CONTROL OF TORSIONAL VIBRATIONS IN DRILL-STRINGS VIA DECOMPOSITION OF TRAVELING WAVES

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Summary Torsional vibrations in drill-strings, especially stick-slip vibrations, are detrimental to the drilling process as they slow down the rate of penetration and may lead to failure of the drilling equipment. A method for controlling these vibrations is presented, based on an exact decomposition of the drill-string dynamics into two traveling waves traveling in the direction of the top drive and in the direction of the drill bit. No down hole measurements along the string and at the bit are necessary, which is a major advantage compared to other control concepts for drill-string dynamics. The proposed algorithm is implemented for both a numerical example and an experimental setup; results show that the control concept works very effectively.

DRILL-STRING DYNAMICS AND CONTROL

Drill-strings used to drill for oil and gas have a typical length of several kilometers. Due to its extensive length, the diameter-to-length ratio of a drill-string is smaller than that of a human hair. At the lower end of the string, the drill-bit is subjected to friction occurring between drill bit and rock, which is of strongly nonlinear character, see sketch in Fig. 1. A falling friction coefficient over angular velocity of the friction characteristic may lead to instability of the angular motion and the onset of self-excited stick-slip vibrations with large amplitudes. Here, the drill bit comes to a complete standstill, while, due to constant velocity at the top drive, the string winds up. Once the torque at the bit exceeds the sticking friction, the string unwinds rapidly beyond its equilibrium position and the bit comes to another standstill. As friction characteristics may change during the drilling process and as the string may be subjected to various unknown and time-variant external forces and disturbances not only at the bit, but also along the string, several different operational regimes may occur while drilling. As drilling is very expensive and as undesired stick-slip vibrations are detrimental to the drilling process and may lead to lower rate of penetration and even damage of the drill-string, the problem and possible remedies have attracted a lot of interest from the scientific community.

Early approaches aimed at optimizing the drill-string configuration in a way that stick-slip vibrations are less likely to occur, for example via variation of weight on bit or angular velocity of the string. Other approaches develop controllers using classical concepts from control theory like robust µ-synthesis [1] or H_∞-control [2]. These approaches require a good model of the drill-string and the external loads acting upon it. A different approach is taken in [3] and [4], here the relevant dynamics of the drill-string are analyzed with Karhunen-Love-Transform or Proper Orthogonal Decomposition which requires measurements along the string. Although new technology is available which allows measurements along the string while drilling, it is very expensive to obtain these measurements, while for conventional drilling setups virtually no information about the dynamics along the string is available. Measurements are recorded at the bit, but standard measurement-while-drilling devices send this information to the top via mud-pulse technology, which uses the liquid between the string and the borehole to transmit pulses. The bit rate here is only between ten and 40 bps, and, more relevant, the time the pulses take to travel to the top is longer than the traveling time of torsional waves, which is approximately 3000 m/s for typical steel drill-strings, while the propagation speed of the pulses is about 1700 m/s (speed of sound in oil).

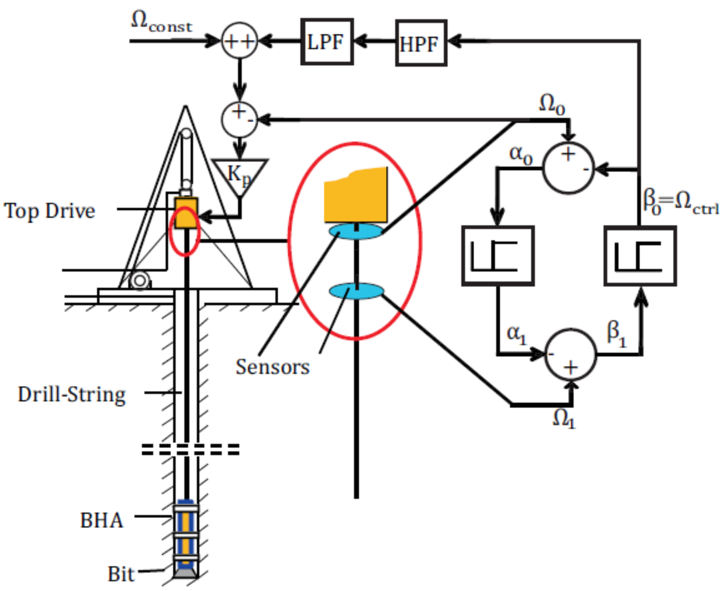

Figure 1: Drill-string, position of sensors and controller

Other control algorithms focus on the fact that the torsional vibrations are governed by the wave equation and each torsional vibration is a superposition of a wave traveling up the string and a wave traveling down the string. In order to eliminate vibration energy from the string, the reflection coefficient of the top drive should be small for the relevant stick-slip frequencies. In [5], [6], [7], control concepts are presented which achieve a low reflection coefficient for a certain frequency band. An optimal control would require knowledge of the evolution over time of the wave traveling in direction of the actuator, thus being able to completely compensate the traveling wave in the top drive and keeping the reflection coefficient zero for the complete relevant frequency range.

We will present an exact decomposition of traveling waves in a continuum governed by the wave equation. We achieve the decomposition by exploiting the finite traveling speed of waves in the continuum and the corresponding delay between two measurement points located close to the top drive. By adding the decomposed wave traveling in the direction of the top drive to the top drive velocity, the top drive acts as boundary controller which compensates the wave traveling in the direction of the boundary. A reflection of undesired torsional vibrations back into the drill-string is prevented, thus absorbing the maximum amount of energy. As inputs for the controller, the velocity of the top drive Ω_0 and the velocity of the first element of the string Ω_1 are measured, see Fig. 1. The delay parameter is set to 0.0015 s, which is calculated using the propagation speed of a torsional wave in steel and corresponds to the traveling time of the wave in the string for a length of approx. 5 m. In order to stabilize the undesired vibrations, the decomposed velocity β_0 is now added to the constant desired velocity of the top drive. The signal from the stabilization controller is filtered with a second-order butterworth high-pass filter (HPF) with corner frequency of 0.02 Hz to allow for the constant velocity and slow variations of the desired velocity to pass the controller, otherwise, the controller would stabilize the velocity at speed zero. A low-pass butterworth filter (LPF) of order six and corner frequency of 80 Hz is used to filter high-frequency noise from discretization. Thus, undesired vibrations in the range between 0.02 Hz and 80 Hz can be stabilized. The resulting stabilization controller then compensates the wave traveling in direction of the top drive, preventing reflection back into the system, as $\alpha(x = 0; t)$ will be zero for $\Omega_0 = \beta_0$. The control concept therefore works in the way that it virtually removes the boundary of the drill-string, and the dynamics behave as if the string was infinitely stretched out instead of being bounded by the top drive.

Figure 2 shows results from numerical simulations for a drill-string with a length of 2000 m. The evolution of the vibrations along the string with friction at the BHA (black line) and at x = ¾ of the total length, where a second stick-slip contact occurs, is presented. The motion behavior is extremely complex before the control is turned on at t=15 s.

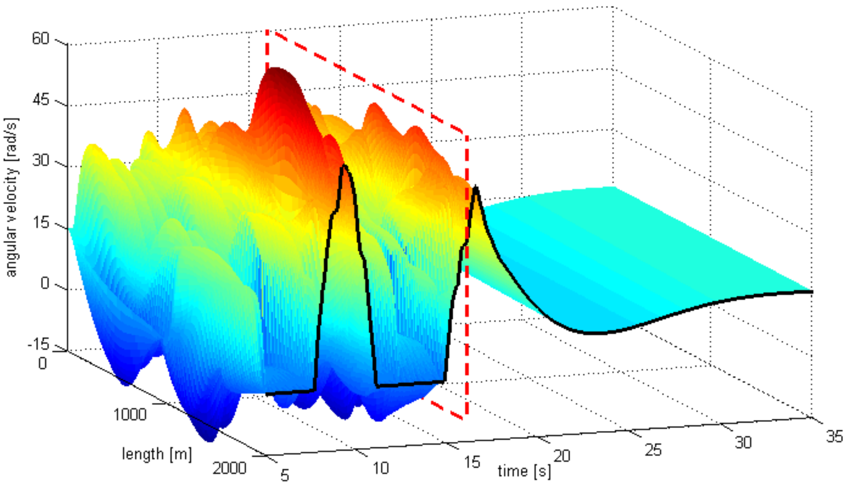

Figure 2: Drill-string vibrations uncontrolled and controlled

We will present a short overview of our experimental setup, and show results from the application of the control concept on our experimental setup.

CONCLUSIONS

The control law is derived, based on a continuum governed by the wave equation, by decomposing the dynamics into a wave traveling in the direction of the actuator and a wave traveling away from the actuator. In order to realize the decomposition into two traveling waves, only two sensors are required. The theoretical approach is not restricted to the use in drill-strings, but could be used for any system governed by the wave equation.

References

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