rotation mechanism is responsible for rotating drill pipe and generating lateral vibration. Three phase 12 hp electric motor rotates the pulley whereas the controller regulates the drill pipe rotational speeds. The V-belts rotate the housing pipe at a specified rotational speed hence the drill pipe rotates at the same rotation speed as it is connected to a chuck as shown in Fig. 1. The three-

Table 1. Main components of the drilling facility.

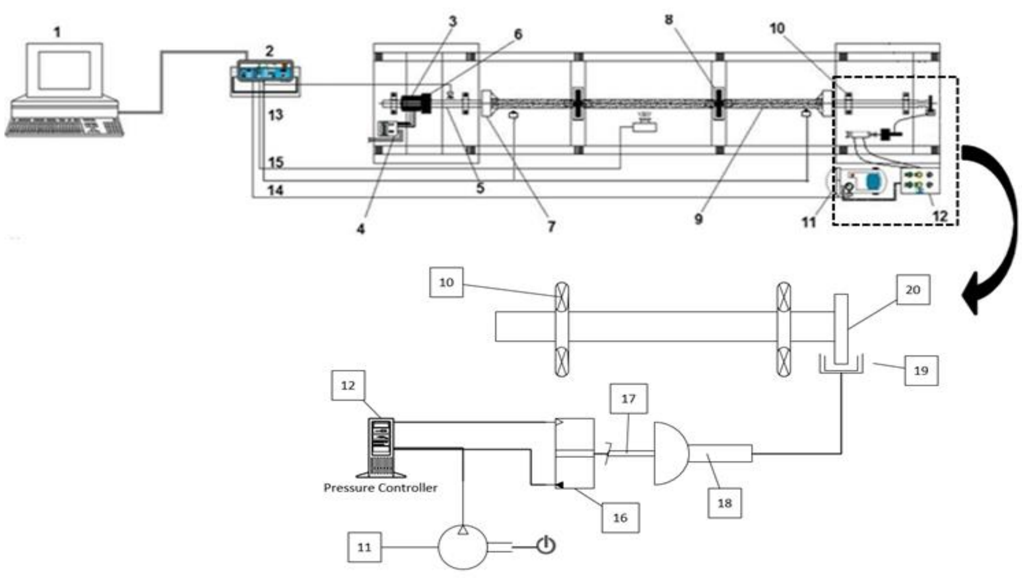
Component/System #.	Nomenclature
1	Computer
2	Data acquisition system
3	3-phase electrical motor
4	Motor speed controller
5	Rotary shaft
6	Pulleys and belts
7	Chuck and flange assembly
8	Stabilizer
9	Specimen (drill pipe)
10	Pillow block bearing
11	Air compressor
12	Pressure controller
13	Hall effect sensor
14	Brake on/off switch
15	Ultrasonic sensor
16	Linear pneumatic actuator
17	Brake pedal
18	Master cylinder
19	Caliper and pads
20	Brake disc

jaw chuck is connected to the housing pipe. A similar housing pipe and a chuck are fixed on the other end of the testing facility. The housing pipe guides the drillstring through these for about 0.5 m on each end of the facility to provide stability and rigidity to the drill pipe. The housing pipes are also guided through two pillow block bearings. Such configuration allows for smooth rotation. A number of test specimens (mild steel pipes) representing drillstrings of various external diameters (1″, 2″, and 3″) were used during testing. The drill pipe is 6 m long; however, the length between the two chucks is 5 m. A total of 1 m of the drill pipe is inserted inside the two sides of housing pipes using three-jaw chuck and pillow block bearing. Fig. 1a illustrates a zoomed-in image of the drill pipe, chuck and flange to housing pipes connection.

2.2 *Braking Mechanism*

A brief description of the braking mechanism is discussed in this section. The braking mechanism is used to provide time varying resistance to simulate wellbore rock formation resistance and prompt torsional stress in the drill pipe. Such engagement should also simulate stick-slip phenomenon in drilling operations. Table 2 includes images of the braking system along with other attached sub-systems and deliverables.

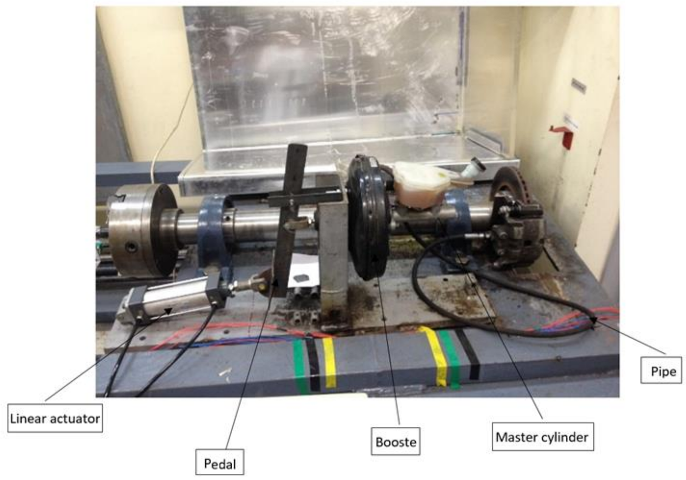
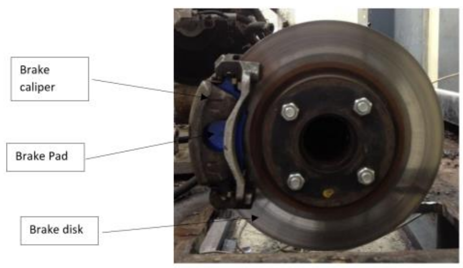
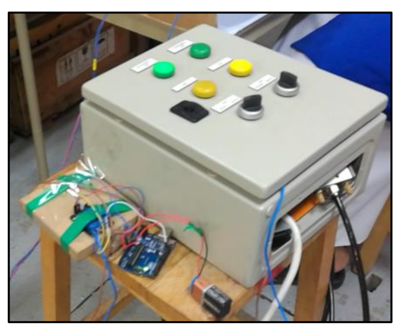
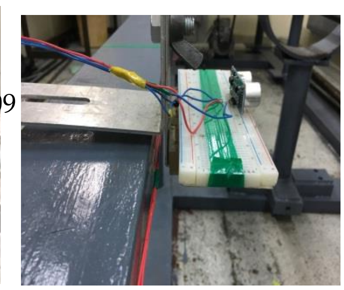
(a)

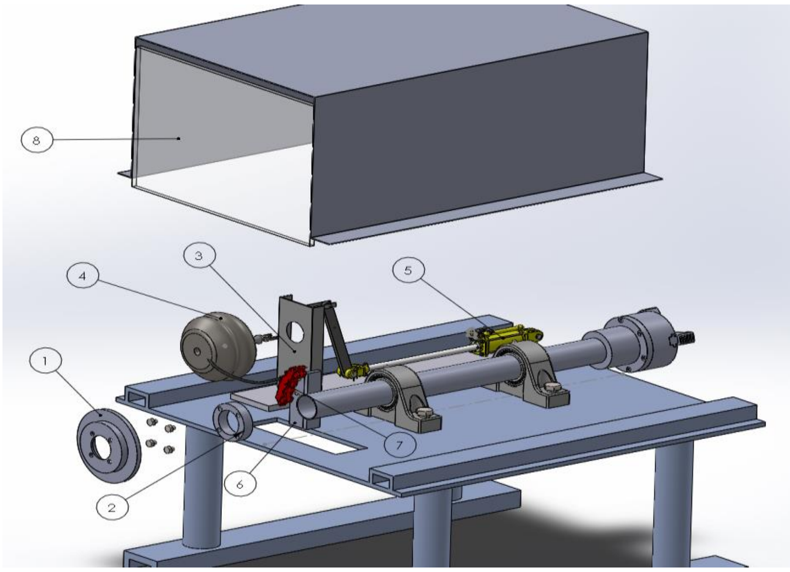


(b)

Figure 1. Drillstring testing facility (a: image of the testing facility and loading mechanism, b: schematics shows individual components).

Table 2. Braking mechanism along with deliverables of the sub-mechanism.

Part/subsystem	Picture	Deliverables
Braking Mechanism		✓ Less than 10 cm stroke length ✓ Pressure supply of 8 bar ✓ Time required to brake and frequent duration are possible ✓ Repeatability of mimicking stick-slip condition
Braking Pads		✓ Easy assembly to a system. ✓ Parts are available. ✓ Potential to mimic stick-slip motion.
Control Unit	 	✓ Brake actuator has a control switch ✓ Can be controlled automatically or manually ✓ For automatic control, the delay time varies from 1second up to 1 hour
Measuring Sensors	 	✓ Ultrasonic sensor and Hall-effect sensors have been installed ✓ RPM at both ends of the string and deflection in the middle of the string are measured.



#.	Nomenclature
1	Brake Disk
2	Brake Hub
3	Booster Stand
4	Brake Booster
5	Pneumatic actuator
6	Caliper Stand
7	Brake Caliper
8	Safety Box

Figure 2. Configuration of parts of the braking mechanism.

The braking mechanism consists of a steel hosting structure and a linear pneumatic actuator that is connected to the brake pedal to initiate braking action. Booster and master cylinder are both bolted into a C-channel, which is welded to the testing facility base. Pneumatic double acting actuators with controlling valves are used in the system. Required pressure needed to actuate the braking mechanism is provided by 12 bar compressor. A control unit, as shown in Table 2, has been utilized to control stroke pressure, the braking time and the time of engagement. Figure 2 configures exploded view of the brake mechanism parts using 3D CAD modeling. Table 2 also illustrates parts of breaking mechanism.

3. Results and Discussion

The experiments were carried out under controlled loading and unloading conditions to examine the facility performance and investigate the effects of inducing lateral vibration on the drill pipe fatigue failure. One of the useful characteristics is to rotate the drill pipes near their resonances. This allows for quick testing using constructed facility despite the high strength of the component. The typical drill pipes diameters used in the tests are 1″, 2″ and 3″. Two steel rings are placed to constrain the drilling pipe in case of catastrophic failure for safety reasons. Ultrasonic displacement sensors are used to measure the displacement at the middle of the drill pipe. Two Hall Effect sensors are placed; one near the first chuck and the other near the second chuck. The sensors are utilized to record the pipe's rotational speed near the motor and the braking mechanism. Displacement, deformation and rotational speed have offered a complete description of the drill pipe's dynamic vibration profile. The drill pipe rotational speed is constrained up to a certain critical rotation close to the drill pipe resonance.

Sets of 1″, 2″, and 3″ diameters and 6 m long drill pipes were selected and utilized in the testing procedure. The first few experiments were performed by rotating the 1″ diameter drill pipes at various rotational speeds. The lateral vibration amplitudes (deflection from the center axis of the drill pipe) were then measured using ultrasonic deflection sensors. The experiments were repeated using drill pipes of 2″ and 3″ diameters. The drill pipes' lateral deflections versus the rotational speeds for different pipe sizes is shown in Fig. 3 The maximum lateral vibration amplitude (donated as AMP) takes place at the middle of the drill pipe. It can be observed from Fig. 3 that the deflection is lower when a larger drill pipe diameter is used and is higher when a smaller diameter pipe is used for corresponding rotational speed. The lateral vibration frequency increases almost linearly as the drill pipe rotational speed increases.

Figure 4 illustrates a 1″ diameter drill pipe that has been subjected to a rotational speed near its resonance or critical speed. The deflection suggests that any further increase in the rotational speed might lead to unacceptable deformation of the drill pipe. Theoretical resonance rotational speeds of the three drill pipes used in the experimental work were calculated using Eq. (1) and presented in Table 3.

$$f = \frac{\lambda}{2\pi}\frac{\sqrt{gEI}}{\mu l^4} \tag{1}$$

Table 3. Theoretical resonance rotational speeds of the drillstrings.

	Drillstring Diameters in (inches)		
	1″	**2″**	**3″**
Resonance rotational speed (rpm)	660	1089	1518
90% of Resonance rotational speed (rpm)	594	980	1366

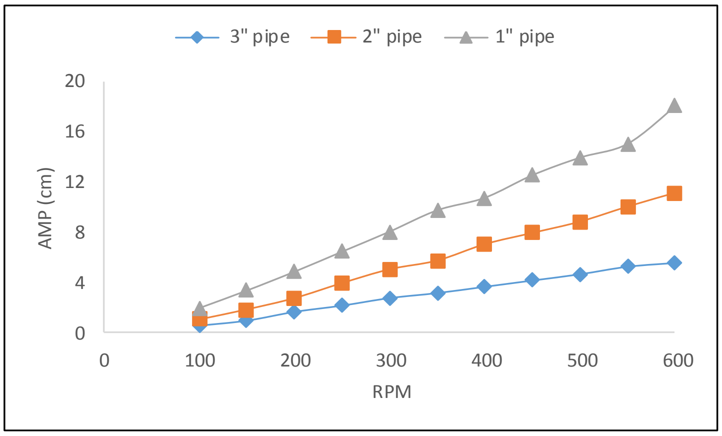


Figure 3. Drillstrings behavior at various rotational speeds.

Figure 4. Large deflection of the 1″ diameter drill pipe at rotational speed close to its resonance.

f: Natural frequency
g: Gravitational constant
E: Modulus of elasticity
I: Moment of inertia
l: Span length
λ: Frequency factor, dimensionless
μ: Weight per unit length

The second set of tests was performed to examine the fatigue failure due to induced lateral vibration in the drill pipes. Drill pipes of three sizes were rotated at various rotational speeds and the number of cycles to fatigue failure were recorded (crakes were also visually observed). Figure 5 shows number of cycles to fatigue failure for each drill pipe against various rotational speeds. It can be noticed from the figure that the number of cycles to failure is decreased for all drill pipes as the rotational speed is increased. Meanwhile, the number of cycles to failure are increased as the diameters of drill pipes are increased. Figure 5 also demonstrates that operating at a rotational speed near the resonance of

each drill pipe, which is approximately at 10% less than the resonance rotational speed as it is given in Table 3, has significantly reduced the number of cycles to failure. The reduction in the number of cycles to failure in the vicinity of resonance is due to the high lateral vibration induced in each drill pipe as the rotational speed is about 90% of the drill pipes resonance rotational speed. The 90% resonance rotational speeds for the three-size drillstrings are presented in Table 3. It is worth mentioning here that rotating drillstrings at a speed higher than 90% of their critical speeds leads to yielding of drillstrings. Figure 6 shows a 1″ diameter drillstring that has been yielded due to its operation at about 94% of its critical speed (620 rpm). The drillstring yielded after rotating the drillstring for a few thousands of cycles. Measured lateral deflections
(amplitude, AMP) at 620 rpm were around 11.5 cm.

Figure 7 shows fatigue failure of a 1″ diameter drill pipe when it was rotated near its resonance rotationed speed. The pipe failed at 53110 cycles due to operation at a rotational speed of 594 rpm which is corresponded to 90% of the drill pipe resonance rotation speed. It is apparent that operating near resonance rotational speed is a useful characteristic in testing as it allows quick test results and provides important information about the number of cycles to failure if operated near resonance rotation speed.

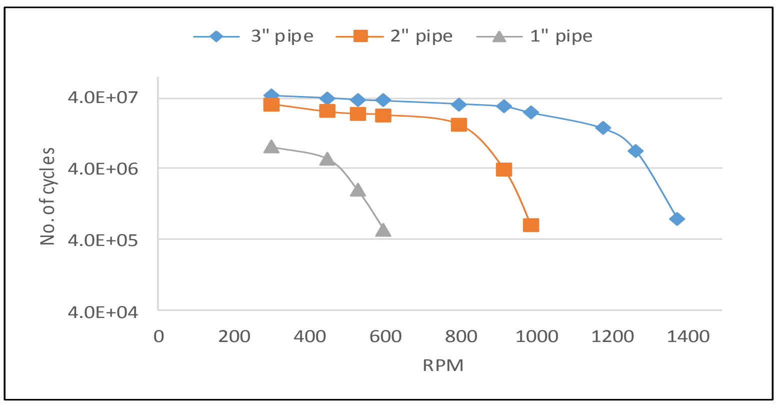


Figure 5. Drillstrings rotational speeds versus number of cycles to fatigue failure.

Figure 6. Yielding of 1″ diameter drillstring due to operating at 94% critical speed.

Figure 7. Fatigue failure of 1″ diameter drillstring.

4. Conclusion

An experimental setup was developed to imitate the vibration modes induced in the drillstring when it runs downhole in oil or gas wells. The drilling operation setup is capable of investigating fatigue failure of drillstrings due to individual and coupled modes of vibrations. Design and construction of the testing facility as well as its testability were the focus of this paper. Drill pipe fatigue failures due to lateral cyclic stresses induced in the drill pipe have also been investigated. The performance of the testing facility was first validated. Then, tests were executed to investigate the effects of rotational speeds and vibration amplitudes on drillstrings fatigue life for various drill pipe sizes. Results have shown that the drill pipe size, rotational speed and lateral vibration amplitude have significant effects on the drillstring fatigue life. Investigations have also illustrated that operating near resonance of drill pipe reduced the number of cycles to fatigue failure. Results also showed that operating on a rotational speed higher than 90% of the pipes resonance rotational speeds prompts yielding in the drill pipes. It has also been established that drillstring is yielded due to its operation at 94% of its critical speed (620 rpm). The drillstring yielded after rotating the drillstring for a few hundreds additional cycles beyond its critical speed. Lateral deflections (Amplitude) at 620 rpm were almost 11.5 cm. The design and construction of such test facility as well as the conducted tests and obtained results from this study should offer appropriate technical indicators for oil and gas drilling operation. The work is currently under way to test and present full vibration profile including torsional, axial and stick-slip phenomenon. This can certainly lead to better control of drilling parameters and reduce instances of failure in drillstrings.

Conflict of Interest

The authors declare no conflicts of interest.

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