

## Optimal drill string design for acoustic borehole communication



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### ABSTRACT

The acoustic telemetry used the drill string as a communication channel, which allows data transfer without interrupting drilling operations. This technology suffers from stop-bands that reduce the feasible bands for transmission up to 60 percent. The stop bands come due to the structure of the drill string constructed from pipes and tool joints. In this paper, we optimized the design of the drill string main components, which are pipes and tool-joints lengths, with an aim to increase the pass-bands total bandwidth. Using the verified drill string channel model, we proved that, with optimal lengths of pipes and tool joints, we can make the whole drill string channel bandwidth available for transmission. We also investigated the effect of small deviation from the optimal lengths on the channel transmission bands. The results showed that an increase of more than 138 percent in the available transmission bandwidths compared with standard drill string dimensions.

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### 1. Introduction

Hydrocarbon resources such as oil, gas and etc..., are located underground at high depths, ranging from 3000ft up to 7000ft. To extract these resources, we need complex and high-risk drilling operations. The typical drilling machine is constructed from drill string which is a series of pipes that are connected together via tool joints. In advance of the drill string, a drill bit is mounted for the purpose of crushing the rock formations. To optimize the oil well drilling operations, usually, different types of sensors are equipped near the drill bit to collect information about temperature, humidity, etc. The most challenging part in drilling operations is how to transfer the collected data from the down-hole up to the surface.

There are three popular methods of telemetry that have been proposed. The first one is electromagnetic telemetry (Harrison et al., 1990), where the information is modulated and transmitted using electromagnetic waves. This method offers a high data rate, but it suffers from high attenuation. The second is the mud-pulse telemetry, where it exploits the mud that is pumped through the drill

pipes to carry formations cuttings out of the well during the drilling process, where a valve is equipped at the end of the drill string to control the mud flowing from down-hole. The information bits are modulated by pulses that are generated by closing and opening the valve. On the surface, there is a hydrophone receiver sensing these pulses. In fact, this telemetry does not interrupt the drilling process. Still, it has a very low data rate (Hutin et al., 2001; Klotz et al., 2008). The last method is acoustic telemetry where the information bits are modulated and sent using acoustic waves that propagate through the drill string body (Drumheller, 1992). This method does not interrupt the drilling operations because it uses the drill string as a communication medium. However, it suffers from destruction and construction interference phenomena, due to the abrupt transition at the interfaces between pipes and tool joints, where some part of the incident wave reflects. This results in passbands and stops bands channel frequency response. As a result, the available bandwidth for transmission reduces considerably.

Acoustic telemetry can provide data rates up to several hundreds of bits in a typical environment. The main challenge of this technology is the stopbands that reduce the available bandwidth for transmission, which is due to the structure of the drill string that causes the transmitted signal to be reflected forward and backward. This leads to a comb-like channel frequency response, as shown in Fig. 1. We can notice that more than 60 percent of the frequency band 0 – 10000Hz are blocked

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because of stopbands. From the well-known Shannon's capacity theorem, the capacity of a communication channel has a linear relationship with the transmitted bandwidth, which means, as we have more bandwidth for transmission, the data rate will increase linearly. Many papers have modeled the channel frequency response of the drill string in

terms of dimensions of the drill string components (Lous et al., 1998; Gutierrez-Estevez et al., 2013; Wang et al., 2006; Drumheller, 1989). Sizes of pipes and tool joints are standard and designed to fulfill the mechanical requirements to perform the drilling process properly without considering the usage of the drill string as a communication channel.

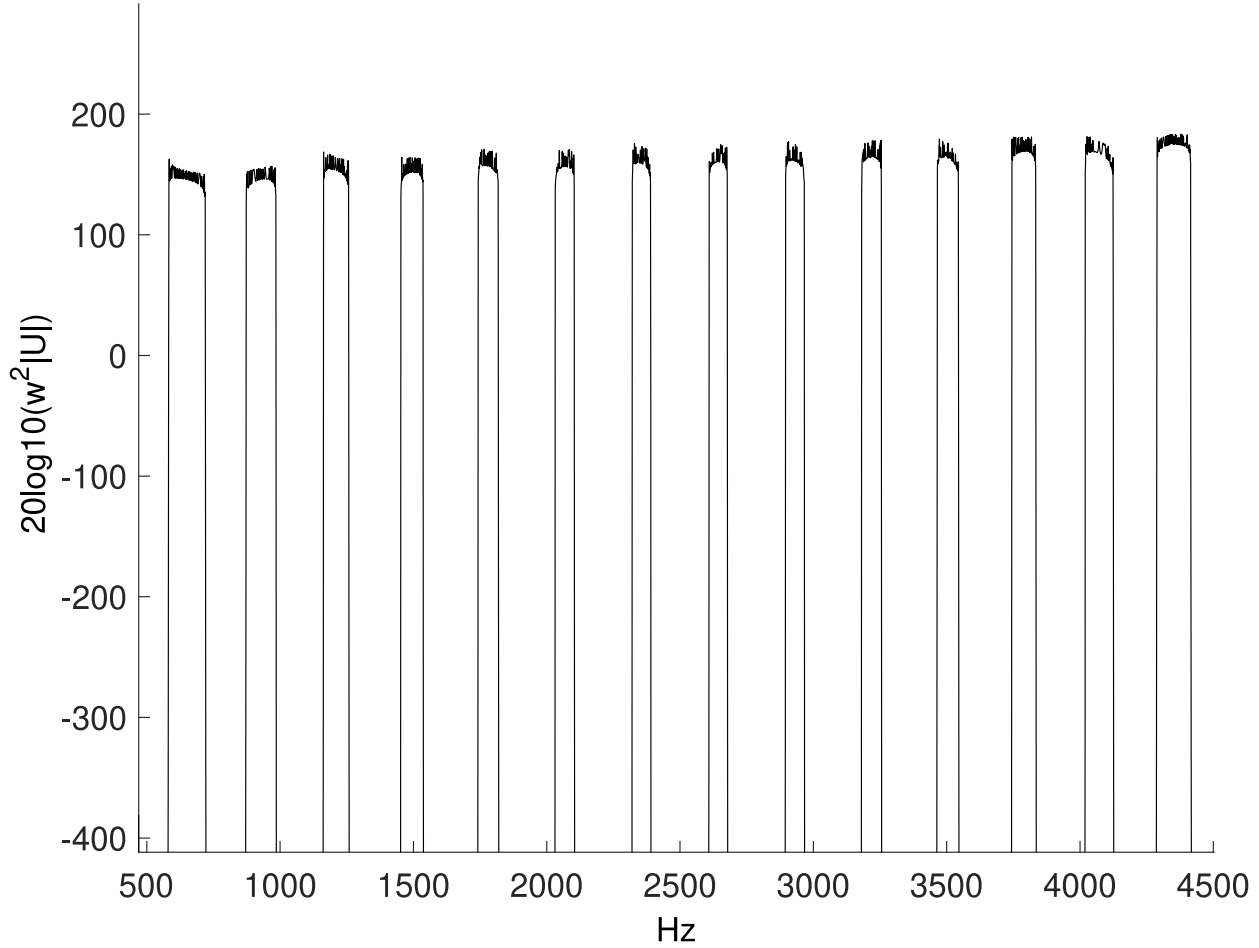


Fig. 1: Drill string channel frequency response

In this paper, we consider the design of the drill string components to obtain the maximum usable bandwidth for transmission. We consider the frequency band that ranges from 0 – 10000Hz because of its reasonable attenuation.

The organization of the paper is as follows: Section 2 demonstrates the model of the drill string channel frequency response using the transfer matrix method. In section 3 the optimization problem and the optimal solution are presented. The discussion of the results and the conclusion are introduced in section 4 and section 5, respectively. Fig. 2 shows sound waves propagation through the drill string.

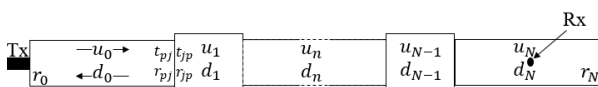


Fig. 2: Sound waves propagation through drill string

## 2. Acoustic drill string channel model using transfer matrix method

The drill string channel frequency response can be modeled by solving the wave equation for longitudinal displacement wave  $U(x, t)$  (Weaver et al., 1990).

$$\frac{\partial^2 u}{\partial t^2} - c^2 \frac{\partial^2 u}{\partial x^2} = 0. \quad (1)$$

Therefore, the solution is the summation of sound waves traveling in the opposite direction on the x-axis:

$$U(x, t) = (u_j e^{ikx} + v_j e^{-ikx}) e^{-i\omega t} \quad (2)$$

where  $x$  is the drill string axis and  $k = \omega/c$  is the angular wavenumber, which is the ratio of angular frequency to the sound speed in the drill string medium. In this model, we assume that the pipes are ideally cylindrical, hollow, vacuum, have a constant

thickness, and are made of steel. Sound waves are assumed to propagate through the pipes with a speed of  $c = 5130\text{m/s}$ . This model is acceptable as long as the wavelength  $\lambda$  is greater than the thickness of pipes and tool joints at the interested frequencies. We assume the thickness of pipes is  $h_p = 1\text{cm}$  and the thickness of the tool-joint is  $h_j = 3.5\text{cm}$  for the considered drill-string. Hence the model is valid for frequencies up to  $f < c/h_j \approx 146\text{kHz}$ . The interested frequencies in this paper is up to  $10\text{kHz}$ , due to the attenuation at higher frequencies.

The transfer matrix method models wave propagation through drill string segments using matrices. Fig. 2 shows the propagation of up-going  $u_n$  and down-going  $d_n$  waves through pipes and tool joints of the drill string. We have assumed an incident wave  $u_0$  launched via a transmitter near to drill-bit, toward an acoustic receiver that mounted at a pipe near to the surface. At the boundaries between pipes and tool-joints, some part of the incident wave will be reflected by an amplitude  $r$ , and the other part is transmitted by an amplitude  $t$  to the next tool-joint. By assuming that pipes and tool-joints are made from the same metal, then the reflection coefficient for wave reflected from the tool-joint boundary is  $r_{pj} = (A_p - A_j)/(A_p + A_j)$ , where  $A_p$  and  $A_j$  are the cross-section area of the pipe and the tool-joint segments, respectively. The transmission coefficient for a wave transmitted from a pipe to a tool joint is  $t_{pj} = 1 - r_{pj}$ . On the other hand, the reflection and transmission coefficients of a wave propagating through a tool joint are  $r_{jp} = -r_{pj}$  and  $t_{jp} = 1 - r_{jp}$ , respectively.

The wave propagation, transmission, and reflection through a tool-joint can be modeled (Lous et al., 1998) by  $T$  and  $R$ :

$$T = \frac{t_{pj}t_{jp}}{1-r_{jp}^2s^2} \quad (3)$$

$$R = 2i \frac{r_{pj}\sin(kl)}{1-r_{jp}^2s^2} \quad (4)$$

where  $s = e^{ikl}$ .

Hence, the sound wave traveling from a transmitter located at one end of the drill string to a sound receiver that is mounted at the other end of the drill string as shown in Fig. 2, can be modeled using the transfer matrix method as follows:

$$\begin{bmatrix} u_N \\ d_N \end{bmatrix} = \prod_{n=1}^N Q_n M Q_{n-1} \begin{bmatrix} u_0 \\ d_0 \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} u_N \\ d_N \end{bmatrix} = G^N \begin{bmatrix} u_0 \\ d_0 \end{bmatrix}$$

where,

$$Q_n = \begin{bmatrix} e^{ik\frac{l_p}{2}} & 0 \\ 0 & e^{-ik\frac{l_p}{2}} \end{bmatrix} \quad (6)$$

describes the wave propagation from the middle of the pipe segment till the boundary, and,

$$M_n = \begin{bmatrix} T_n^2 - R_n^2/T_n & R_n/T_n \\ -R_n/T_n & 1/T_n \end{bmatrix} \quad (7)$$

describes wave transmitted and reflected from a tool-joint.

Eq. 5 produces two equations with four variables. To solve it, we need to add two more equations at both ends of the drill string. The first, is the acoustic transmitter equation, let  $A_0$  be the amplitude of the launched wave from the edge of the transmitter pipe,

$$u_0 = A_0 e^{ikl_p/2} + r_0 e^{ikl_p} d_0 \quad (8)$$

where  $r_0$  is the reflection coefficient at the interface between the pipe and the air. The second equation describes the down-going wave  $d_N$  at the receiver pipe,

$$d_N = r_N e^{ikl_p} u_N \quad (9)$$

where  $r_N$  is the reflection coefficient at the receiver pipe edge.

By solving the four equations in 5, 8, and 9 for the four variables  $u_0$ ,  $d_0$ ,  $u_N$  and  $d_N$ , then the drill string channel frequency response will be  $U_N = u_N + d_N$ ,

$$U_N = \frac{A_0 e^{ik\frac{l_p}{2}} (1+r_N e^{ikl_p}) G_{11}^N}{1-(r_0 e^{ikl_p} G_{11}^N + G_{12}^N)(r_N e^{ikl_p} G_{11}^N + G_{12}^N)} \quad (10)$$

Fig. 3 shows acoustic drill string channel frequency response.

For a large number of segments we use the following expressions to simplify the drill string channel implementation (Lous et al., 1998):

$$G_{11}^N = \frac{1}{\lambda_1 - \lambda_2} [(G_{11} - \lambda_2)\lambda_1^N - (G_{11} - \lambda_1)\lambda_2^N] \quad (11)$$

$$G_{12}^N = \frac{1}{\lambda_1 - \lambda_2} [G_{12}\lambda_1^N - G_{12}\lambda_2^N] = -G_{21}^N \quad (12)$$

$$G_{22}^N = \frac{1}{\lambda_1 - \lambda_2} [(G_{22} - \lambda_2)\lambda_1^N - (G_{22} - \lambda_1)\lambda_2^N] \quad (13)$$

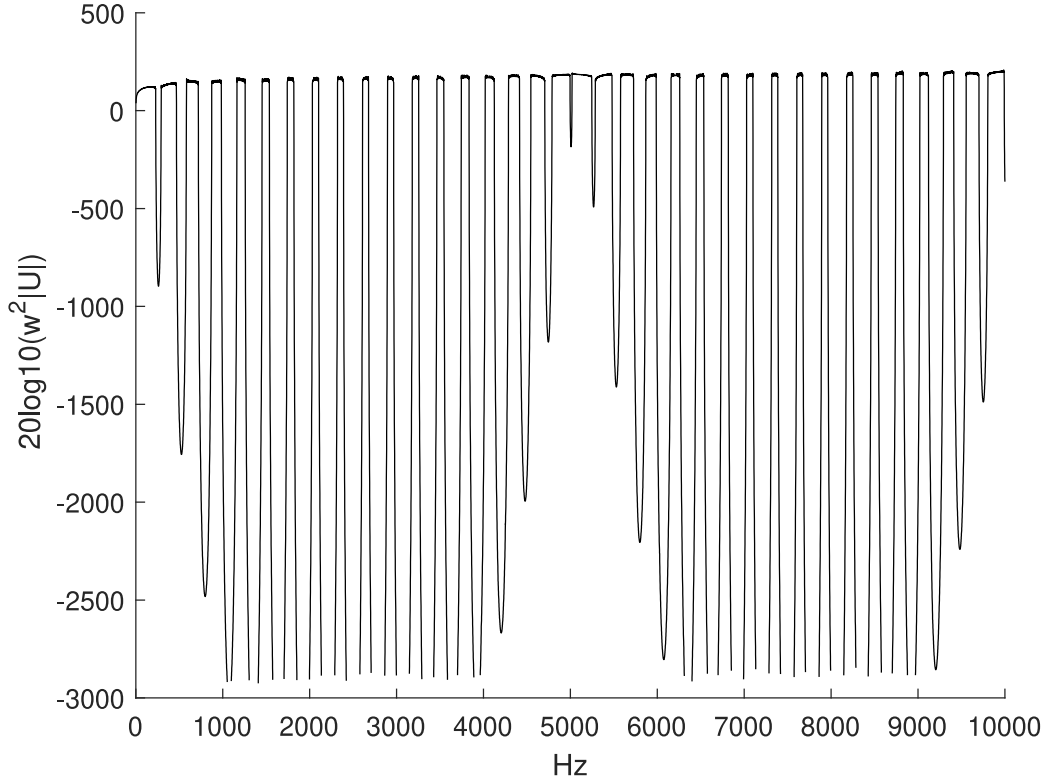
where,

$$\lambda_{1,2} = \tau \pm \sqrt{\tau^2 - 1} \quad (14)$$

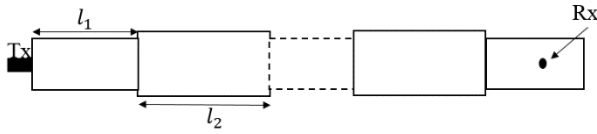
and,

$$\tau = \frac{1}{2} (G_{11} + G_{22}) \quad (15)$$

In standard drill string, the pipe length is  $l_p = 9.18\text{m}$  and the tool-joint length is  $l_j = 0.5\text{m}$ , the pipe and tool-joint thicknesses are  $A_p = 24.52\text{cm}^2$  and  $A_j = 129\text{cm}^2$ , respectively. We assumed that the sound propagation speed is  $c = 5131\text{m/s}$  and both pipes and tool-joints are made from the same metal. Fig. 3 shows the acoustic drill string channel frequency response of the drill string with  $N = 299$  segments and Fig. 4 shows male-female pipes-string.



**Fig. 3:** Acoustic drill string channel frequency response



**Fig. 4:** Male-female pipes-string

### 3. Optimization problem

Fig. 3 shows the acoustic drill string channel frequency response contains pass and stop bands periodically, due to the structure of the drill string, where the mismatch at interfaces between pipes and tool-joints cause considerable parts of the incident wave to be reflected. This results in constructive and destructive interference. Since a communication channel capacity,  $C$  can be computed using Shannon's capacity theorem (Fitz, 2007).

$$C = B \cdot \log_2(1 + SNR) \quad (16)$$

where  $B$  is the channel bandwidth, and  $SNR$  is the Signal-to-Noise Ratio. The channel capacity has a linear relationship with the channel bandwidth.

Our primary goal in this paper is to redesign the drill string to obtain the maximum pass-bands bandwidth. Up to our knowledge, no study has considered the redesign of drill string components dimensions to maximize the acoustic drill string channel available bandwidth. In this paper, we consider the optimization problem of maximizing pass-bands bandwidths in the frequency band  $0 - 10000\text{Hz}$ , with constraints on the lengths of pipes and tool-joints to be reasonable. In other words, we

assume the drill string is constructed from male and female pipes as shown in Fig. 4, and our goal is to find the optimum lengths of these pipes, that result in maximum pass-bands bandwidth feasible for establishing a communication channel.

The objective function is the total sum of pass-bands bandwidths. Thus, we define the bandwidth of a passband to be the frequency range that has an amplitude at least less than the peak by  $X\text{dB}$ . The optimization problem is:

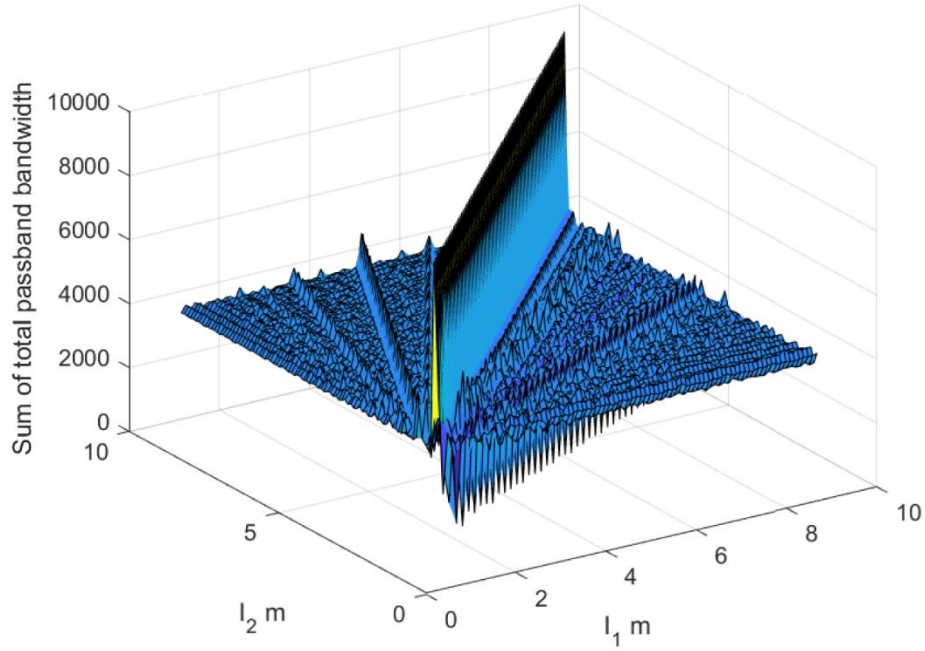
$$\begin{aligned} &\underset{l_1, l_2}{\text{maximize}} && \sum_{f=0}^{f_{\max}} f_o(f, l_1, l_2) \\ &\text{subject to} && x_{\min} \leq l_1 \leq x_{\max} \\ &&& y_{\min} \leq l_2 \leq y_{\max} \end{aligned} \quad (17)$$

where,

$$f_o(f, l_1, l_2) = \begin{cases} 1, & \text{if } U_N(f, l_1, l_2) > X\text{dB.} \\ 0, & \text{otherwise.} \end{cases}$$

where  $l_1$  and  $l_2$  are the lengths of male and female pipes, and  $f_{\max}$  is the maximum frequency of the interested band.

The objective function is the summation of the pass-bands bandwidths over the frequency range  $0 - f_{\max}\text{Hz}$ . Fig. 5 shows the plot of the objective function with the optimization variables  $l_1$  and  $l_2$  for  $f_{\max} = 10\text{kHz}$ ,  $x_{\min} = 0.5\text{m}$  ( $y_{\min}$ ) and  $x_{\max} = 9\text{m}$  ( $y_{\max}$ ). It is clear from Fig. 5 that the objective function is non-convex, but it is easy by inspection to notice that the objective function attains its maximum value when  $l_1 = l_2$ .



**Fig. 5:** Sum of total bandwidths of drill-string channel

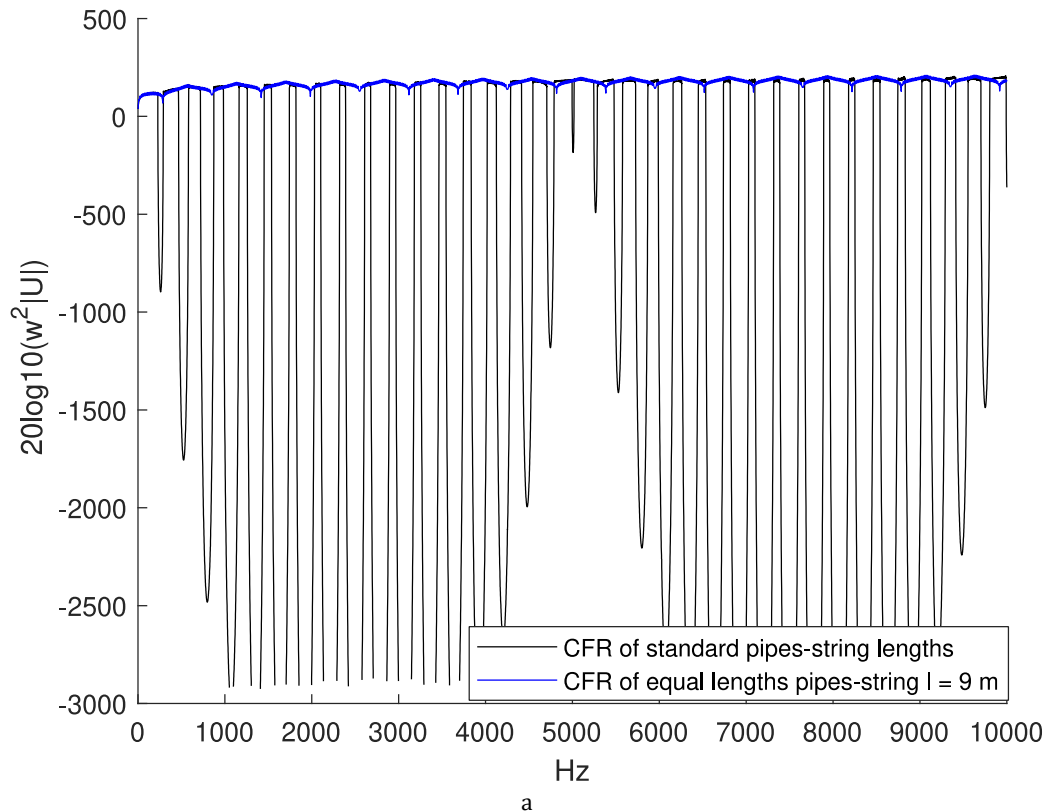
#### 4. Results and discussion

In the previous section, we found that the objective function, which is the total sum of passbands bandwidths it attains its maximum value when  $l_1 = l_2$ . Fig. 6 shows channel frequency responses for both standard and equal ( $l_1 = l_2$ ) pipes lengths. In Fig. 6, it is noticed that when  $l_1 = l_2 = 9m$ , the whole band is feasible for transmission and there are no stopbands. We can calculate the

percentage increase in bandwidth using the following equation:

$$BW(\%) = \frac{BW_{opt.} - BW_{Reg}}{BW_{Reg}} * 100 \quad (18)$$

where  $BW_{opt.}$  is the total bandwidth for the optimal drill-string design, and  $BW_{Reg}$  is the total bandwidth for the regular drill string design. Table 1 shows the values used to generate the drill-string channels for both optimal and regular designs.



a

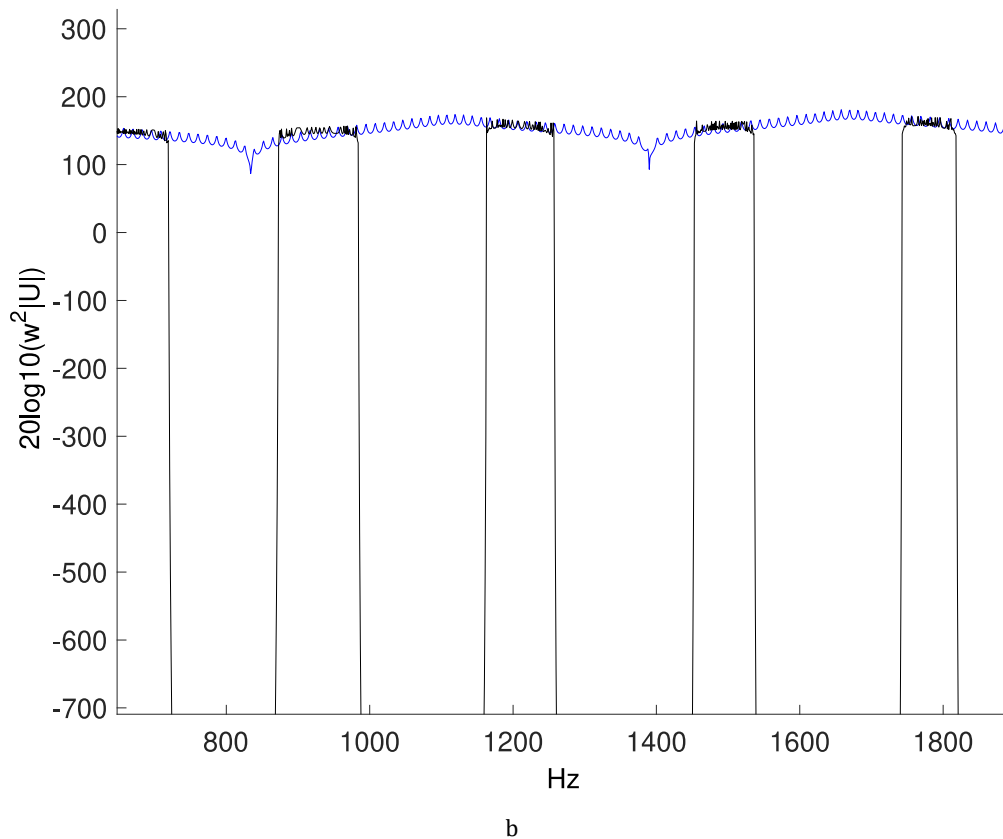


Fig. 6: a) Channel frequency response for standard and equal lengths drill-strings; b) Zoom-in of a

Table 1: Drill-string design parameters

Parameter	Regular	Optimal
$A_p$	$24.52\text{cm}^2$	$24.52\text{cm}^2$
$A_j$	$129\text{cm}^2$	$129\text{cm}^2$
$l_1$	$9.18\text{m}$	$9.18\text{m}$
$l_2$	$0.5\text{m}$	$9.18\text{m}$

According to Table 1 values, the total bandwidth values for optimal and regular channel drill string designs are  $BW_{Reg.} = 4207\text{Hz}$  and  $BW_{Opt.} = 10000\text{Hz}$ , respectively. Hence, using Eq. 18, the percentage increase in bandwidth is  $BW(\%) = 138\%$ .

Since there are many optimal points, in the following subsections, we investigated the channel frequency response characteristics at different optimal points. We also examined the sub-optimal points where there is a small difference between  $l_1$  and  $l_2$ .

#### 4.1. Channel frequency responses for other optimal points

Fig. 6 shows the drill string channel response for optimal point  $l_1 = l_2 = 9\text{m}$ . Since there are many optimal points, as long as  $l_1 = l_2$ . If we constraint ourselves to lengths that range from  $2\text{m}$  till  $9\text{m}$  to investigate the drill string channel frequency responses. Fig. 7 displays the CFR for different optimal points. In the equal lengths drill string, it is observed that the CFR contains some stop-bands. This number of stop-bands is almost equal to two times the length of the pipe in meter ( $2l$ ). For example, if  $l = 5$ , then the number of stop-bands equal to  $2 * 5 = 10$ , and so on.

#### 4.2. Small deviation from the optimal pipes lengths

The solution of the objective function in section 3 suggests using male and female pipes with equal length to get the maximum value of the function. However, the lengths of pipes could not be exactly equal to each other. In this subsection, we study the effect of small deviation from optimal points on the objective function. We assume that  $l_1 - l_2 = \Delta l$ , and see the effect of  $\Delta l$  on the CFR of the drill string. Fig. 8 reveals that the influence of a small deviation of pipes length from the optimal lengths on the drill string channel frequency response. From Fig. 8, we can deduce that the more the difference between pipes length increases, the total sum of passbands bandwidths decreases.

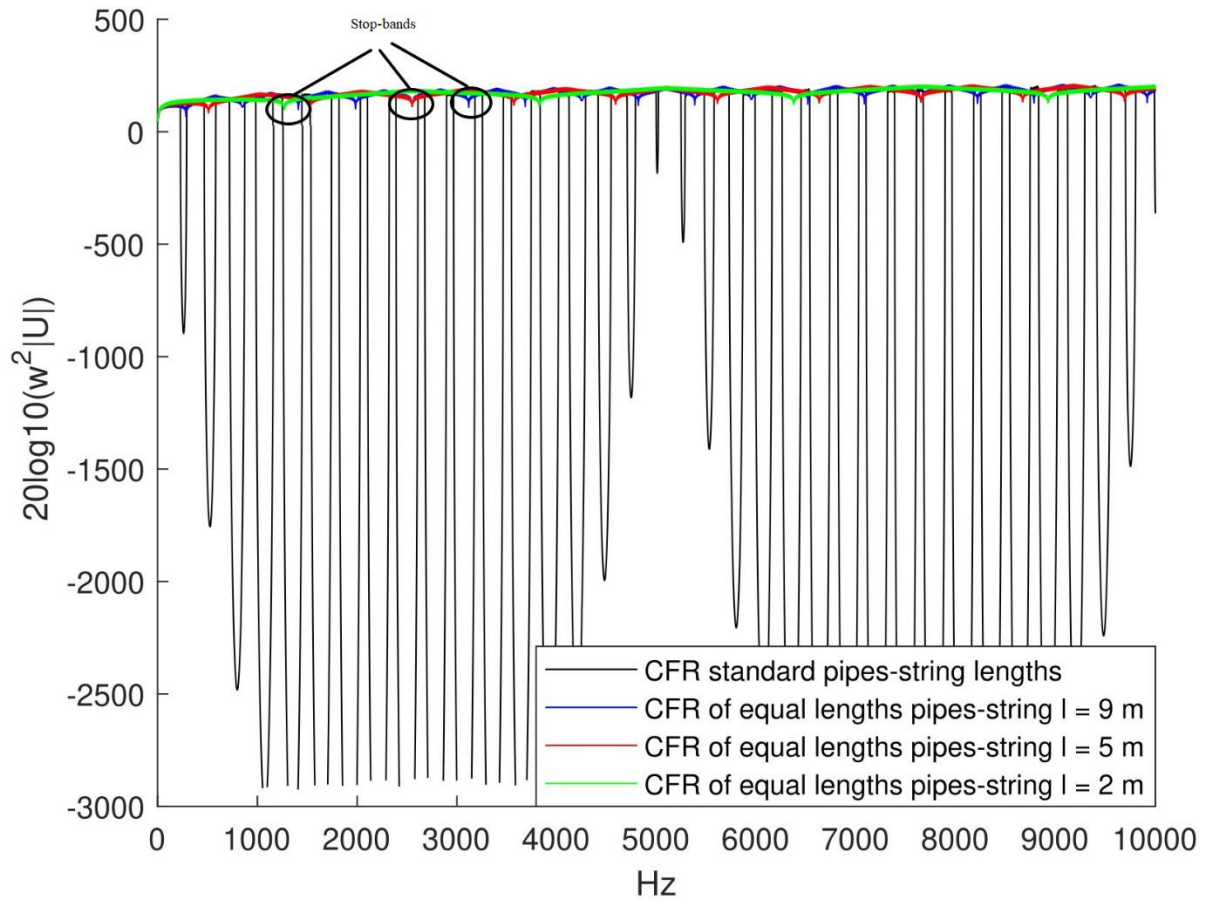
#### 5. Conclusion

An analytical drill string channel model is used to find the optimal design of drill string components. The objective function is the total sum of the passbands bandwidths in the frequency range of  $0 - 10000\text{Hz}$ . We assumed that the drill string was constructed from male and female pipes. The optimization problem is to find the optimal lengths of the male and female pipes that result in the

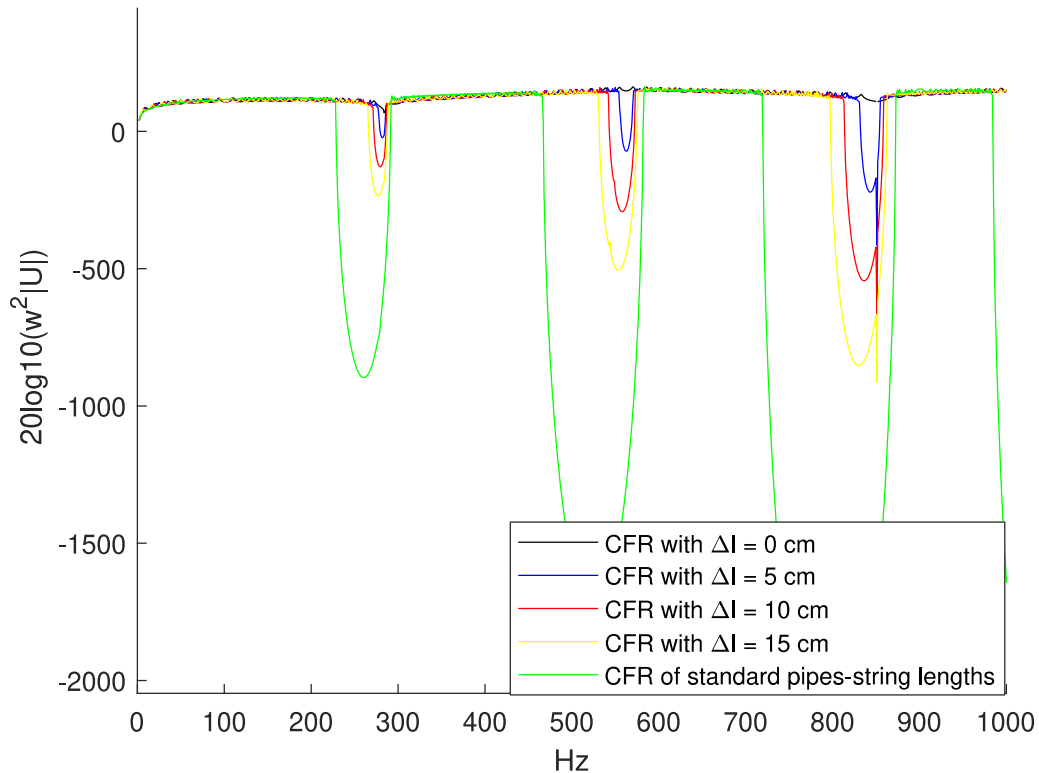


maximum objective function. We found that the objective function reaches the maximum when the male and female pipes have the same length. At the

optimal lengths, the increase in the available transmission bandwidth is more than 138 percent compared to the standard drill string channel.



**Fig. 7:** Pipes-string channel frequency response for standard and several equal lengths values



**Fig. 8:** Drill-string channel frequency response with a small deviation from the optimal lengths

## Compliance with ethical standards

## Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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