Structure-borne sound transmission loss

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ABSTRACT

Structure-borne sound transmission losses of a straight beam (reference), of a straight beam with an attached mass and of a beam with right angle is measured. Two different methods are compared: general two-excitation method and simplified symmetric-joint method. Since the beams are symmetrical around the junction, the two methods agree well. The results of the transmission losses agrees well with the theoretical, that is, no transmission loss for a straight beam, an increase of transmission loss with higher frequencies when mass is added and 3 dB transmission loss for all frequencies at the right angle.

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1 INTRODUCTION

1-1 Task

The task is to measure and compare structure-borne sound transmission losses of a straight beam (reference), of a straight beam with an attached mass and of a beam with right angle. This is performed by using two different methods: general two-excitation method and simplified symmetric-joint method.

1-2 Test objects

The test objects are a 2 mm straight steel beam with and without the attached mass (110 g) and a 2 mm steel beam with a right angle, figure 1. The quality of the measurements is much improved when the reflections from the end sections are suppressed. To ensuring low reflection from the ends, they are embedded in sand, figure 1 and 2. This arrangement reduces the influences of the accelerometer mass. In the case of the right angled beam, the corner is hung up and supported by rubber band, to the right in the left part of figure 1.

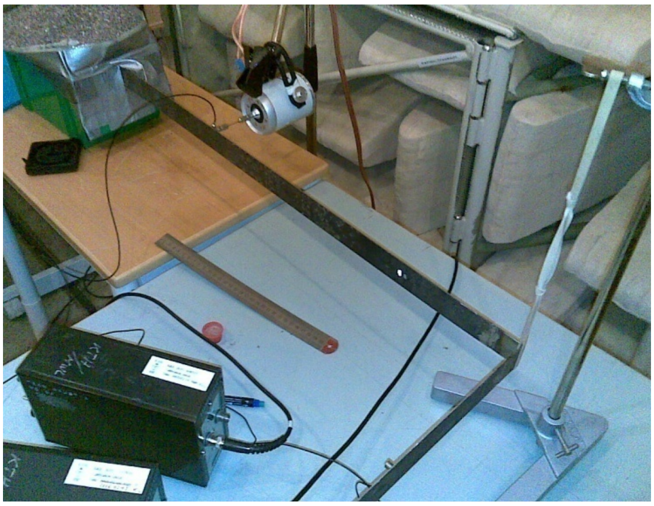

Figure 1: *The test objects and their arrangement. To the left the right angled steel beam and to the right the straight steel beam with a magnet mass attached. The beams are embedded in sand boxes in the end to suppress reflections. The right angled beam is supported with a rubber band at the corner.*

The properties of the test objects are as follows:

- 2 steel beams: A straight beam and a beam bend to right angle at the centre.
  - Cross section (S = W × H): 0.002 m × 0.036 m
  - Density (ρ): 7850 kg/m^3
  - Young´s modulus (E): $2.1 \cdot 10^{11}$ Pa
  - Loss factor (η): 0.01

2 THEORY AND METHOD

2-1 Theory

To reduce the influence of external noise and to avoid influence of any possible changes in the system during the measurements, transfer function is measured with the excitation force used as reference. Refer to section 10.3 in the lecture notes [1] for measurement theory.

2-2 Method

Two methods are used: general two-excitation method and simplified symmetric-joint method where the following formulas are used to calculate the transmission loss and the reflection coefficient of the respective method (refer to [1]):

$$\begin{bmatrix} r_a & t_{ba} \\ t_{ab} & r_b \end{bmatrix} = \frac{1}{A_-^1 B_-^2 - B_-^1 A_-^2} \begin{bmatrix} A_+^1 B_-^2 - B_-^1 A_+^2 & A_-^1 A_+^2 - A_+^1 A_-^2 \\ B_+^1 B_-^2 - B_-^1 B_+^2 & A_-^1 B_+^2 - B_+^1 A_-^2 \end{bmatrix}$$

$$\begin{bmatrix} r \\ t \end{bmatrix} = \frac{1}{A_-^2 - B_-^2} \begin{bmatrix} A_- A_+ - B_- B_+ \\ A_- B_+ - B_- A_+ \end{bmatrix}$$

r_a and r_b are reflection coefficient for waves towards the joint at the point $x_a = 0$ and $x_b = 0$. t_{ab} and t_{ba} are transmission coefficients from beam A to beam B or from beam B to beam A. The point closer to the discontinuity is denoted as point 1. Only flexural waves are considered. The test arrangement is shown in figure 2. Since there are two propagating waves at each beam, two transfer functions are needed at each side of the joint. The measured transfer functions are used to calculate the unknowns in the formulas above:

$$\begin{cases} A_- = \frac{H_1 e^{jks} - H_2}{2j\sin(ks)} e^{-jks} \\ A_+ = \frac{H_2 - H_1 e^{-jks}}{2j\sin(ks)} e^{jks} \\ B_- = \frac{H_4 e^{jks} - H_3}{2j\sin(ks)} e^{-jks} \\ B_+ = \frac{H_3 - H_4 e^{-jks}}{2j\sin(ks)} e^{jks} \end{cases}$$

This calculation is done for both beams connected. For the straight beam it is assumed that there is a joint in the middle and the two sides are considered to be different beams. The measurement points are a certain distance away from discontinues such as junctions and shaker mounting point to avoid influence of near-field solutions, refer to figure 2. The distance between discontinuities and the measurement points should be at least 0.15 m for frequencies of 100 Hz and above in order to reduce error occurring from discontinuity of a 2 mm steel beam to one tenth [1]. The distance between point 1 and 2 (b_1 and b_2 or a_1 and a_2 in figure 2) is chosen to $s = 0.025$ m. I.e.:

$$ks \approx \begin{cases} 0.11\pi \text{ at } 100 \text{ Hz} \\ (0.22\pi \text{ at } 400 \text{ Hz}) \\ 0.8\pi \text{ at } 5 \text{ kHz} \end{cases}$$

(The flexural wave number k is calculated from the dispersion relation: $k_B^4 = \omega^2 \rho S / D$, where D is the bending stiffness). This choice avoids the problem that will occur when the condition $ks = n\pi$, $n \in \mathbb{Z}$ is fulfilled. Values close to it will increase measurement errors.

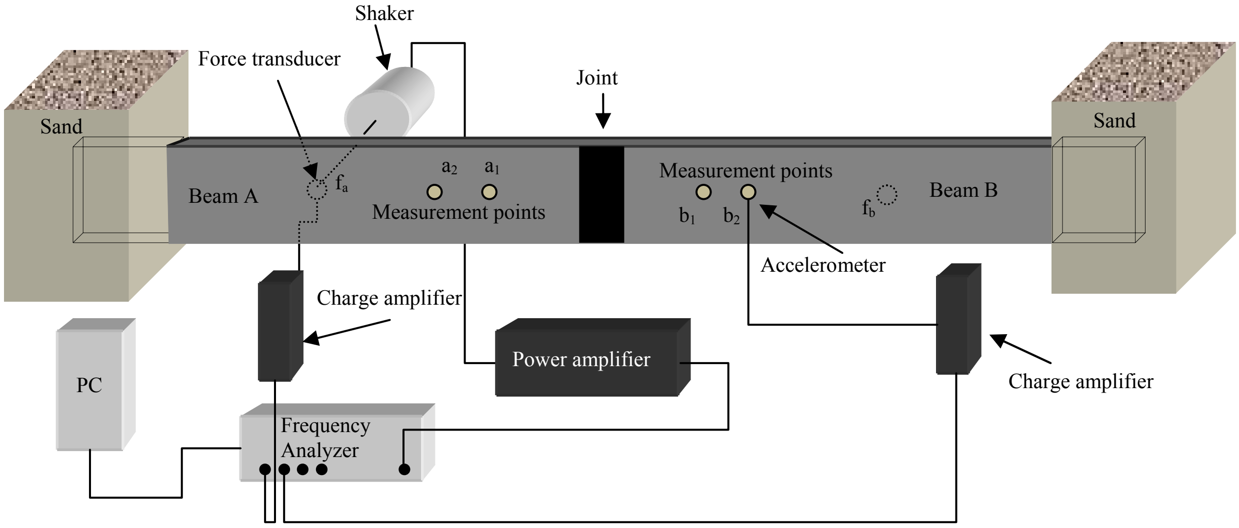

Figure 2: *Illustrating of the test arrangement. When measure the right angled beam the same arrangement is used, the corner is in that case located at the hypothetical joint.*

3 MEASUREMENTS

3-1 Measurement environment

The environmental data and date are as follows:

- Measure location: The semi-anechoic room at MWL, KTH in Stockholm Sweden
  - Dimensions (L×W×H): 9.05 m × 5.95 m × 4.6 m
  - Cut off frequency: 80 Hz
- Date: 21 October 2008

3-2 Instrumentation

The following equipment is used for the measurement with the straight beam:

- Fourier Analyzer: Tektronix type 2630
  - Serial No.: B010319
- 2 Charge amplifier: Brüel & Kjaer type 2635
  - Serial No.: 1799669 (accelerometer)
  - Serial No.: 1447225 (force transducer)
  - Unit out (both): 100 mV
- Accelerometer: Brüel & Kjaer type 4393V (2.4 g)
  - Serial No.: 2127837
  - Sensitivity: 0.319 pC/(ms^2)
- Shaker: Ling Dynamics type V203
  - Serial No.: 51384-26
- Power amplifier: Zachry D250
  - Serial No.: 614142
- Force transducer: Brüel & Kjaer type 8200
  - Serial No.: 1895664
  - Sensitivity: 4.07 pC/N
- Personal Computer

The following equipment is used for the measurement with the right angled beam:

- Fourier Analyzer: Tektronix type 2630
    - Serial No.: B010177
- 2 Charge amplifier: Brüel & Kjaer type 2635
    - Serial No.: 638515 (accelerometer)
    - Serial No.: 1117816 (force transducer)
    - Unit out (both): 100 mV
- Accelerometer: Brüel & Kjaer type 4393V (2.4 g)
    - Serial No.: 2127834
    - Sensitivity: 0.318 pC/(ms^2)
- Shaker: Ling Dynamics type V203
    - Serial No.: 46904/1
- Power amplifier: NAD C370
    - Serial No.: H0ZC37006007
- Force transducer: Brüel & Kjaer type 8200
    - Serial No.: 1895665
    - Sensitivity: 4.05 pC/N
- Personal Computer: Serial No.: 8903363

The equipment is connected as in figure 2 in section 2-2. The output of the analyzer is set to random noise and 500 mVrms and it is connected via the power amplifier to the shaker. The shaker is supported of a rubber strap and is mounted via a thin rod screwed to the force transducer which is glued on the steel beam. The force transducer is connected via the charge amplifier to channel 1 on the Analyzer and the accelerometer (mounted with beeswax) is connected via the other charge amplifier to channel 2. All measurements are performed in the frequency range 0 – 5 kHz base band. Further settings of the instruments, refer to page 141 in [1].

3-3 Measurement procedure

As mentioned in section 1, three cases are measured: a straight beam (reference), a straight beam with added mass, and a beam with a right angle. The excitation is performed by the shaker applied via the force transducer to f_a or f_b, refer to figure 2. Measurements are performed at all four points (a_2, a_1, b_1 & b_2 in figure 2) for each excitation. The measurement points are symmetric about the centre of the hypothetical joint (or corner when suitable), figure 2. The hypothetical joint is assumed to have the same length as the added mass, that is, 0.07 m. For the straight beam, the distance between the measurement point a_1 (or b_1) and the centre of the "joint" is chosen to 0.26 m and the distance between a_1 and a_2 (or b_1 and b_2) (s in section 2-2) is 0.025. The distance between f_a and a_2 is 0.238 m and between b_2 and f_b is 0.28 m. For the beam with a right angle, the distance between the measurement point b_1 (or a_1) and the inside of the corner is chosen to 0.175 m and the distance between b_1 and b_2 (or a_1 and a_2) is 0.025 m as before. The distance between f_a and a_2 is 0.36 m and the distance between b_2 and f_b is 0.33 m. These distances fulfil the requirements according to section 2-2.

The following steps are performed:

1. The shaker and force transducer are mounted to the excitation point of beam B (f_b). The transfer functions are measured between the acceleration at each of the

four measurement points and the applied force (XFER21). Coherence is verified to satisfactory and the data is saved.

2. The mass of 110 g are mounted (2 magnets on one side and 1 on the other) at the location of the hypothetical joint and the first step is repeated.
3. The shaker and force transducer are mounted to the (second) excitation point of beam A (f_a) and steps 1 and 2 are repeated.
4. Step 1-3 is performed for the steel beam with the right angle.
5. The measurement data are converted to Matlab readable format and the structure-borne sound transmission losses for all three cases are calculated by using both the general method and the simplified method.

3-4 Results

Figure 3 shows comparison between the structure-borne sound transmission losses of the three cases. The average of the two groups of measurements is used in the plot. The difference between the two groups of measurements is shown in figure 4 in the appendix. Only transmission loss using simplified symmetric-joint method is used in this plot. The method agrees well with the general two-excitation method and is shown in figure 5 in the appendix.

Figure 3: *Comparison of the measured structure-borne sound transmission loss of the reference beam, the straight beam with added mass and the right angled beam. The average of the two groups of measurements is used with the simplified symmetric-joint method.*

4 DISCUSSION

Since the junctions are symmetrical, the two methods used yield similar results, especially over 400 Hz as shown in figure 5 (in the appendix). The measurement errors are probably increased under 400 Hz as the values getting closer to the condition $ks = n\pi$, refer to section 2-2. These errors could be reduced if there were separate measurements for the low frequency range and increase the distance s. The mass of the accelerometer has probably some influence of measurements (even though it is reduced by sand), especially for the beam with right angle since the reflections from the angle are significant, but this could be reduced by using a lighter sensor or a laser vibrometer.

When analyzing figure 3, the structure-borne sound transmission loss of the reference beam is zero as expected for a straight beam. Minor variations could be due to the influence of the support of the shaker and the influence of accelerometer mass. The difficulty to measure the exact distance between the measurement points which have an effect on the reciprocity also has some influence. When adding the mass at the beam however the losses increase with higher frequencies due to the fact that high frequency waves will be more damped when travelling thru the junction than low frequencies. The transmission loss is substantial at approximately 4550 Hz which could be due to the fact that the junction (mass) has a certain acoustical length. If the masses were spread out the transmission loss should increase over a larger frequency range. The transmission loss for the beam with a right angle is close to 3 dB for all measured frequencies which is the theoretical value of transmission loss of such junction.

When comparing the two groups of measurements in figure 4 (in the appendix) one could see two mayor discrepancies, both when using the exciting point of beam A. The peak at approximately 4 kHz for the case of added mass (figure 4b) could be due to the asymmetry of the joint. The fact that the masses were heavier on one side could also have an influence. The narrow transmission loss dip at 4350 Hz for the case of right angle (figure 4c) could originate from the error caused by the distance between the shaker, measurement points and the joint since it cannot be ensured that the distance is exact same for the two groups of measurements. The dip is also shown in figure 3 since using the average. These discrepancies are method independent as shown in figure 4.

5 REFERENCES

[1]: Leping Feng, Acoustical measurements, Lecture notes, TRITA-AVE 2007:07, ISSN 1651-7660, 2nd print (2008)

6 APPENDIX

Figure 4a - c shows comparison between the two exciting points and its average for both methods on the reference beam, the added mass beam and the right angled beam respectively. Figure 5 shows the comparison between the two methods used to measure the transmission loss of the three cases of beams, the average is used.

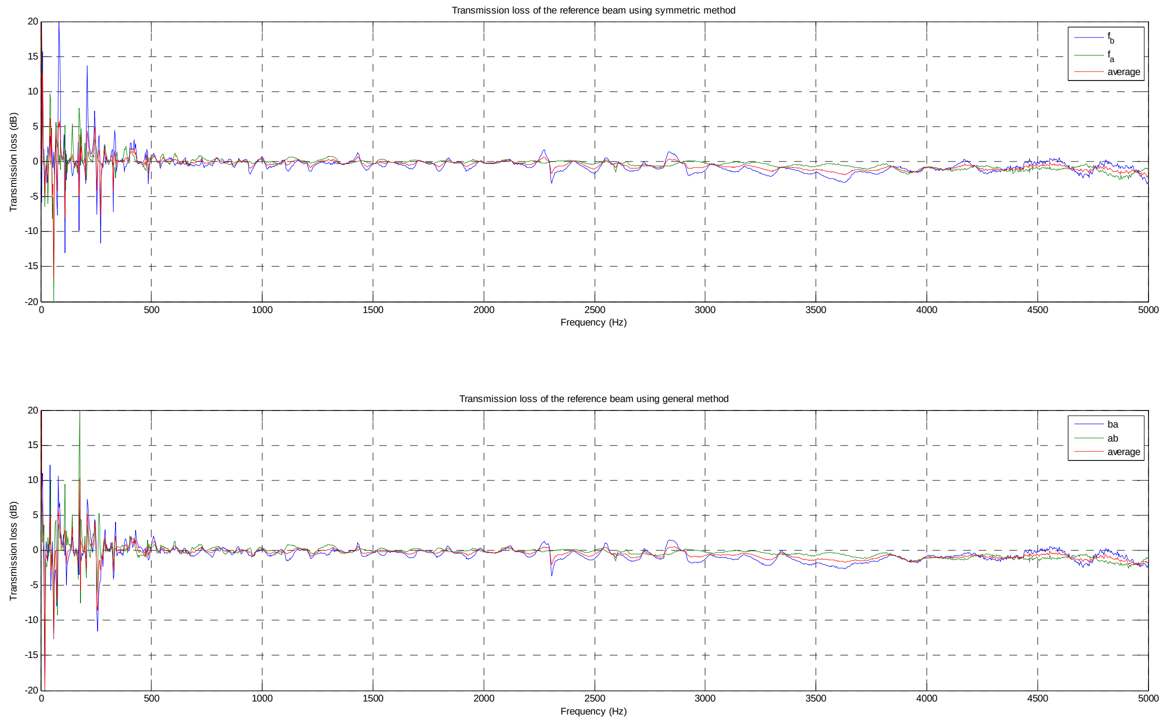

Figure 4a: *Comparison of the two groups of measurements and its average of the measured structure-borne sound transmission loss of the reference beam. The upper curve is showing the simplified method and the lower curve is showing the general method. The red curve is average of the two groups of measurements.*

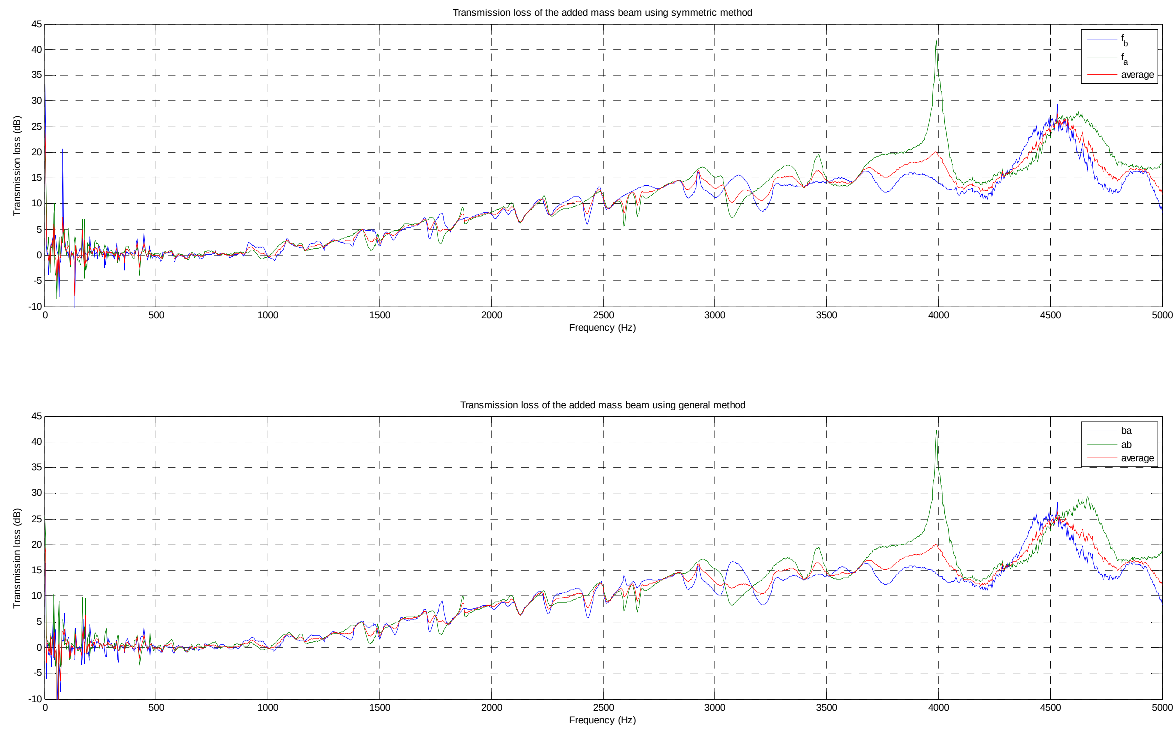

Figure 4b: *Comparison of the two groups of measurements and its average of the measured structure-borne sound transmission loss when mass is added to the beam. The upper curve is showing the simplified method and the lower curve is showing the general method. Note the peak at 4 kHz when exciting point of beam A is being used.*

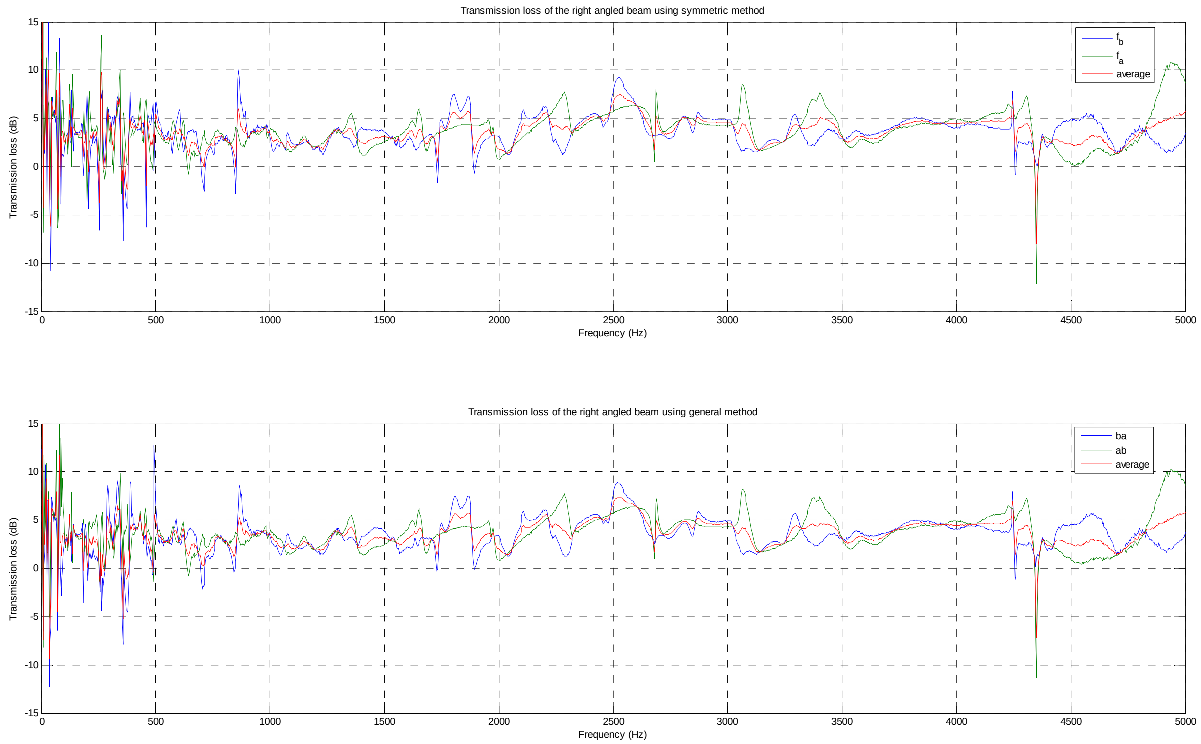

Figure 4c: *Comparison of the two groups of measurements and its average of the measured structure-borne sound transmission loss of the right angled beam. The upper curve is showing the simplified method and the lower curve is showing the general method. Note the dip at 4350 Hz when exciting point of beam A is being used.*

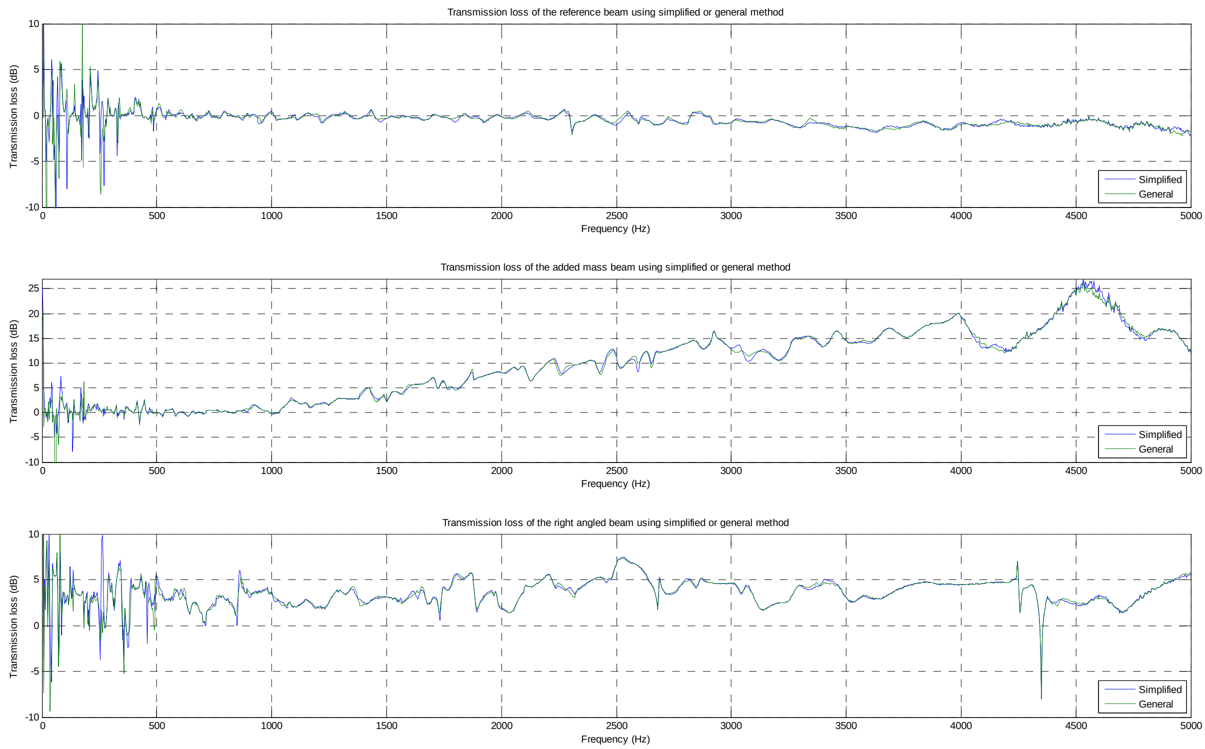

Figure 5: *Comparison of the two methods used to measure the transmission loss of the three different cases of beams. There are discrepancies under 400 Hz.*