

Dynamic Torque Characteristics of the Hydrodynamic Torque Converter

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ABSTRACT

The objective of this investigation is to characterize the torsional characteristics of the hydrodynamic torque converter. Analytical and experimental techniques are used to quantify the relationship between torsional oscillations imposed on the pump to those at the turbine as a function of frequency, operating point and design. A detailed model of the hydrodynamic torque converter based upon one-dimensional flow theory is used to establish fundamental torsional behavior independent of the downstream mechanical system. A simplified linear spring-mass-damper representation of the hydrodynamic torque converter is derived whose coefficients are proportional to pump speed for a particular design. A transmission dynamometer test cell with the capability to produce torsional oscillations was used to develop frequency response functions for various torque converters in a transmission, operating at steady state conditions. It was found that the torque converter behaves like a low pass filter with a cutoff frequency dependent upon operating speed, torque and design. Angular vibrations below 20 Hz were found to pass through the torque converter with sufficient energy to excite natural frequencies of downstream drivetrain components.

INTRODUCTION

A significant amount of published literature exists on torque converter operation, design optimization, analysis or testing of internal flow and cavitation, which the reader is referred to [1, 2, 3, 4] for more detail. There is also substantial published work on torque converter modeling to assess the complete drivetrain for low frequency dynamic behavior, typically less than 10 Hz, see [5, 6, 7, 8, 9, 10]. However, a survey of the literature revealed little if any discussion on the characteristics of the torque converter represented as a spring,

mass, damper torsional element. More specifically limited published information exists about how the torque converter behaves as a function of frequency in coupling with the upstream and downstream components. The objective of this paper is to quantify its frequency response function using analytical models and test measurements obtained using a transmission dynamometer test cell.

The most fundamental relationship for any torque converter is its K-factor, given by,

$$K = \frac{N_p}{\sqrt{T_p}} \quad (1)$$

which states that for an operating condition the ratio of pump speed to the square root of pump torque is a constant. The K-factor relationship is not a constant over an entire engine - transmission input (turbine) speed range, but is a function of the ratio of turbine to pump speed, referred to speed ratio, SR. From the definition of damping for a torsional system, it can be seen that K-factor can be rearranged and differentiated on speed to become a steady state damper rating for the torque converter, as noted in [equation 2](#):

$$\frac{\partial T}{\partial N} = c = \frac{2N_p}{K} \quad (2)$$

The steady state damper rating from [equation 2](#) is simply the tangent of the pump torque - pump speed curve, as shown in [Figure 1](#) for three speed ratios typical of positive engine torque operation. A couple of things to note from [Figure 1](#) are that as pump (engine) speed increases, damping increases and as SR increases, damping decreases. Both of these observations are fundamentally expected.

The conventional notion is that fluids in shear cannot transfer high frequency torsional vibration. As engine speed increases so too does engine firing frequency, leading to higher damping. At SR's above the coupling point, pump and turbine speeds are nearly equivalent, and torque is no longer multiplied, the flow velocity within the converter torus decreases sharply. As the flow velocity decreases so too does the pressure differential between pump, turbine and stator elements, leading to the postulate that the fluid can respond more readily to perturbations.

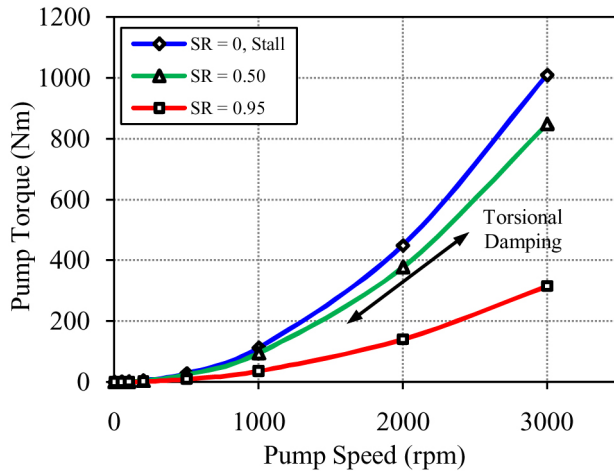


Figure 1. Steady state damping property of the torque converter at various speed ratios.

Torque converters are not coupled to torque sources that run at constant speed and torque, but instead are typically coupled to reciprocating internal combustions engines that can impose significant speed and torque fluctuations onto the pump. These fluctuations are generally assumed to be nearly perfectly attenuated by the hydrodynamic torque converter when the lockup clutch is not applied. Equation 1 and 2 describe the behavior of the torque converter at steady speeds and torques, but for conditions of oscillating speed and torque a new equation is required as

$$T_{total} = T_m + T_a = \frac{1}{K^2} (N_{p,m} + N_{p,a} \cos \omega t)^2. \quad (3)$$

From this, the dynamic torque of the torque converter is defined. The unknown is how the torque converter turbine responds when operated with excitation at non-zero frequencies.

DYNAMIC MODEL

1-D FLOW THEORY

A detailed dynamic model of the torque converter is considered to assess the frequency response to torsional vibration, see [5, 6, 7, 8, 9, 10] for more details. The model is

based on one-dimensional flow theory and the basic principles of fluid dynamics are used, namely the conservation of angular momentum and the conservation of energy.

$$T = \frac{\partial}{\partial t} \int_{CV} (\vec{r} \times \vec{v}) \rho dV + \int_{CS} (\vec{r} \times \vec{v}) \rho \vec{v} d\vec{A} \quad (4)$$

$$\frac{dE}{dt} = P_p + P_t + P_s - P_l \quad (5)$$

The assumptions for this model are that the flow is turbulent and incompressible, acting about the design path of the converter torus at the blade angles of the pump, turbine and stator. Since the model is 1-D, the annular flow area of the torus is assumed constant, with uniform speed. For the designs considered in this paper, these assumptions are satisfied, with the exception of thin torii converters. Fluid losses include shock losses at blade inlets and outlets as well as blade friction. These values are tuned to achieve best correlation to measured dynamometer performance data, an example of which is shown in Figure 2. By tuning the empirical loss functions of the model, an error of less than three percent was produced from stall up to 0.95 SR.

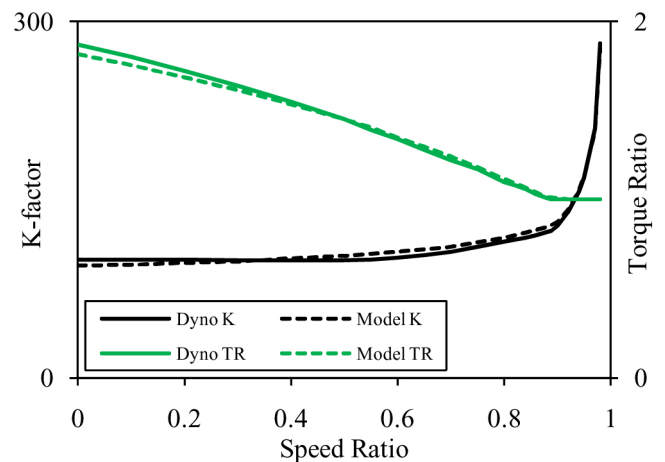


Figure 2. Dynamic torque converter model correlation to dynamometer test data.

Three torque converter designs were used to make dynamic models for this investigation. The details of the designs, diameter and K-factor are not reported for proprietary reasons, and will be referred to as D₁, D₂ and D₃, corresponding to the order of increasing diameter and decreasing K-factor. D₂ and D₃ are nearly perfect geometrically scaled designs, meaning K-factor scales by the ratio of diameters to the 5/2 power. All three models resulted in errors similar to that shown in Figure 2. With the assumptions of the 1-D dynamic model and the degree of

correlation to performance data, it was deemed acceptable to proceed with the frequency response analysis.

MODEL RESULTS

The dynamic torque converter models are set up independent of upstream or downstream mechanical systems, i.e. engine or transmission. The source excitation on the torque converter pump is a sinusoidal velocity with amplitude of ± 1 rpm at a specified mean pump speed, with turbine speed also set to a specific mean speed to achieve a desired SR. The frequency of the sine wave is swept at 1.5 Hz/sec from 0 to 250 Hz. Signal processing of the model outputs entailed computing a frequency response function (FRF) given by

$$H_1(\omega) = \frac{G_{fx}}{G_{ff}} \quad (6)$$

where the input, f , is dynamic pump speed and the output, x , is dynamic turbine torque. The variables of pump speed and turbine torque best determine how the torque converter behaves in the powertrain, regulating engine speed and providing torque to the downstream drivetrain. This is not the typical arrangement of variables for a frequency response function of vibration to force. Instead, it is the ratio of torque response to torsional velocity. The units of this FRF come out to Nm/rpm, meaning the quantity may be interpreted broadly as an indicator of damping. The reference units for torque and speed in dB are 1 Nm rms and 1 rpm rms, respectively.

Torsional FRF results for the D₃ converter at stall with pump speeds ranging from 200 to 2500 rpm and frequencies from 1 to 250 Hz are shown in Figure 3. The general shape of the curve is as expected, having a near flat response at low frequencies, mimicking a pure damper, and then at higher frequencies acting like a low pass filter. As stall speed increases the cutoff frequency of the low pass filtering behavior increases, extending the flat response portion. This is similar to the steady state damper analogy noted in Figure 1 for stall in that damping increases as the speed differential between pump and turbine increases. At 200 rpm the cutoff is at approximately 6 Hz and increases to 60 Hz at 2500 rpm. Having a flat response out to 60 Hz at 2500 rpm is most likely not a concern, as firing frequency is well above this. However, for typical idle speeds (500 to 1000 rpm) the possibility of the torque converter passing torsional vibrations could be a concern for idle quality, as the axles will receive an alternating torque component that can be reflected back to the driver as objectionable vibration. Results similar to those in Figure 3 were obtained for the D₁ and D₂ converters.

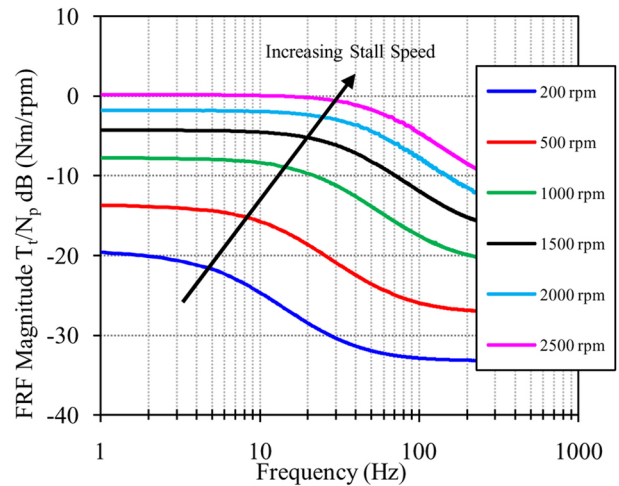


Figure 3. Dynamic torque converter model FRF results for D₃ torque converter at stall.

Figure 4 contains torsional FRF data for torque converter D₃ at speed ratios between 0 and 0.95 at a pump speed of 1000 rpm. As SR increases from zero, the torsional FRF is nearly the same as for stall. The low frequency response remains nearly unchanged as speed ratio increases up to the coupling point, SR ~ 0.9 . Once torque multiplication ceases above the coupling point, the shape of the FRF curve changes more significantly, strictly decreasing from 1 Hz and above. At increased SR's the cutoff frequency decreases, moving from approximately 25 Hz at stall to 4 Hz at 0.95 SR. Beyond the cutoff frequency all torsional FRF's drop off abruptly, especially for the higher SR conditions. With the exception of the low frequency, high speed ratio FRF results, these findings are consistent with the damper analogy noted previously in Figure 1 for steady state operation.

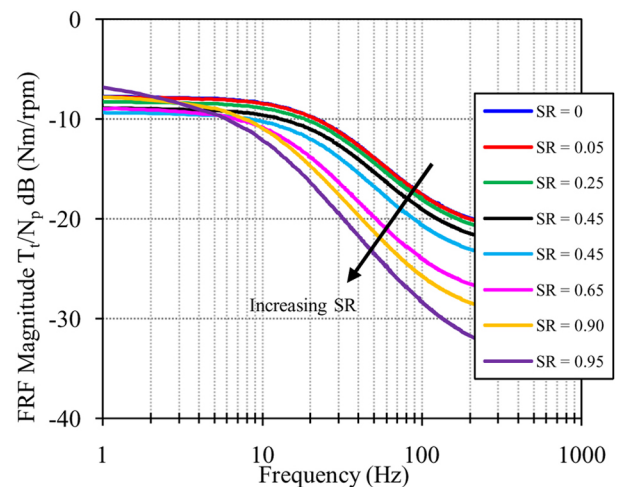


Figure 4. Dynamic torque converter model FRF results D₃ torque converter, 1000 rpm mean pump speed and various SR.