Automotive Torque Converter Sound Power Measurement and Design Parameter Correlation

Craig Reynolds[1], Jason R Blough[1]*, Carl Anderson[1], Mark Johnson[2], Jean Schweitzer[3]

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Abstract

This paper discusses the development of a novel measurement technique for sound power of automotive torque converters in a dynamometer test stand. The full development of the method is presented along with the development of specialized calibration sources. The measured sound power data is then used to develop a dimensional correlation which allows the sound power due to cavitation of a torque converter to be predicted based on torque converter design variables and operating conditions.

Keywords

Cavitation — Sound Power — Dimensional Analysis – Torque Converter

[1] *Mechanical Engineering – Engineering Mechanics Department, Michigan Technological University, Houghton, MI, USA*
[2] *School of Technology, Michigan Technological University, Houghton, MI, USA*
[3] *GM Global Powertrain, General Motors Company, Pontiac, MI, USA*
***Corresponding author**:

INTRODUCTION

As the desire for more fuel efficient vehicles increases due to more stringent fuel efficiency standards for automobiles new torque converter concepts are being developed to help meet these efficiency goals. The torque converter is undergoing a change in its basic dimensional characteristics as it is pressured to decrease in both axial length and diameter to allow automatic transmissions to add more gears in the same amount or less space in a transmission. In addition, the size of the hydrodynamic portion of the torque converter is being reduced to make space for added content in the torque converter clutch and damper assembly. The clutch is applied at lower engine speeds for improved fuel economy. With the large changes in the sizes and configurations of the torque converters, comes new challenges. It has been seen in testing that as the converters decrease in size, cavitation may become more significant both in acoustic power as well as occur over a broader range of operating conditions.

This paper discusses how sound power can be measured on a torque converter in a space constrained torque converter dynamometer fixture along with the justification for why sound power as opposed to sound pressure level. The sound power results are then used as inputs to a dimensional analysis to form correlations between the peak sound power generated during cavitation and the various torque converter design specifications and operating conditions.

1. METHODS

1.1 Sound Power Measurement Approach

Sound power was required for this research instead of sound pressure level because it was desired to understand if the noise generated by a cavitating torque converter is loud enough to be detected inside a vehicle. In order to do this analysis, sound power is used because it is independent of the environment in which it is measured. Sound pressure levels are dependent on the environment. The developed methodology allows sound power to be measured in a dynamometer fixture and its value used to predict levels in a vehicle.

Automotive torque converter performance and noise testing at Michigan Technological University is completed in an enclosed metallic test fixture which inhibits the use of standardized sound power measurement methods due to volume and space limitations. The measurement of sound power is typically done using one of several different SAE or ISO standards such as ISO3741:2012[1] or ISO3744:2012[2]. ISO3744 requires a free field environment which is not possible in an enclosed dynamometer cell and so is not applicable for torque converter work without a very expensive anechoic environment to simulate the free field. ISO3741 requires a large reverberant environment which is also not easily or cheaply created in a torque converter dynamometer cell. ISO3741 requires that the sound source be less than 1% of the volume of the reverberant chamber.

Since there were no applicable SAE or ISO standards for the torque converter measurement environment which was accessible for this project, a new sound power measurement procedure was created and validated for the particular test environment used. This new procedure used a sequence of calibration steps derived from the

ISO standards and a large amount of subsequent testing to validate the approach and microphone locations employed. A set of sound sources were created, each similar in size and volume to torque converters to be tested, that could be calibrated in an anechoic chamber to a given sound power. These calibrated sound power sources were then used in the torque converter test fixture to calibrate the fixture environment which allowed a limited number of microphone positions to be used to estimate the sound power of a torque converter. A statistical study was done to determine the most robust microphone locations for the sound power measurements[3,4,5,7].

1.2 Sound Power Measurement Procedure

The first step in this procedure was the development of a noise source(s) that accurately represented the torque converters' geometry, material properties, and both sound directionality and power. After several iterations of speaker configurations, a source was developed which had a tweeter inside and used both the torque converter pump and cover. Holes were drilled through both components to increase noise propagation. Multiple sizes of the noise sources were constructed to represent torque converter geometries used in a variety of vehicle applications. Different sizes were necessary due to the violation of the source size in the reverberant test chamber as they were much larger than 1% of the volume. The chamber in this case is approximately 0.9 meters in diameter and 0.7 meters axially, while the torque converters range from approximately 0.23 – 0.31 meters in diameter and 0.1 to 0.25 meters axially.

Four sizes of the source were assembled. These size and assembly configurations were used to determine the effect that source size and geometry has on sound pressure level measurements in the test chamber.

Previous research had shown the dominant frequency range of cavitation noise from automotive torque converters to be above 6 kHz [4, 6, 8, 9, 10]. This led to the selection of a tweeter as the noise producing element of all sources. A tweeter was placed in the center of each source to generate white noise in the same frequency range of cavitation.

Next, the sound sources were installed inside the test chamber so that the geometry and location of the source matched a test torque converter. Sound pressure level measurements were made at a variety of radial positions surrounding the source. Characterization of the sound field was accomplished by determining the variation between sound pressure levels at the measurement positions.

A statistical analysis was performed to determine the ideal microphone positions to capture the average sound pressure level throughout the chamber. These optimal positions ensured measurement of the most representative SPLs during testing which were required for accurate sound power estimation. The accuracy of the measurements was determined by analyzing the normalized variance in the SPL measurements using a method adapted from Lubman [5].

The last step to determine the sound power in a volume deficient chamber is the determination of sound power correction factors. The sound power levels of the representative sources were determined using the reverberation comparison method as describe in ISO standard 3741:2012 [1]. With the sound power of the sources known, the sound pressure measurements of each source were used to estimate the sound power correction factors in the test chamber for each source. Sound power of a torque converter being tested in the dynamometer test chamber could then be determined.

1.3 Sound Power Correction Factor Determination

Once the sound power levels of the sources were known, they were used to calibrate the test environment. The calibration process is presented below.

The first step is measurement of the SPLs produced by a source of known sound power. In this case, an ILG Industries squirrel cage fan was used as the reference source. The sound pressures were measured at multiple locations in the reverberation chamber as prescribed by the ISO standard. The second step is measurement of the SPLs produced by the unknown source. In this case this was the torque converter sources. Determination of sound power and the environmental correction factors for each 1/3 Octave of the chamber were determined from the measurements as shown in Eq. (1) adapted from [1].

$$\mathrm{L}_{\mathrm{W}_{\mathrm{unknown}}} = \mathrm{L}_{\mathrm{P}_{\mathrm{measured}}} + \left(\mathrm{L}_{\mathrm{W}_{\mathrm{known}}} - \mathrm{L}_{\mathrm{P}_{\mathrm{known}}}\right) \qquad (1)$$

where:

- $\mathrm{L}_{\mathrm{W}_{\mathrm{unknown}}}$ is the newly calculated sound power of the device
- $\mathrm{L}_{\mathrm{P}_{\mathrm{measured}}}$ is the measured SPL of the device in the reverberation chamber
- $\mathrm{L}_{\mathrm{W}_{\mathrm{known}}}$ is the tabulated sound power of the reference source
- $\mathrm{L}_{\mathrm{P}_{\mathrm{known}}}$ is the measured SPL of the reference source inside the reverberation chamber

The equation determines both the sound power of the sources at each 1/3 Octave bands and the correction factors. The quantity $\mathrm{L}_{\mathrm{W}_{\mathrm{known}}} - \mathrm{L}_{\mathrm{P}_{\mathrm{known}}}$ represents the 1/3 Octave based environmental correction factors for the reverberation chamber. Next, the sources were installed in the torque converter test chamber as close as possible to the position of a torque converter in normal operational test setup. The SPLs were measured for each source and used to calibrate the test fixture environment, for sound power of each source configuration. Calibration was accomplished through calculation of environmental correction factors just as in the reverberation chamber. The environmental correction factors were then used in the following equation to estimate the sound power of each torque converter tested, adapted from [1].

$$L_{W_{TC}} = L_{P_{TC}} + \left(L_{W_{source}} - L_{P_{source}}\right) \quad (2)$$

where:

- $L_{W_{TC}}$ is the sound power of an operational torque converter
- $L_{P_{TC}}$ is the measured sound pressure of the operational torque converter
- $L_{W_{source}}$ is the sound power of the calibrated reference source
- $L_{P_{source}}$ is the sound pressure of the calibrated reference source measured in the test chamber

The terms in parentheses, $\left(L_{W_{source}} - L_{P_{source}}\right)$, represent the environmental correction factors for the test fixture on a 1/3 Octave band basis. This equation allows sound power to be estimated in the test chamber for torque converters similar in size and geometry to each size source.

1.4 Reference Source Development

The development of a reference source to represent the torque converter in terms of geometry, material properties, and noise output was critical to determining the correct sound power correction factors.

The first attempt to develop a sound source resulted in a source which generated standing waves and highly directional results. This is expected in small enclosures. To reduce these effects an improved source was developed.

Testing of the improved sources resulted in sound pressure variances between microphones which were significantly less than the first source as the improved source was much less directional in sound radiation and deemed much closer to an actual torque converter. The improved reference source consisted of the torque converter pump and cover with the stator, turbine, and torque converter clutch removed. A tweeter was mounted in the torque converter, and holes drilled through the pump and cover as shown in Figure 1. The holes were drilled to allow sound to propagate from the source.

Figure 1: Reference source with holes of varying size drilled in a random pattern through both the pump and cover.

Figure 1 shows the random pattern and sizing of the holes drilled in the converter. Without the holes, the enclosed source did not produce significant enough sound pressure levels for accurate sound power determination. The random pattern and hole sizes reduced the risk of higher attenuation of any one frequency.

The reference sources consisted of four different diameter torque converters.

1.5 Test Chamber Characterization

The test chamber in this study is the test fixture in a torque converter dynamometer test cell. The test fixture is shown in Figure 2 with the chamber door closed. This test fixture is larger than typical for a torque converter dynamometer test enclosure to allow room for microphone placement and for absorptive acoustic foam for other types of testing.

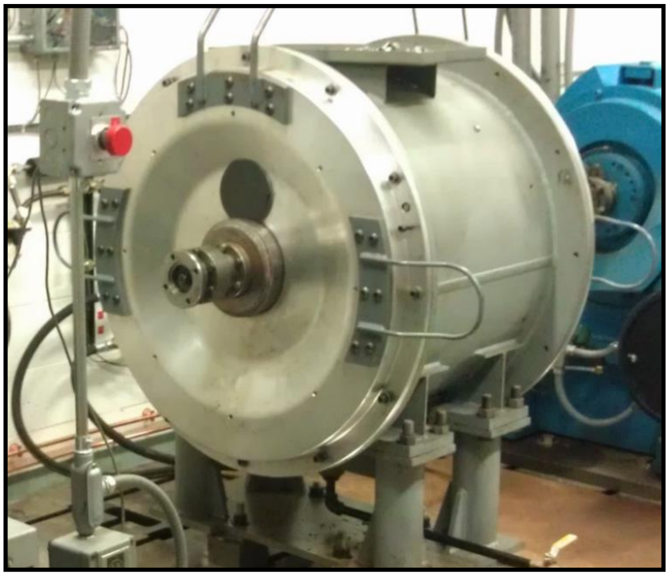

Figure 2: Exterior of the specially designed torque converter test chamber with front of chamber sealed.

The interior of the test chamber is shown in Figure 3. The 12 microphone locations evaluated are indicated on the aluminum mounting ring in similar positions as a clock face.

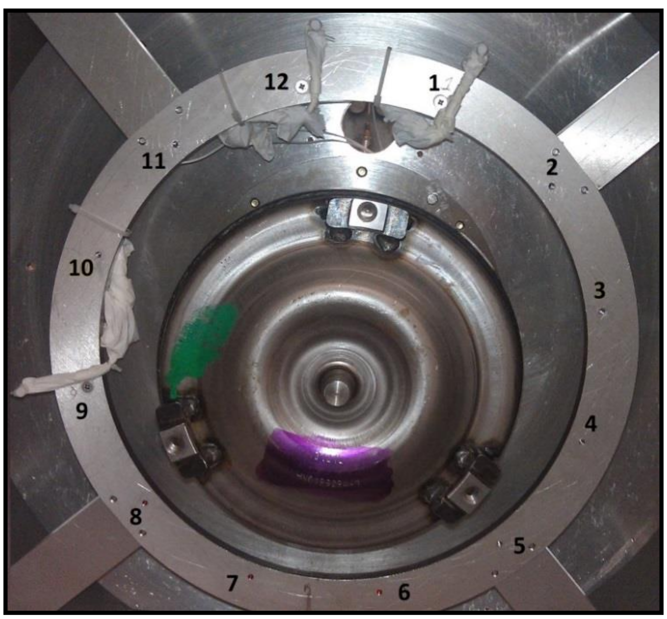

Figure 3: Interior of the test chamber with the measurement locations indicated by numbers 1 - 12 with a torque converter installed as in normal operation.

A torque converter is shown mounted in the test fixture as it would be during normal dynamometer testing. The SPL measurements were made at all positions in Figure 3, and three source amplitude levels were tested with approximately 3 dB difference between each level. The different source levels did not provide any useful information in this testing relative to determining ideal microphone locations.

The test chamber was characterized to determine the average sound pressure level in the chamber using all of the microphone positions. This required extensive SPL measurements in many microphone positions. As many positions as possible should be investigated to provide a more representative overall SPL average and higher statistical significance. The measurements were made using five microphones at a time due to limited microphone supply. This required three rotations of the microphones to measure all 12 positions.

1.6 Data Acquisition

The microphones used in this investigation were ¼ inch pre-polarized pressure microphones with a pre-amplifier. Calibrations were validated with a single point calibrator at 1 kHz and 94 dB. All measurements were examined in 1/3 Octave bands calculated using the root mean squared (RMS) sound pressure level. The data acquisition and processing were completed using a sampling frequency of 51.2 kHz. A frequency resolution of 1.25 Hz was used with 20 averages in determination of the frequency spectrum. A Hanning window and an energy correction factor were applied to all measurements. 1/3 Octave autopower sprectra were then synthesized from this narrowband data.

1.7 Microphone Positions

The microphone positions that best represented the overall sound pressure levels in the fixture were determined by finding the positions with the least variation between the SPL at each position and the average SPL of all the measurements made for a certain test. The analysis was done on a 1/3 Octave band basis in pascals.

The overall average SPL was calculated at each 1/3 Octave band and individually for each source type, source size, and at each of the three source amplitude levels. A linear average was used for all measurements in a specific group as the variation analysis was completed for each of the conditions.

The variation between the SPL at each position and the overall average was calculated utilizing a metric called the normalized variance (NV) and therefore termed the Variance method.

The details of this analysis are provided in Reynolds [11]. The end result was that only three microphones were required to accurately estimate the sound power of the torque converters.

2. TORQUE COVNERTER SOUND POWER TESTING

Having calibrated the torque converter fixture and microphones to allow the measurement of sound power, the next step was to actually measure the sound power of many different torque converters. A matrix of 23 different torque converters were tested with a range of K-factors from 120 to 260 and a range of diameters from 220mm to 258mm. The torque converters also had several different torus designs ranging from a traditional round design to designs with reduced axial length and torus's with their inner radius' moved further out away from the rotational axis.

Operating conditions tested in this study included torques from 136 Nm to 400 Nm and charge pressures from 70 psi to 130 psi, where the back pressure was controlled be 30 psi less than the charge pressure.

For this study, the particular data of interest was the maximum sound power level generated by a torque converter during cavitation. Based on experience and the fluid dynamics of the torque converters it is known that the operating condition of maximum cavitation is near stall. For a torque converter, stall is defined as occurring when output over input speed ratio is equal to zero. This condition occurs in a vehicle, for instance, while at a stoplight when the automatic transmission is in "Drive" but the vehicle is not moving. Tested torque levels, however, are higher than those encountered at engine idle.

A test procedure was developed which mimics this situation in the dynamometer test cell. This condition is achieved by operating the input and output dynamometers as shown in Figures 4 and 5. To achieve these rpm and torque profiles the input dynamometer is operated in torque control mode with a prescribed constant torque and the output dynamometer is operated in speed control mode with a prescribed rpm profile. This combination of operating parameters excites cavitation in the torque converter very near the start of test. Cavitation then diminishes and ceases as speed ratio increases from stall.

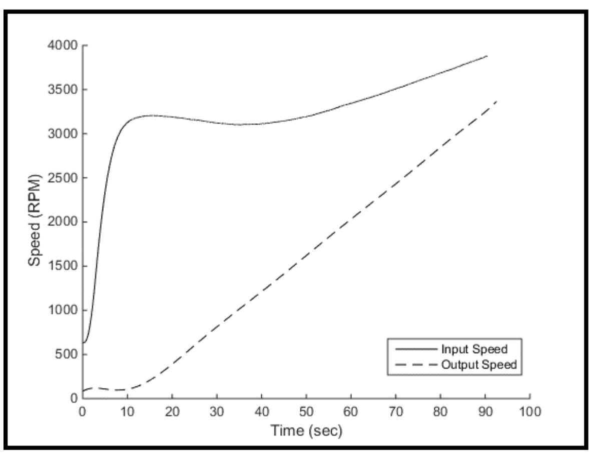

Figure 4: Input and output dynamometer rpm for sound power test.

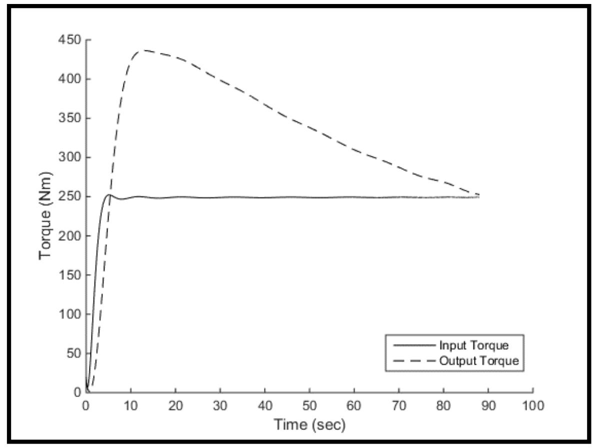

Figure 5: Input and output dynamometer torques for sound power testing.

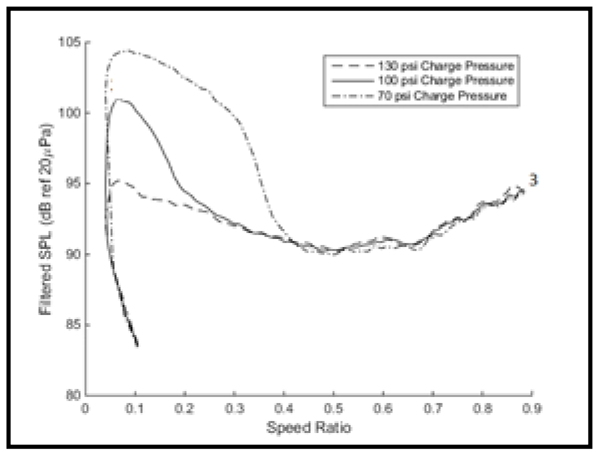

Figure 6: Filtered sound pressure level measured during stall simulation condition

Figure 6 shows a typical sound pressure level measured during the simulated stall test. Note that this measurement is sound pressure level and not sound power level. This overall sound pressure level is computed by using a high-pass filter to attenuate all frequency content below 6 kHz, followed by computing the RMS level of this filtered signal. In Figure 6 it can clearly be shown that the sound pressure level is much higher near the start of the test and drops in level as the cavitation ceases to be excited at higher speed ratios. This is very typical of torque converter cavitation.

The measured sound pressure data is then used to compute sound power levels using the earlier described procedure in this paper and the averaging of the 3 microphone positions which were used.

The sound power data of interest is the maximum level which occurs near stall, below a speed ratio of 0.15. Since this level is at or near stall it is expected to be caused by cavitation which is essential to building a valid correlation. If a maximum level were used which was not close to stall there is the possibility that it may not be caused by cavitation. Any correlation requires that all data be caused by the same physics.-

3. DIMENSIONAL CORRELATION

3.1 Correlation Development

For the sound power measurements to be useful to torque converter designers it is desired that there be an understanding of how the various design variables and operating conditions effect the cavitation of the torque converter [6,9]. While previous correlations have been developed for torque converter cavitation, the correlations have been relative to conditions where a converter starts to cavitate or ceases to cavitate and have not pertained to the actual sound level during cavitation.

The dimensionless groups were developed from the various torque converter design variables and operating conditions shown in Table 1 and Figure 7 along with sound power level.

Table 1: Variables used in Dimensional Correlation

Variable	*Definition of Variable*
sK_f	Stall K factor (input speed/square root of torque)
ρ	Fluid density at maximum sound power
µ	Fluid viscosity at maximum sound power
k	Thermal conductivity
Ni	Pump speed at maximum sound power
No	Output Speed
T_T	Turbine Torque
T_P	Pump Torque
T_S	Stator Torque (Turbine Torque-Pump Torque)
C_p	Specific Heat at constant pressure
P_{avg}	Average of charge and back pressure at maximum sound power

Figure 7 below shows the rest of the variables used in the correlation development graphically.

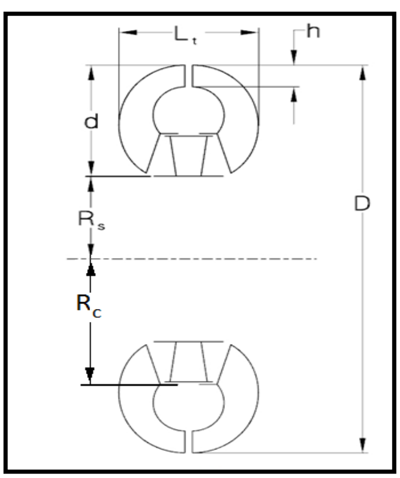

Figure 7: Schematic graphically showing torque converter dimensions used in correlation

In this paper, dimensionless groups are developed using the variables defined above for the correlation as shown in Tables 2 and 3.

Table 2: Dimensionless Group Names

Regressor	*Dimensionless Group Name*
Pr	Prandtl Number
uTs	Dim. Stator Torque
SFAR	Stator flow area ratio
LTD	Torus aspect ratio - Lt/D
ReR	Rotational Reynolds Number
Uo	Unit Output Speed
Nsb	Number of Stator Blades
TAR	Torus area ratio
uTp	Dim. Input Torque

Table 3: Dimensionless Group (Regressor) Definitions

Regressor	*Dimensionless Group Definition*
Pr	$Pr = C_p * \mu/k$
uTs	$uT_s = (T_T - T_P)/\left(D^3 * P_{avg}\right)$
SFAR	$SFAR = (R_c^2 - R_s^2)/(h * (D - h))$
ReR	$ReR = \rho * Ni * D^2/\mu$
LTD	$\mathrm{LTD} = L_t/D$
Uo	$\mathrm{U}o = No(\rho * D\hat{}5/T\_T\ )\hat{}0.5$
nsb	nsb = number of stator blades
TAR	$\mathrm{TAR} = 4 * \frac{h(D-h)}{D^2}$
uTp	$uTp = (T\_P\ \ )/(D\hat{}3 * P\_avg\ )$

Combinations of these dimensionless groups were used to develop the important terms of the dimensionless correlation which was developed using the Response Surface Model [12] as shown in Equation 3.

$$\hat{y} = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=1}^{k} b_{ij} x_i x_j + \varepsilon (3)$$

where:

- $\hat{y}$ is the predicted response
- b are the estimated regression coefficents
- x are the regressors
- ε is the residuals

3.2 Correlation Results

Several correlations were explored using different subsets of torque converters, operating conditions...etc. The best overall correlation at the time of the writing of this paper is shown in Figure 8. As mentioned above this correlation includes torque converters of many different sizes and designs. The root mean square error (RMSE) of the correlation is 2.3% and the adjusted coefficient of multiple determination (R_a^2) is 0.86. Both of these parameters are indicators as to how good the correlation fits the actual measured sound power data.

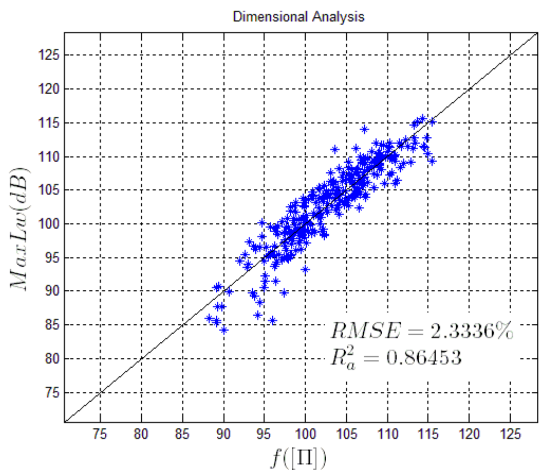

Figure 8: Dimensionless correlation of all torque converters tested vs. Maximum Sound Power

Figure 8 was generated based on a correlation which included the dimensionless groups shown in Table 4.

Table 4: Dimensionless groups used in correlation of Figure 8.

'Pr'
'uTs*SFAR'
‘SFAR’
'ReR'
'Pr*RER'
'LTD*Uo'
'nsb'
'TAR'
‘uTp^(2)

The development of improved or additional correlations is a topic of ongoing research while the estimated regressor coefficients are considered proprietary at this time.

4. CONCLUSIONS

This paper developed the procedure which can be used to make sound power measurements in a volume deficient space, and in particular in this paper a torque converter dynamometer test stand. Having developed the process to measure the sound power of automotive torque converters, sound power data was acquired on 23 different automotive sized torque converters operating at several different charge pressures and torques. The goal of this testing was to determine the overall sound power of the torque converters when they were cavitating near stall.

The acquired cavitation sound power data was then used to develop a dimensional correlation between torque converter design variables and operating conditions and the measured overall sound power. A correlation was established which used 8 dimensionless groups and resulted in a RMSE of 2.3% and an R_a^2 value of 0.86. Both of these indicators suggest that the correlation is sufficient to estimate the sound power due to cavitation near stall early in the design process to aid torque converters designers and development engineers in optimizing torque converter performance and cavitation noise.

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REFERENCES

[1] ISO 3741:2012, “Acoustics -- Determination of sound power levels and sound energy levels of noise sources using sound pressure -- Precision methods for reverberation test rooms”

[2] ISO 3744:2012, “Acoustics -- Determination of sound power levels and sound energy levels of noise sources using sound pressure – Engineering methods for an essentially free field over a reflecting plane”

[3] Alfayez, L., Mba, D., Dyson, G., “The Application of Acoustic Emission for Detecting Incipient Cavitation and Best Efficiency Point of a 60 kW Centrifugal Pump: Case Study,” NDT & E International, Vol. 38, Issue 5, pp. 354-358, 2005.

[4] Kowalski, D., Anderson, C., and Blough, J., "Cavitation Detection in Automotive Torque Converters Using Nearfield Acoustical Measurements," SAE Technical Paper 2005-01-2516, 2005, doi:10.4271/2005-01-2516.

[5] Lubman, David. "Precision of reverberant sound power measurements." Acoustic Society of America 56 (August 1974): 523-533.

[6] Robinette, D., Anderson, C., Blough, J., Johnson, M. et al., "Characterizing the Effect of Automotive Torque Converter Design Parameters on the Onset of Cavitation at Stall," SAE Technical Paper 2007-01-2231, 2007, doi:10.4271/2007-01-2231.

[7] Schlatter, William R. "Sound power measurement in a semi confined space." Master of Science, Massachusetts Institute of Technology, 1971. HYPERLINK "http://hdl.handle.net/1721.1/44687" *http://hdl.handle.net/1721.1/44687*

[8] Strasberg, M., Taylor, D., “Propeller Cavitation Noise After 35 Years of Study”, Noise and Fluids Engineering 1977.

[9] Walber, C., "Torque converter turbine noise and cavitation noise over varying speed ratio", PhD Dissertation, Michigan Technological University, 2012.

[10] Zeng, L., Anderson, C., Sweger, P. O., Narain, A., “Experimental Investigation of Cavitation Signatures in an Automotive Torque Converter using a Microwave Telemetry Technique”, 9th ISORMAC, 2002.

[11] Reynolds, C.D., Anderson, C., Blough, J.R., Johnson, M., and Schweitzer, J., “Sound Power Measurement in a Semi-Reverberant, Volume Deficient Chamber”, SAE Technical Paper 2015-01-2359, SAE Noise and Vibration Conference, June 2015, Grand Rapids, MI.

[12] Robinette, D., "Detecting and Predicting The Onset Of Cavitation In Automotive Torque Converters", PhD Dissertation, Michigan Technological University, 2007.

[13] Reynolds, C., "Characterization of Torque Converter Cavitation Sound Power Level Over Varying Speed Ratio", PhD Dissertation, Michigan Technological University, 2015.