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In-situ acoustic impedance measurements on air-injected liners under grazing flow

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ABSTRACT
Acoustic liners, that are used in aero-engines and that have an adaptable impedance for different phases of flight, have a strong appeal to the aerospace industry that seeks further ways to reduce noise. A way to control the impedance of a liner is by injecting air into it. This idea - proposed by Tester and Dean in the seventies - has gained renewed interest for application in the nacelle and at the inlet-lip - combined with anti-icing - of turbofans. This has led to the current study that was part of the European “SILENCE(R)” project. The research was aimed at (i) applying an in-situ multiple microphone impedance measurement technique on 3DOF air-injected liners under grazing flow conditions and (ii) improving a prediction model. At low cell or through flow rates, tests in an impedance tube showed good agreement between measured impedances using tube instrumentation and liner in-situ instrumentation. At high flow velocities however, significant differences were found in the measured resistance due to pressure distortions, picked-up by in-situ instrumentation and related to high flow velocities at perforated septa. Results can improve when the diameter of the septum orifices and liner cross-area are reduced. In a wind tunnel, measurements on air-injected liners in grazing flow showed that the through-flow could change the (facing sheet) resistance significantly. An increase or even decrease is possible depending on the ratio of orifice velocity and skin friction velocity (proportional to respectively cell flow and grazing flow Mach number). The results were used to raise an improved, though simple prediction model.

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National Aerospace Laboratory NLR

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E.R. Rademaker and E.A. Demmenie

This report is based on a paper to be presented at The 33rd International Congress and Exposition on Noise Control Engineering, at Prague, Czech Republic on 22-25 August 2004.

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Summary

Acoustic liners, that are used in aero-engines and that have an adaptable impedance for different phases of flight, have a strong appeal to the aerospace industry that seeks further ways to reduce noise. A way to control the impedance of a liner is by injecting air into it. This idea - proposed by Tester and Dean in the seventies - has gained renewed interest for application in the nacelle and at the inlet-lip - combined with anti-icing - of turbofans. This has led to the current study that was part of the European “SILENCE(R)” project. The research was aimed at (i) applying an in-situ multiple microphone impedance measurement technique on 3DOF air-injected liners under grazing flow conditions and (ii) improving a prediction model. At low cell or through flow rates, tests in an impedance tube showed good agreement between measured impedances using tube instrumentation and liner in-situ instrumentation. At high flow velocities however, significant differences were found in the measured resistance due to pressure distortions, picked-up by in-situ instrumentation and related to high flow velocities at perforated septa. Results can improve when the diameter of the septum orifices and liner cross-area are reduced. In a wind tunnel, measurements on air-injected liners in grazing flow showed that the through-flow could change the (facing sheet) resistance significantly. An increase or even decrease is possible depending on the ratio of orifice velocity and skin friction velocity (proportional to respectively cell flow and grazing flow Mach number). The results were used to raise an improved, though simple prediction model.

Contents

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1 Introduction

Acoustic liners for aircraft engines whose impedance can be adapted for different phases in flight have a strong appeal to the aerospace industry that looks for new ways to further reduce turbofan engine noise. Controlling the liner impedance by varying the amount of injected air into the liner was first proposed by Tester and Dean in the seventies [1]. In the eighties, alternatives like tangential blowing (i.e. injecting air in the direction of a grazing flow) were investigated at several places, also at NLR [2].

The renewed interest in the use of air-injected liners in the nacelle and in the intake lip, the latter in combination with an anti-icing device, has led to the current study, that was a part of the European Growth project GRD1-2000-252597 SILENCE(R).

This paper gives the results of applying an in-situ multiple microphone measurement technique on air-injected liners and discusses the validity of the technique. Finally a simple prediction model for air-injected septa or facing sheets under grazing flow is presented and compared with measurements.

2 Experimental set-up

2.1 Description of the tested liners

Fig. 1 shows a sketch of typical 3DOF air-injected liner that was tested. Each liner consists of a plenum, mid-chamber (in case of a 3DOF liner) and upper-chamber. Above the plenum, a *Perfolin* layer functioned as a flow rectifier. *Perfolin* -developed and patented by Stork Veco and Fokker - is an electrically formed Nickel porous sheet with horn-shaped orifices (typical throat diameter: 30 μm). *Perfolin* has a low non-linear DC-flow resistance. For each liner the facing sheet and mid-septum, see Fig. 1, had identical geometry. They were made of perforated plate, porosity (between 5% and 10%) and orifice diameters (0.3 to 2.0 mm) were varied. The inner diameter of the liner samples was 29 mm. One sample had a 16 mm inner diameter. Fig. 1 shows transducer positions, fig. 2 a few photos of a 3DOF liner.

2.2 Test set-ups in an impedance tube and in the NLR acoustic flow duct facility

The measurements on the air-injected liners were carried out in an impedance tube and under grazing flow in the NLR acoustic flow duct facility. The acoustic flow duct facility is a suction tunnel. In the test-section (length: 1.05 m; cross-area 0.30 x 0.15 m^2) the grazing flow Mach number can be varied between 0 and 0.7. Fig. 3 shows the test-section. At one of the vertical walls of the section, a horn with four loudspeakers was installed aside to the liner sample. A splitter plate opposite to the liner sample and horn was positioned at half a wavelength from the liner surface to obtain a standing wave and to ensure there was no phase difference across the liner surface. The airflow through the liner cell was regulated with a sonic venturi. The maximum cell-flow Mach number was 0.026. To validate the impedance measurement technique under cell flow conditions with liner in situ transducers (see next section for details) measurements were carried out in an impedance tube using the well-known two-microphone technique. Fig. 4 shows this set-up. Note the slit at the tube end near the loudspeaker that allows the injected air to escape.

2.3 The liner in-situ multiple-microphone measurement technique

For the in situ impedance measurements the liner had a transducer pair in the upper chamber and a transducer in the facing sheet. Assuming plane waves, the transducer pair measures the amplitude of the “incident and reflected wave”, and thus the particle velocity just under the facing sheet. Across the facing sheet continuity of mass flow was assumed and with the measured facing sheet pressure the specific acoustic impedance of the liner sample follows:

$$Z = \frac{P_1 P_{ref}^* \sin(k\Delta)}{P_3 P_{ref}^* i \cos(kx_2) - P_2 P_{ref}^* i \cos(kx_3)} \tag{1}$$

with: P_n complex amplitude of the acoustic pressure at the facing sheet (*n = 1*, see Fig.1) or at the transducers in the upper chamber (*2* and *3*, see Fig. 1)

- P_{ref} complex amplitude of the acoustic reference pressure (at position *1*, *2* or *3*)
- k wave number
- Δ distance between transducer *3* and *2*
- x_2, x_3 position of the transducers in the upper cell
- * complex conjugate

Apart from this technique an alternative was applied for the 3DOF liner-samples: a transducer pair in the mid-chamber was used to determine the particle velocity at the mid-septum. With a single transducer in the upper-chamber the particle velocity at the facing sheet surface can be calculated. The following expressions can be given for the specific acoustic impedance:

$$Z = \frac{G_{ref,1}}{P_{ref}^* A - P_{ref}^* B} \tag{2}$$

$$P_{ref}^* A = \frac{P_{ref}^* C e^{-ikL} - P_{ref}^* D e^{ikL} + G_{ref,2} e^{-ikx_2} e^{ikL}}{e^{-ikL} - e^{-2ikx_2} e^{ikL}} \tag{3}$$

$$P_{ref}^* B = G_{ref,2} e^{-ikx_2} - P_{ref}^* A e^{-2ikx_2} \tag{4}$$

$$P_{ref}^* C = \frac{G_{ref,4} e^{-ikx_4} - G_{ref,5} e^{-ikx_5}}{e^{-2ikx_4} - e^{-2ikx_5}} \tag{5}$$

$$P_{ref}^* D = \frac{G_{ref,4} e^{ikx_4} - G_{ref,5} e^{ikx_5}}{e^{2ikx_4} - e^{2ikx_5}} \tag{6}$$

In these expressions is:

$G_{ref,n}$	cross power of the complex conjugate of P_{ref} and P_n
n	$n = 1$ for facing sheet transducer, *2* for the transducer in the upper-chamber (could also be transducer 3) and *4* or *5* for a transducer in the mid-chamber
L	depth of the upper-chamber (= position of the mid-septum)
x_n	location of transducer n
P_{ref}	reference pressure (this can be the pressure of transducer *1, 2, 4* or *5*)
A, B	incident and reflected wave amplitude in the upper-chamber of the liner
C, D	incident and reflected wave amplitude in the mid-chamber of the liner

It is remarked that the cross and auto powers that are used in the expressions above are *averaged cross and auto powers.* In the tests, the cell flow (Mach number) was incorporated in the wave numbers. For convenience this was omitted in the expressions presented here. Incorporating the cell flow velocity only had a minor effect on the calculated impedances.

3 Experimental results

3.1 Results impedance tube measurements

When there is no through flow or moderate through flow, there is an excellent agreement between the liner impedances that are measured with impedance transducers and different sets of in-situ transducers. Figure 5 illustrates this for a 3DOF liner resistance for a relatively low cell flow Mach number (= M_c) of 0.011. When the cell flow is increased further, the differences become larger (Fig. 5). In that case high flow velocities occur at the orifices of the septa, e.g. for M_c = 0.017 and 10 % porosity the velocities are about 60 m/sec. At these high orifice velocities, the measured particle velocities above and under the facing sheet differ (see Fig. 6, where the particle velocity ratios are given obtained from respectively in-situ and tube transducers). The measured facing sheet pressure (transducer was in the center of the tube/liner cell) and calculated facing sheet pressure (using tube transducers) hardly differ, see the pressure ratios.

An explanation for this is that the in situ transducers are too close to the septa, where the injected or cell flow is far from uniform and where evanescent modes have a strong influence on the measurements. These effects are more serious at higher flow velocities and are confirmed by the results of phase difference measurements between two transducers that are at the same distance from a septum (see Fig. 7). Measurements could be improved by reducing the inner diameter of the liner cell and the diameter of the orifices.

At high orifice velocities differences occur between the measured resistance of the facing sheet and the mid-septum, while both have the same geometry. The distance between facing sheet and mid-septum was 15 mm. This can be seen in Fig. 8 that shows the resistances (for another 3DOF liner than in Fig. 5, 6 and 7) at M_c of 0.011 and 0.017. Explanations for this could be the limitations of the measurement technique already mentioned and/or the non-uniform flow impinging on the facing sheet, which is downstream of the mid-septum.

3.2 Results measurements in the NLR acoustic flow duct facility

In the acoustic flow duct, impedance measurements were carried out on the air-injected liners under grazing flow conditions. Liner in-situ transducers were used. Similar limitations were encountered as in the impedance tube, i.e. measured impedance differences for different transducer sets at high orifice flow velocities.

In [1] an expression is given for the resistance of a septum for a liner, placed under grazing flow and injected with air: $R_{fs} = f(\sigma, k, d, l, C_D, \mathrm{Re}) + \max\left(\frac{C_2 M_c}{\sigma^2}, \frac{C_1 M_{gf}}{\sigma}\right)$ (7)

with *f()* function of porosity, wave number, orifice diameter & length, discharge coefficient and Reynolds number

M_c cell or through flow Mach number

C_2 empirical constant (varies usually between 1 and 2)

C_1 empirical constant (varies with orifice diameter)

The second term on the right determines the resistance. The expression indicates that a combination of grazing flow and cell flow does not lower the resistance.

However, the measurements show that in some cases a combination of grazing flow and cell flow can result in a lower impedance than when one of the two is absent. Figure 9 shows the normalized resistance of the facing sheet (thickness 0.45 mm, 10 % porosity and orifice-diameter 2.0 mm) at M_{gf} = 0 and 0.45. As expected for perforate liners, the resistance increases (linearly) with the grazing flow Mach number (constant C_1 is here 0.3). However there is a resistance decrease when air is injected in the liner, the decrease becomes less if more air is injected into the liner (compare M_c = 0.0044 with M_c = 0.0088).

4 Prediction method

The second objective was to improve a prediction model (7) in relation to the work previously carried out at NLR (see Ref. 2). Therefore, the skin friction velocity and velocity at the orifice are determined. The skin friction velocity is defined as the root of the ratio of the skin friction shear stress (τ_w) at the wall and the fluid density at the wall (ρ_w): $V_{skin} = \sqrt{\tau_w / \rho_w}$ (8)

The following expression approximates the skin friction velocity, that remains more or less constant in the test section of the acoustic flow duct facility at NLR:

$$V_{skin} = 10.56 \cdot M_{gf} + 0.4 \quad \text{[m/s]} \tag{9}$$

If the velocity at the orifice ($V_{orif} = M_c{*}c\,/\Delta$) is less than four times the skin friction velocity, then the facing sheet resistance is assumed to be:

$$R_{fs} = \frac{C_1 M_{gf}}{\sigma} \tag{10}$$

The empirical constant C_1 depends on the diameter of the orifices, the porosity is noted with σ. If the orifice velocity is larger than four times the skin friction velocity the following expression should be used for the facing sheet resistance.

$$R_{fs} = \frac{C_2 M_{cell}}{\sigma^2} \tag{11}$$

In this expression is C_2 an empirical constant usually between 1 and 2. For the liners, that were investigated, the average value was between 1 and 1.3.

In table 1 results of the prediction method are presented and compared with an average of the measured facing sheet resistances for a 3DOF liner. There is a fair agreement between the prediction and averaged measured resistance. Fig. 10 shows a few examples of predicted resistances and the measured resistances of the facing sheet of this liner at M_{gf} = 0.25. The figures show there are large differences between prediction and measurement at the individual frequencies.

The prediction method proposed here is based on the assumption that the facing sheet resistance is independent of the grazing flow, if the skin friction velocity is smaller than one fourth of the velocity of the injected air at the orifice (comparable to the findings in [2]). However this assumption deserves to be validated further in future tests.

5 Conclusion

In the absence of grazing flow, the resistance of a perforate septum (or liner) increases by air-injection into the liner (cell flow). Under grazing flow, the facing sheet (liner) resistance can be increased or decreased by the cell flow. To predict the facing sheet resistance at grazing flow and cell flow, a method, which is based on the ratio of skin friction velocity and cell flow velocity, has been proposed. The method deserves to be validated further.

At high orifice velocities differences occur between the measured resistance of the facing sheet and a mid-septum, while both have the same geometry. For a liner prediction method it should be identified if the behaviour of a facing sheet is influenced by non-uniform flow conditions caused by the upstream mid-septum.

It is remarked that at high orifice velocities, liner in-situ impedance measurements can be hampered by evanescent modes and non-uniform flow near the septa. This can be improved by using smaller orifices (keeping the porosity the same) and by a smaller inner diameter of the liner. Measurements in an impedance tube at a sufficient distance from the facing sheet were not effected and provided a good reference for the in-situ impedance measurement technique.

Acknowledgement

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References

[1] Dean, P.D. and Tester, B.J., “Duct Wall Impedance Control as an Advanced Concept for Acoustic Suppression”, *NASA CR-134998*, November 1978

[2] Kooi, J.W. and Sarin, S.L., “An Experimental Study on Acoustic Impedance of Helmholtz Resonator Arrays under a Turbulent Boundary Layer”, *AIAA paper 81-1998*, October 1981

Tables

Table 1: *Predicted resistance of a facing sheet and measured (and averaged) resistance under grazing and cell flow*

Liner	σ [%]	M_{gf}	M_{cell}	R_{gf} (C_1 = 0.24)	R_{cell}	4*V_{skin} > V_{cell} ?	$R_{pred.}$	$R_{meas,avg}$
C200216	10.1	0.25	0.0081	0.6	0.8	No	0.8	0.5
			0.015		1.5	No	1.5	1.5
			0.019		1.9	No	1.9	2.0
			0.0225		2.3	No	2.3	2.3
			0.026		2.6	No	2.6	2.5
		0.45	0.0044	1.1	0.8	Yes	1.1	1.1
			0.019		1.9	No	1.9	1.9
			0.0225		2.3	No	2.3	2.3
			0.026		2.6	No	2.6	2.6
		0.55	0.0044	1.3	0.8	Yes	1.3	1.5
			0.019		1.9	No	1.9	2.1
			0.0225		2.3	No	2.3	2.3
			0.026		2.6	No	2.6	2.7

Figures

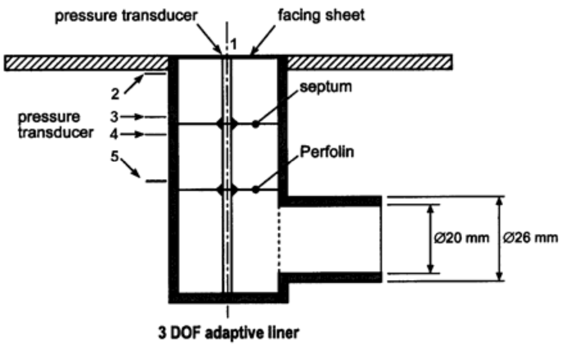


Figure 1: 3DOF air-injected liner sample

Figure 2: Photos of a 3DOF air-injected acoustic liner sample

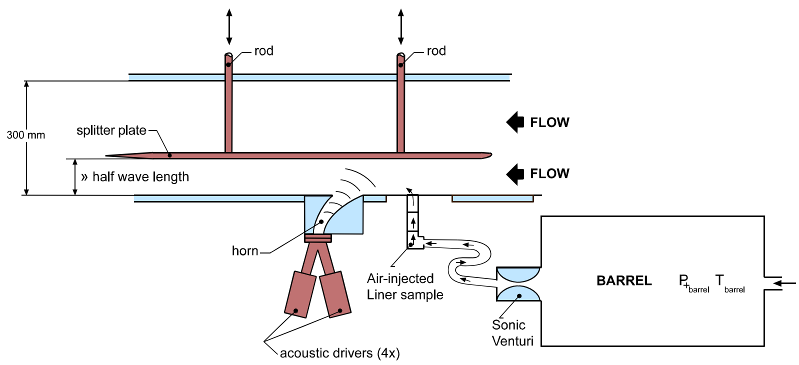


Figure 3: Set-up of the air-injected liner sample in the acoustic

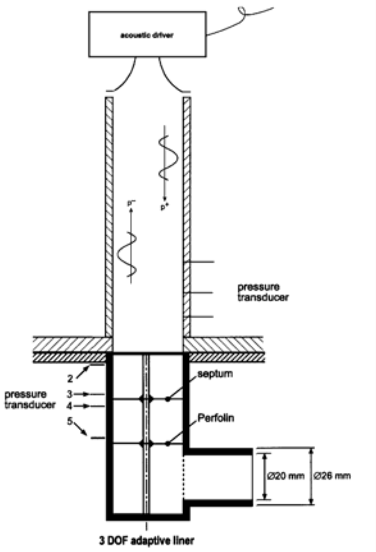


Figure 4: Impedance tube set-up flow duct facility of NLR

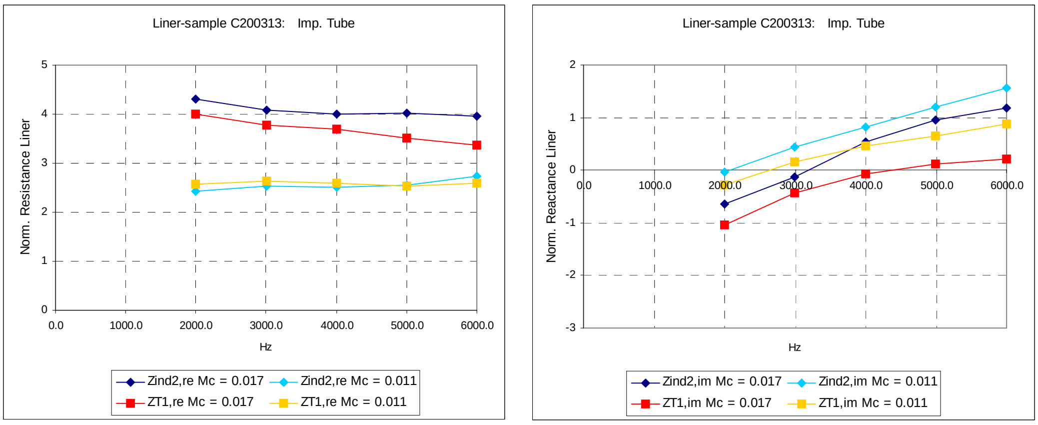
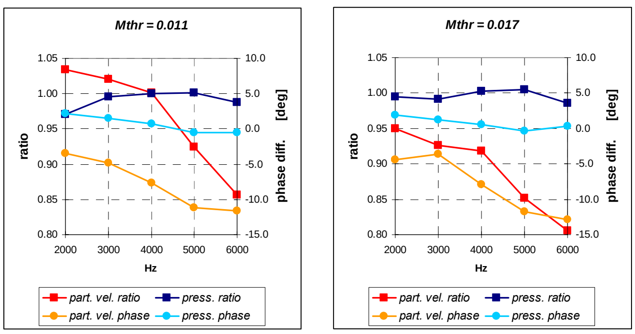


Figure 5: Measured impedances of a 3DOF liner using different transducer sets at a low and a high cell flow Mach number (M_c respectively 0.011 and 0.017)



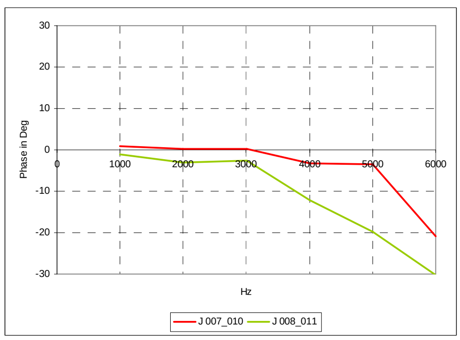


Figure 6: Ratios of pressures at the facing sheet and of particle velocities obtained with tube and septa at high facing sheet or liner in-situ transducers

Figure7: Phase differences between transducers at equal distances from orifice flow (M_c = 0.017, σ =10 %)

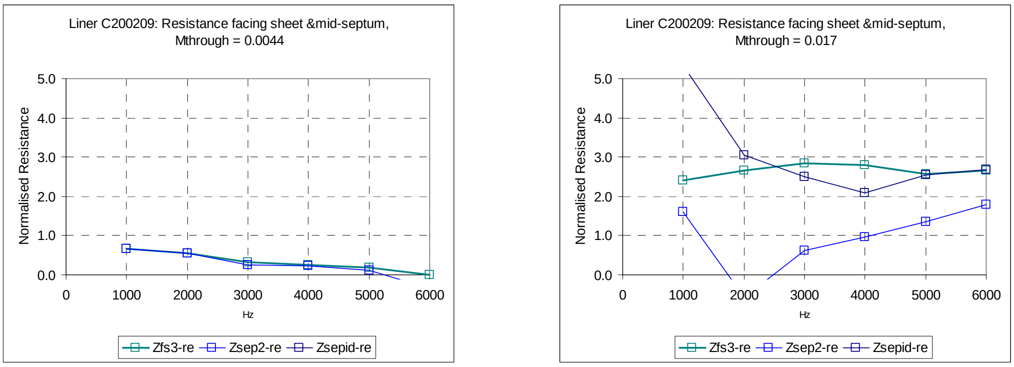


Figure 8: Impedance of mid-septum and facing sheet (both identical, porosity σ = 10 %) at two through or cell flow Mach numbers (Zfs3 = facing sheet impedance; Zsep2 and Zsepid are mid septum impedances measured with "different transducer sets")

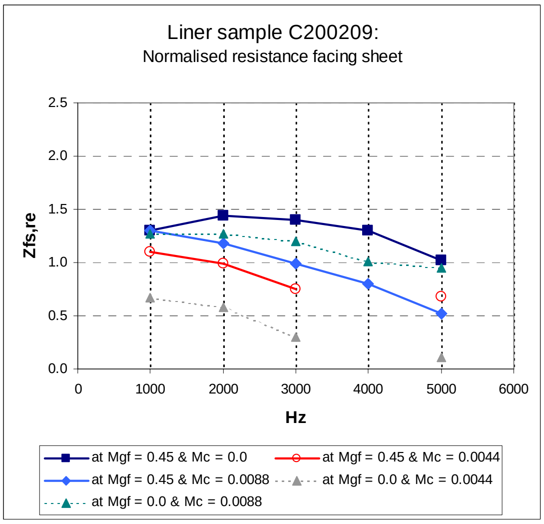


Figure 9: Comparison of facing sheet resistance and without or with cell flow, M_{gf} = 0.45, M_c = 0 and 0.0044

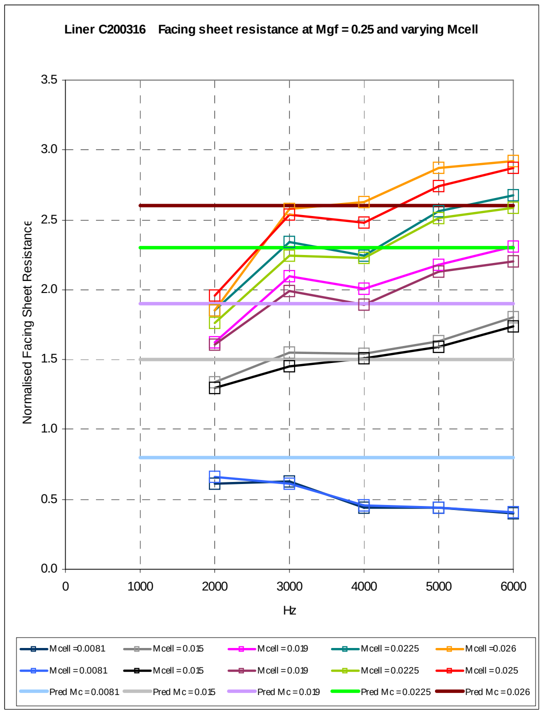


Figure 10: Comparison between measured predicted resistance