Application Note

EMI Filter Selection in Class-D Amplifier a Post Filter Feedback Benefits and Design Considerations for TAS27X

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ABSTRACT

Class-D amplifier outputs are switching outputs, having carrier frequency along with the audio signal content. These switching frequencies lead to concerns with EMI radiation due to long traces running to speaker loads. To meet the EMI radiation specs like FCC/CE, Class-D amplifier outputs typically have EMI filters. In this application note we briefly describe the different techniques used to select and realize EMI filters . The *Post filter Feedback* feature in TAS27XX family of devices is also explained and filter selection care abouts regarding the same are also listed. The audio amplifier performance is also measured in the presence of the bead. Further an excel sheet based calculator is provided to the user to help assess the feasibility of EMI filter to be used for post filter feedback with some examples.

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Trademarks

1 Introduction

EMI filters at the Class-D output can be realized using the following techniques.

1.1 Capacitor Only Connected at the Class-D Outputs

A large capacitance >1nF can be connected to the amplifier output directly. This connection is not recommended as the output impedance of the Class-D is of a very low order approximately 0.5Ω which does not offer significant filtering (Filter cutoff> 300MHz). Further, in TAS27xx generation of devices increasing the capacitance at the Class-D output has negligible impact edge rate. Also, any capacitor directly connected to the Class-D output can significant degrade device efficiency and cause very high switching currents which can cause the device to shut down or reliability issues. For these reasons in TAS27XX family of devices the recommendation is to not connect maximum 200pF capacitance directly at the Class-D output.

1.2 LC Filter Connected at the Class-D Outputs

L-C filters connected at the Class-D output are a relatively good option, since the inductor can offer high impedance at higher frequencies hence providing sufficient of EMI filtering and prevent high frequency switching currents. The downside to LC filters is the following: High price and foot print of inductor (BOM cost) and extremely high current at resonant frequency of the filter, which can cause device shutdown. The key advantage however is that LC Filters are linear, which means there is not THD+N degradation at the output of the filter (across the speaker)

1.3 Ferrite Bead Filters

Ferrite beads are relatively low cost and non-linear EMI filters. The impedance of the ferrite bead changes significantly with the current through the ferrite bead, which makes this component non-linear. The ferrite bead can be modeled as a resistor parallel with an inductor, which damps the resonance and reduces extremely high current.

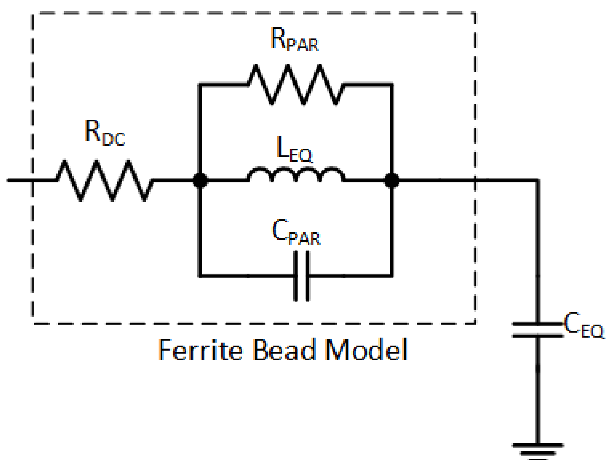

Figure 1-1. Ferrite Bead Equivalent Model

The inductor in the filter can be realized using a ferrite bead, which is a lot more cost optimum compared to a regular inductor, but comes with non-linearities. Using the cost-optimum ferrite beads degrades the THD performance of the audio after the filter, affecting the audio performance of the end system. Such concerns force the customers to go back to an inductor-based filter, or use a more expensive ferrite bead which doesn't degrade the THD performance, increasing the cost of the end system. Another concern with using a filter at output of class-D amplifier is that the filter degrades the frequency response of the output depending upon the cut-off frequency selected for the filter. This too affects the audio performance across frequencies.

Table 1-1 compares cost of different inductors and ferrite beads. TI's Post filter feedback configuration allows usage of MPZ1608S221A and 2506036017Y2 kind of ferrite beads which is significantly lower cost design, without the performance degradation associated with these components.

Table 1-1. Comparison of Inductive Filters *(As of June 2024)*

Part Number	Type	9k unit price	Performance
MAKK2016TR24M	Inductor	3.1c	High
NFZ2MSM181SN10L	Ferrite bead	11.1c	High
MPZ1608S221A	Ferrite bead	2.1c	Low
2506036017Y2	Ferrite bead	1.9c	Low

2 EMI Filter Considerations

2.1 Impedance Consideration of EMI Filter

When using EMI filters, the inductor or bead and cap combination must be chosen appropriately to avoid extremely high currents due to resonance which can potentially trigger an the OCP (Over current protection) mechanism in the device. A simple guidance to avoid this is to use a filter with cutoff frequency (ω_0) greater than 1.5MHz. This step is to avoid high currents due to resonance with audio, ultrasonic content as well as Class-D switching frequency energy at 384KHz and 768KHz. Further if resonance related over current shutdown is still observed even with higher cutoff frequencies. The recommendation is to increase the bead or inductor value and reduce the parallel capacitance to maintain same cutoff frequency.

2.2 Device Reliability Constraint for High Output Voltage

While using an EMI filter the device pin *VSNS* voltage can overshoot beyond OUTP and can theoretically go up to as high as twice the voltage. For example, the maximum PVDD voltage TAS2764 is 16V, which means the VSNS can overshoot to 32V. TI recommends that if the voltage overshoot at VSNS goes beyond 30V in TAS2764 and 40V in TAS2780, 81, 83, is mandatory that an external resistor of (easily available) 1KΩ, 4.7KΩ can be connected in series before connecting the feedback from speaker to VSNSP and VSNSM. This is required to limit the current through the device internal ESD cell on the VSNS pin, which activates to clamp due to high voltage ringing at the speaker node.

2.3 EMI Filter Current Reliability

When selecting an EMI filter or ferrite bead make sure that the component is rated for the maximum load current through the speaker. For instance, in TAS2780, 81 devices the peak speaker current can be as high as 4A and RMS current of 2.8A, while in TAS2764 the device RMS current can be order of 2A. Hence the bead must be chosen appropriately to make sure reliability and avoid significant de-rating. For example 2506036017Y2 bead is rated for maximum 2A current hence are not appropriate to use high power applications

3 Post Filter Feedback

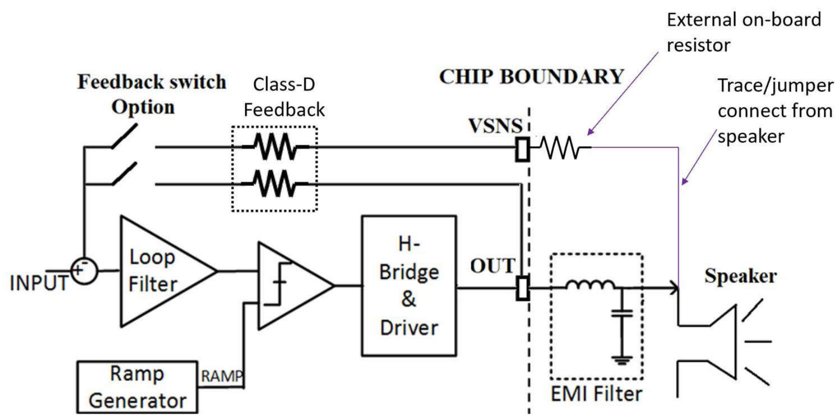

Figure 3-1. Class-D Loop with Post Filter Feedback (PFFB)

TI's Post filter feedback allows the user to add the ferrite bead inside the class-D loop as shown in Figure 3-1. This change in loop configuration makes sure that the errors added by ferrite beads are added inside the class-D loop, and are corrected by the loop gain. This coupled with the high loop gain that comes with TI's 4th order class-D amplifiers in TAS 2764, 2780, 2781, and TAS2783 makes sure that THD degradation due to the ferrite bead addition are minimized, allowing users to use the more cost optimum ferrite beads without worrying about the adverse effects of these beads. Also, since the loop is closed after the ferrite beads filters, there is no dip in the frequency response of the amplifier, giving the amplifier a flat amplitude response across the audio band of frequencies. Figure 3-2 compares the THD+N vs Frequency for TAS2560 with 2506036017Y2 ferrite bead filter coupled with a 100pF parallel cap. As shown in Figure 3-2, the THD degrades significantly at higher frequencies when the Ferrite bead is kept outside the class-D loop like in legacy class-D amplifiers. But with the new PFFB configuration, the performance degradation due to ferrite bead is greatly reduced and the performance is almost identical to that of the Class D output without the presence of bead.

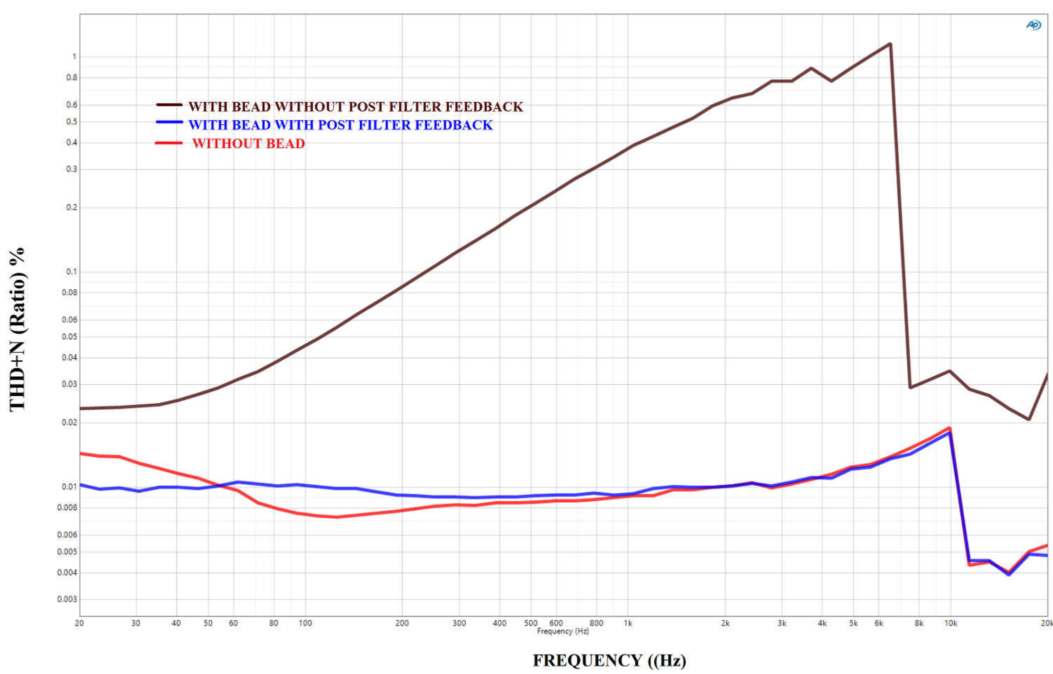

Figure 3-2. THD+N vs Frequency With and Without PFFB at 1W Power 4Ω on TAS2780

4 Loop Stability With Post Filter Feedback

Since the ferrite bead filter is now inside the class-D loop, there are extra poles added in the system, which adversely affects the stability of the loop. The user needs to take into account extra guidelines to choose the correct configuration of the filter, which can make sure that the class-D loop is stable. To find a stable configuration of the EMI filters, the equivalent model of the EMI filter needs to be drawn. The filter needs to be approximated into a second order filter as shown in Figure 1-1. Ferrite beads impedance can be divided into three main regions, for example, inductive, resistive, and capacitive. These regions can be easily determined by looking at impedance plots of ferrite bead data sheet (as shown in Figure 4-1), where Z is the impedance, X is the reactance and R is the resistance of the bead.

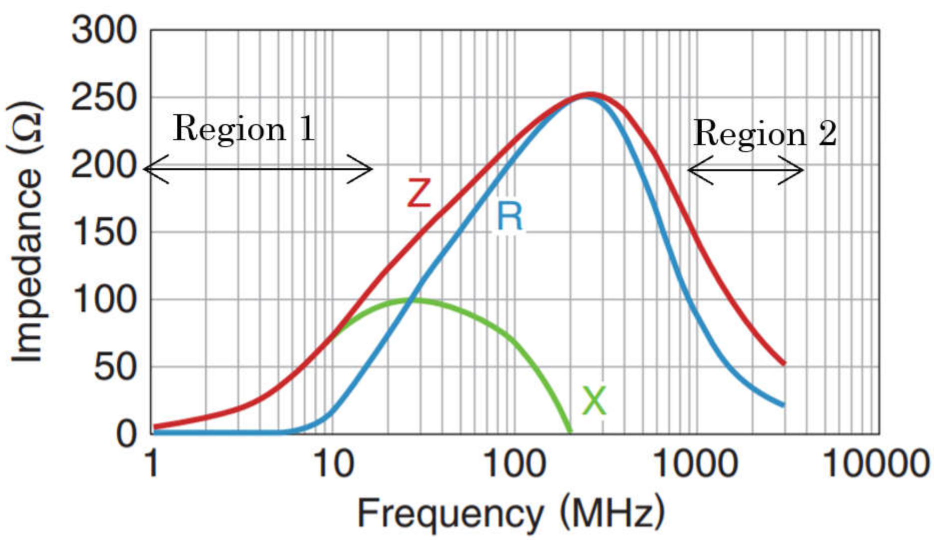

Figure 4-1. Impedance Curve for MPZ1608S221A

For the region of the impedance plot where the bead appears mostly inductive (region 1 in Figure 4-1), the L_{EQ} can be calculated by using the Equation 1, where X_L = impedance of bead at frequency ‘f’. Best practice to take the impedance value at least a decade away from the peak impedance value for accurate calculations. For example, impedance shown in Figure 4-1 at 10MHz for MPZ1608S221A is 70Ω. The L_{EQ} can be calculated as 1.11µH.

$$L_{EQ} = \frac{X_L}{2.\pi.f} \quad (1)$$

The C_{PAR} can be estimated in a method similar to L_{EQ}, by looking at region where the bead appears mostly capacitive (region 2 in Figure 4-1). The C_{PAR} can be estimated using Equation 2 where X_C = impedance of the bead at frequency ‘f’. It is best to take impedance value at least a decade away from the peak impedance value for accurate calculations. For most beads the C_{PAR} is less than 5pF and has no impact on the stability of the loop. User should do the calculations and make sure that this holds true for the bead selected for the use case. For example, impedance shown in Figure 4-1 at 1GHz for MPZ1608S221A is 150Ω. So the C_{PAR} can be calculated as 1pF.

$$C_{PAR} = \frac{1}{2.\pi.f.X_C} \quad (2)$$

The R_{PAR} can be approximated as the peak impedance of the bead. For ease of calculations, the R_{DC} is approximated as zero here, and the entire peak impedance is estimated as R_{PAR}. In Figure 4-1, the R_{PAR} can be calculated as 250Ω

The total output cap (C_{EQ}) needs to include the intentional cap added by the user for the filtering and the parasitic caps due to any other additional elements at output of the ferrite bead such as ESD diodes, board routings, and so on.

Using the model of the filter, the filter cutoff frequency and the Q-factor can be calculated using the following equations:

$$\omega_O = \frac{1}{2 . \pi . \sqrt{L_{EQ} . C_{EQ}}} \tag{3}$$

$$Q = R_{PAR} \cdot \sqrt{\frac{C_{EQ}}{L_{EQ}}} \tag{4}$$

Table 4-1 summarizes the stability criteria for TI's Post filter feedback class-D amplifiers. Users need to make sure that the stability criteria for the selected filter satisfy the guidelines in Table 4-1 for proper functioning of class-D amplifier.

Table 4-1. PFFB Stability Criteria for TAS27XX Series

Cutoff Frequency Range ω_0	Minimum ω_0, Q
ω_0 < 1.5Mhz	NOT VALID
1.5Mhz < ω_0 <= 2.5Mhz	>7.5e5
2.5Mhz < ω_0 <= 3Mhz	>8.9e5
3Mhz < ω_0 < = 4Mhz	>7.5e5
4Mhz < ω_0 <= 5Mhz	>8.3e5
5Mhz < ω_0 < = 10Mhz	>1.5e6
10Mhz < ω_0 <= 20Mhz	>7.7e5
20Mhz < ω_0 =< 30Mhz	>1.54e6
30Mhz < ω_0 <= 40Mhz	>1.25e6
40Mhz < ω_0 <= 50Mhz	>8e5
50Mhz < ω_0 <= 75Mhz	>8e5
75Mhz <ω_0 <= 100Mhz	>7.5e5
100Mhz < ω_0 <= 150Mhz	>9e5
150Mhz < ω_0 <= 250Mhz	>1.5e6
250Mhz < ω_0 <= 500Mhz	>7.1e5

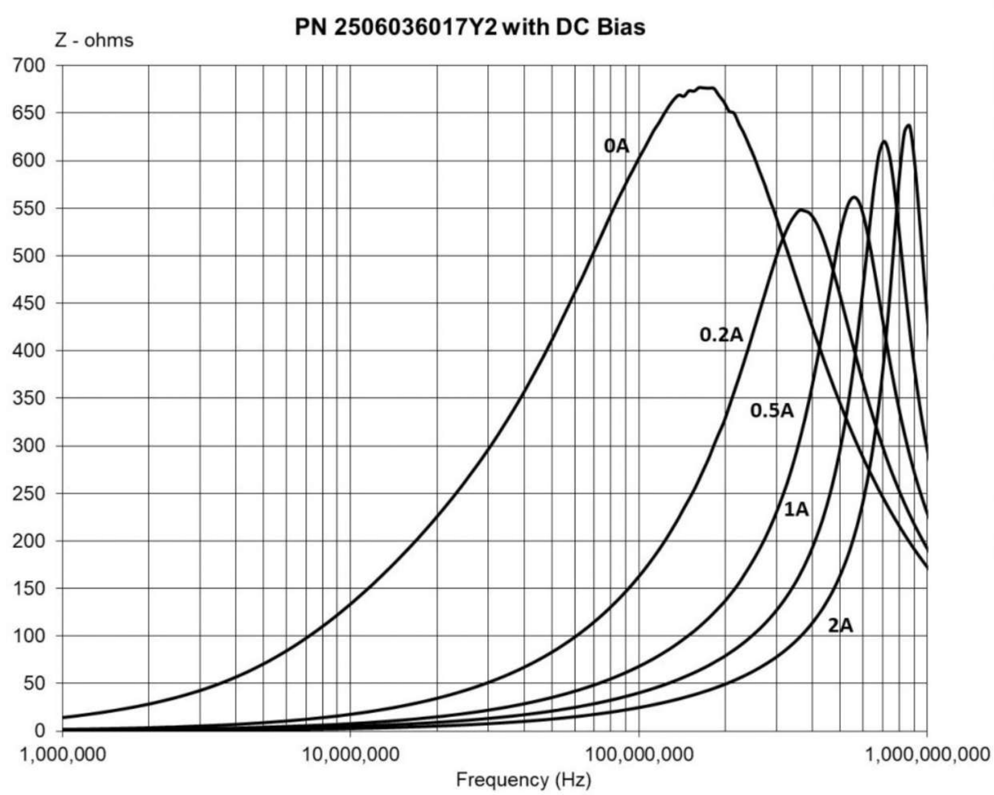

Figure 4-2. 2506036017Y2 impedance vs frequency across DC bias currents

Note that some EMI Filter data sheets provide the impedance derating profile across different dc bias currents. For example, as shown in Figure 4-2, the 2506036017Y2 data sheet provides the impedance curve of the EMI filter for different dc currents of 0A, 0.2A, 0.5A, 1A, and 2A. Hence if the Class-D is to be used in high speaker current applications up to 2A, it is required to verify the stability across each of these settings. Verify the Class-D loop stability of the amplifier in PFFB across the range of bias currents to make sure no instability at any intermediate operating point of the loop

5 User Guide: EMI Filter Modeling and Post Filter Feedback Validation Tool

Since it is relatively cumbersome to do multiple calculations as shown previously to estimate the EMI filter R,L,C parameters and cross the stability criteria for loop stability with post filter feedback for each dc bias current setting, TI has built a custom excel based EMI filter validation tool using simple excel spreadsheet to validate the same to make it easier for users to cross verify (Ferrite Bead Impedance Calculator PFFB Work).

The first step involves back calculating the EMI filter R,L,C model to estimate ω_0 and Q. For this, the user must input the following from the data sheet of the bead, available online.

1. Rdc (dc impedance of the bead)
2. Peaking frequency (Fpeak)
3. Peak impedance (Zpeak)
4. Additional Frequency (Freq2) and impedance at that frequency (Z at freq2)
5. Cpar

For example, consider the case of 2506036017Y2 as per the data sheet for DC bias current=0, the following parameters can be estimated: Rdc= 0.12, Fpeak= 180MHz, Zpeak=675. Additionally if we chose Freq2= 30MHz and Z at Freq2=300. These inputs are given as input to the excel workbook (Green color) and the excel sheet output provides the complete bead R,L,C model as well as the ω_0 and Q. Let us consider Cpar=100pF.

INPUTS FROM BEAD DATASHEET					
Rdc			0.12		
Fpeak			1.80E+08		
Z@Wpeak			675		
Freq 2			3.00E+07		
Z@Freq2			300		
Cpar			1.00E-10	(C2_bead)	
Bead RLC Model Parameters calculated					
Rdc			0.12	0.12	ohm
Rpar			674.88	674.88	ohm
CEQ			5.06E-13	0.51	pF
LEQ			1.55E-06	1548.12	nH
			Wo	12.80	MHz
			Q	5.424	
			Wo/Q	2.36E+06	

Figure 5-1. Snapshot of EMI R, L, C Model and ω_O, and Q Calculator

The outputs Rdc, Rpar, CEQ and LEQ calculated are modeled as per Figure 5-1. Further the calculated ω_0 and Q can be given as inputs to the excel sheet to validate if the EMI filter is acceptable for use in post filter feedback configuration

As observed for these values the ω_0 falls in the 10MHz-20MHz range and the (ω_0 / Q) = 2.36e6 which is >7.7e5 as per Figure 5-1. Hence satisfying the PFFB stability criterion. The two columns *Check for ω_0 input range* and *ω_0/Q Check* are used to validate the same (as shown in Figure 5-2). If both criteria are met as observed in the excel sheet, a green-highlight cell indicates that the filter is valid for use.

Wo input			12.80	MHz		
Q input			5.42			
Wo/Q ratio			2361623.616			
Range	Q max	Min Wo/Q criterion	Check for Wo input range	Wo/Q CHECK	CONCLUSION	
Wo<50KHz	NOT RECCOMENDED DUE TO AUDIO/US		INVALID	INVALID	INVALID	
50KHz <Wo<100KHz	NOT RECCOMENDED DUE TO ULTRASONIC		INVALID	WoBYQ CRITERIA SATISFIED	REDUCE FILTER Q TO USE	
100KHz <Wo<250KHz	NOT STABLE		INVALID	WoBYQ CRITERIA SATISFIED	REDUCE FILTER Q TO USE	
250KHz <Wo<500KHz	NOT RECCOMENDED DUE TO 384K		INVALID	WoBYQ CRITERIA SATISFIED	REDUCE FILTER Q TO USE	
500KHz <Wo<1MHz	NOT RECCOMENDED DUE TO 768K		INVALID	WoBYQ CRITERIA SATISFIED	REDUCE FILTER Q TO USE	
1MHz <Wo< 1.5MHz	0.5	2.00E+06	INVALID	WoBYQ CRITERIA SATISFIED	REDUCE FILTER Q TO USE	
1.5MHz <Wo< 2.5MHz	2	7.50E+05	INVALID	WoBYQ CRITERIA SATISFIED	REDUCE FILTER Q TO USE	
2.5MHz <Wo< 3MHz	2.8	8.93E+05	INVALID	WoBYQ CRITERIA SATISFIED	REDUCE FILTER Q TO USE	
3MHz <Wo< 4MHz	4	7.50E+05	INVALID	WoBYQ CRITERIA SATISFIED	REDUCE FILTER Q TO USE	
4MHz <Wo< 5MHz	4.8	8.33E+05	INVALID	WoBYQ CRITERIA SATISFIED	REDUCE FILTER Q TO USE	
5MHz <Wo< 7.5MHz	4.8	1.04E+06	INVALID	WoBYQ CRITERIA SATISFIED	REDUCE FILTER Q TO USE	
7.5MHz <Wo< 10MHz	4.9	1.53E+06	INVALID	WoBYQ CRITERIA SATISFIED	REDUCE FILTER Q TO USE	
10MHz <Wo< 20MHz	13	7.69E+05	VALID	WoBYQ CRITERIA SATISFIED	VALID EMI FILTER FOR USE	1
20MHz <Wo< 30MHz	13	1.54E+06	INVALID	WoBYQ CRITERIA SATISFIED	REDUCE FILTER Q TO USE	
30MHz <Wo< 40MHz	24	1.25E+06	INVALID	WoBYQ CRITERIA SATISFIED	REDUCE FILTER Q TO USE	
40MHz <Wo< 50MHz	50	8.00E+05	INVALID	WoBYQ CRITERIA SATISFIED	REDUCE FILTER Q TO USE	
50MHz <Wo< 75MHz	62	8.06E+05	INVALID	WoBYQ CRITERIA SATISFIED	REDUCE FILTER Q TO USE	
75MHz <Wo< 100MHz	100	7.50E+05	INVALID	WoBYQ CRITERIA SATISFIED	REDUCE FILTER Q TO USE	
100MHz <Wo< 150MHz	110	9.09E+05	INVALID	WoBYQ CRITERIA SATISFIED	REDUCE FILTER Q TO USE	
150MHz <Wo< 250MHz	100	1.50E+06	INVALID	WoBYQ CRITERIA SATISFIED	REDUCE FILTER Q TO USE	
250MHz <Wo< 500MHz	350	7.14E+05	INVALID	WoBYQ CRITERIA SATISFIED	REDUCE FILTER Q TO USE	

Figure 5-2. Snapshot of EMI Filter Validation Excel for PFFB Stability

If there is no green-highlight then the filter is not valid for use and if the ω_0 > 1.5MHz then Q factor has to be reduced to allowable limit as per Table 4-1. Post modifications in bead or filter cap parameters, the calculator can again be used confirm the stability criteria is satisfied.

6 Summary

This application note describes the different type options available for EMI filtering of the Class-D output and describes the pros and cons of each of them. Specific care-abouts related to use of EMI filters are also detailed. The Post Filter Feedback (PFFB) feature in TAS27XX family of devices is explained and the loop stability constraints are covered in detail with relevant equations. Finally, a user guide for EMI FILTER modeling and excel based post filter feedback stability validation tool is provided to help the user select an appropriate filter configuration by simply providing some inputs from the ferrite bead data sheet

7 References

- Texas Instruments, *Post Filter Feedback Class-D Amplifier Benefits and Design Considerations*, application note.

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