Aeroelastic analysis of Fan System Dynamics

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Abstract

The combination of ANSYS-LINFLOW and ANSYS-CFX-LINFLOW has proven to be invaluable tools in the development of low vibration industrial fan systems. This paper illustrates how the combination of linear structure dynamics and linearized fluid dynamics is used when solving the Aeroelastic equation of motion for industrial fans. The aeroelastic equations system is either solved as a non-linear eigenvalue problem or a harmonic/spectrum response problem. When performing the spectrum response analysis, CFX has been utilized to calculate the pressure oscillations exciting the fan. The frequency spectrum of the pressure oscillations exciting the fan was extracted from the data by using a FFT-analysis.

It has been proven that these types of analysis are creating a deep insight into the characteristics of the aeroelastic properties of industrial fans. The created insight has enabled innovative design changes improving the noise, vibration and fatigue characteristics of the systems.

This paper demonstrates the used methodology on a high power industrial fan systems.

1 BACKGROUND

The cause to the vibration problems in the FalconBridge mine ventilation fan system has been investigated using aeroelastic analysis methodology. The aeroelastic investigation has been performed to study if an aeroelastic phenomenon was a part of the problem. In the first series of aeroelastic analysis, stability of the system was investigated. The purpose was to evaluate aeroelastic eigenfrequencies and damping requirements for the system. The system was investigated with and without the dirt built-up that was found on the blades that had failed in operation. The LINFLOW® aeroelastic software was used for the calculation of the aeroelastic eigenfrequencies and corresponding damping requirements for neutral stability. In the second part of the work an aeroelastic response analysis on the system was performed. The purpose was to study aeroelastic response of the system when the fan is subjected to the pressure fluctuations appearing in the system. The pressure fluctuations that the fan is subjected to were provided from earlier CFX® Navier-Stokes calculations (ref. Cranfield University in UK.). The goal was to study the potential influence on the system dynamic due to the dirt built-up that was found on the blade in operation. The LINFLOW aeroelastic software was utilized for the calculation of the aeroelastic response of the fan.

2 AEROELASTIC ANALYSIS

2.1 Introduction

Investigations of the aeroelastic characteristics of fan systems have previously successfully been performed using the LINFLOW software. As a result of this it has been concluded that this type of investigation was of interest for the FalconBridge mine fan system investigation. The goal of the first part of the work was to study if the aeroelastic characteristics of the system are such that the structure pickup more energy from the fluid dynamics than is lost due to damping in the system. The goal of the second part of the work was to study if the aeroelastic response of the system could produce stress levels that could be critical for the fatigue life of the system. A methodology that takes structure dynamics together with unsteady fluid dynamics solved in the frequency domain is used when studying the aeroelastic characteristics of the system. Through this combination of structure and fluid dynamics it is possible to form what is often referred to as the aeroelastic equation of motion. When solving the aeroelastic equation of motion as a harmonic response problem it is possible to study the response amplitude due a fluid dynamic forcing function such as the pressure oscillations used in this work. In the fluid dynamics in the ventilation fan there exist pressure oscillations that are flow velocity and geometry dependent. These pressure oscillations are due to guide vanes, fan support etc. One example of a aeroelastic phenomena that may appear in the system is that if the frequency of the pressure oscillations is close to the frequency of an aeroelastic mode, that require more damping for the mode to be stable than the damping available in the system, then the aeroelastic mode is said to be unstable and will cause vibration problems.

2.2 Modeling

When performing a numerical aeroelastic analysis both a structure dynamics and a fluid dynamics model are needed. The approach taken when studying aeroelastic characteristics of a system is to use linearized numerical methods both for the structure and the fluid dynamics. The structure was modeled with solid elements and the fluid dynamics was modeled with boundary elements describing the interface between the fluid and the structure. This combined numerical model was when evaluating the aeroelastic response of the system. One model was setup for the case without and one with the dirt build-up on the blades.

2.2.1 Structural Modeling

The structure dynamics of the fan has been modeled using the general purpose FE-program ANSYS. The element types used were 8-noded solid elements and 4-noded shell elements (for the thin layer of cover material on the blades).

The model used in this work is shown in Figure 1.

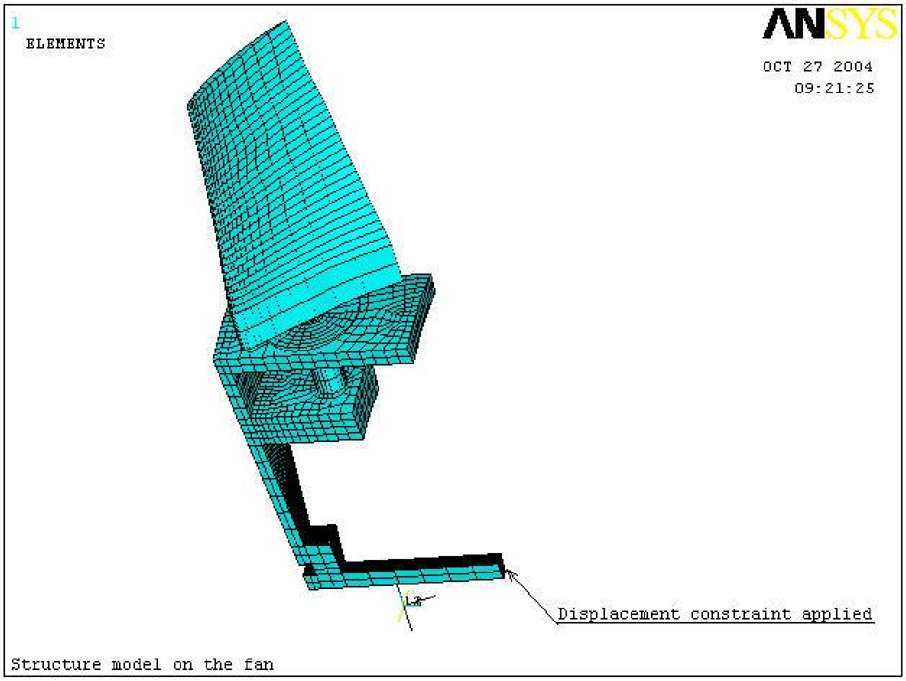

Figure 1	Structural dynamics model used for the fan blade analysis.

Following material properties have been used:

Blade material:
E-modul = 73.5 Gpa
Density = 2750 kg/m3

Blade cover material:
E-modul = 44.0 Gpa
Density = 6000 kg/m3

Hub and blade shaft material:
E-modul = 210 Gpa
Density = 7800 kg/m3

The damping properties of the fan blade system were estimated to 3.0 %, based on the fact that the system contain bearing connections, bolted assemblies etc.. The structural boundary conditions used were such that the fan hub was constrained from translation motion at fan axel location (see figure 1.). The model in figure 1 also includes mode cyclic symmetric boundary conditions on the fan hub cut surfaces. A pre-stressed modal analysis was used to define the structure dynamics of the system. The pre-stressed loading was the angular rotational speed of 890 rpm.

2.2.2 Fluid Modeling

The linearized fluid dynamics model used was a boundary element method (BEM) model of the fan blade. The model used is shown in Figure 2.

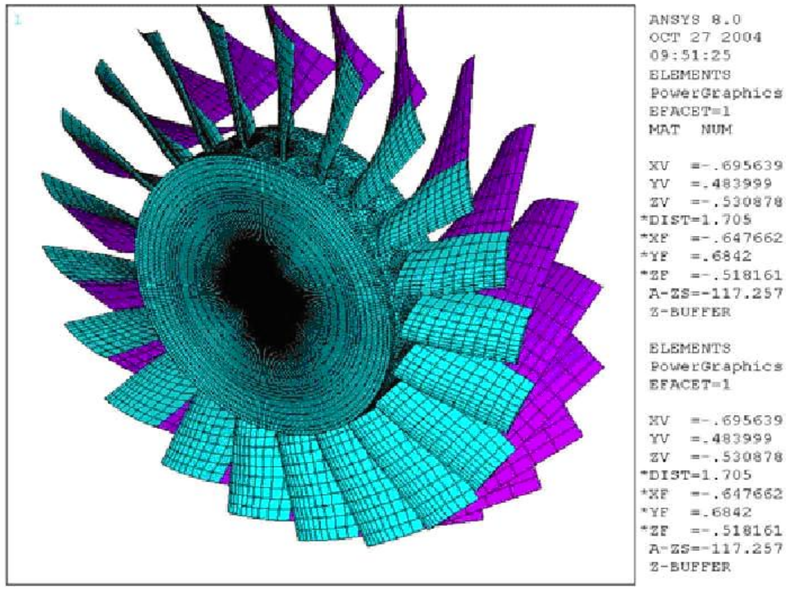

Figure 2: **Fluid dynamics model used for the fan blade analysis. The indigo colored mesh is the wake model**

The following flow conditions have been analyzed for all models:

Reference Pressure = 74550 Pa
Density = 1.2 kg/m3
Angular Velocity = 890 - 920 rpm
Cp/Cv = 1.4
Blade angle of attack 63°

The pressure oscillation load that the fan is subjected to in this work was calculated with the ANSYS/CFX program. The CFX work is not presented in this paper, it was performed by a researcher at Cranfield University in UK, both the guide vanes upstream the fan and the fan itself was included the modelling. A velocity contour CFX plot through the model is seen in figure 3 a) and the time history of this pressure field that a fan blade sees is shown in Figure 3b) below.

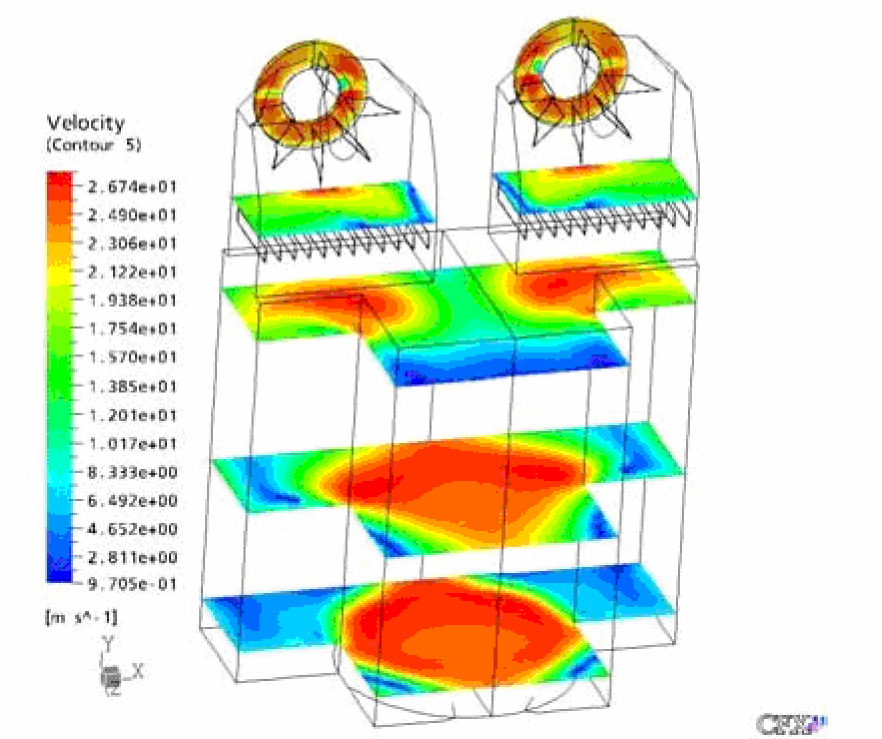

Figure 3a **CFX-generated velocity contours**

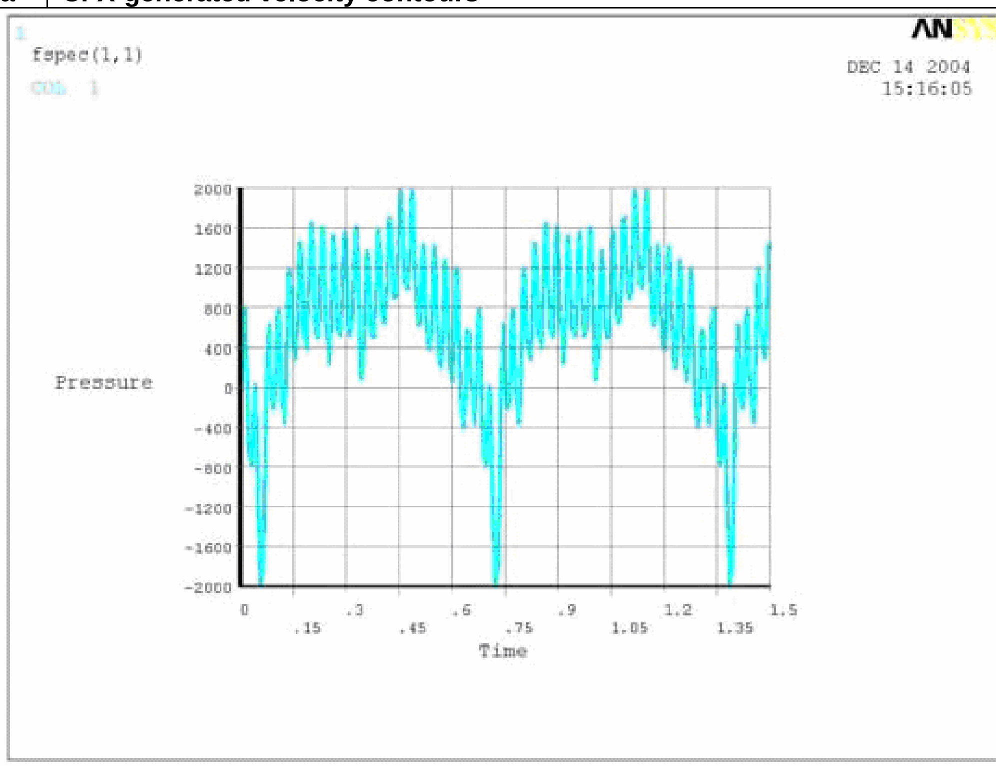

Figure 3b **CFX calculated pressure oscillations at the fan blade at 890 rpm.**

A FFT (Fast Fourier Transform) analysis of the time history in figure 3 gave the pressure amplitude diagram found in figure 4 below. The static part of the pressure was subtracted from the pressure in figure 3 when deriving the dynamic pressure found in figure 4. The static pressure was used as the reference pressure in the fluid dynamic description of the system.

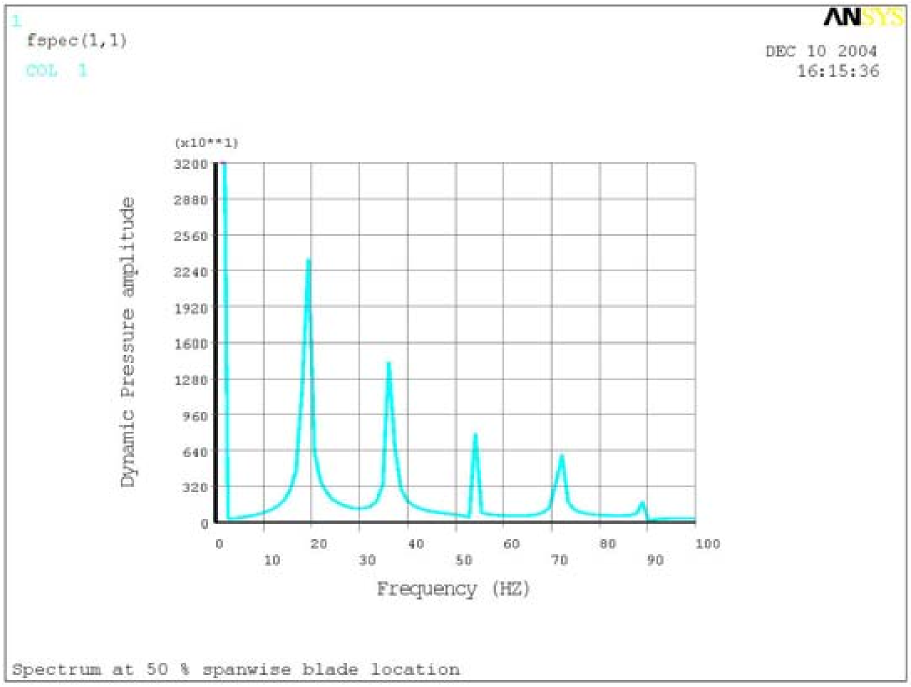

Figure 4	Spectrum of the pressure time history presented in Figure 3b

2.2.3 Aeroelastic Analysis

The linearized fluid dynamics model used was a boundary element method (BEM) model of the fan blade. The model used is shown in Figure 2.

The simulations were performed such that a series of structural modal analysis was performed on each model and a set of modes was selected to be included in a subsequent aeroelastic stability and response analysis.

The aeroelastic analysis was performed on two blade models, one with the original blade geometry and the second with a model including the dirt build-up. In the types of aeroelastic analysis performed in this work we are considering the system behavior in the entire function envelope. Questions such as “are there any flow conditions at which vibration problems may occur” may be easily, reliably, and reliably answered as presented in this paper. In a dynamic aeroelastic analysis the aero-/fuid-dynamics, inertia, and elastic forces interact in one single equation system as illustrated by the picture in Figure 5.

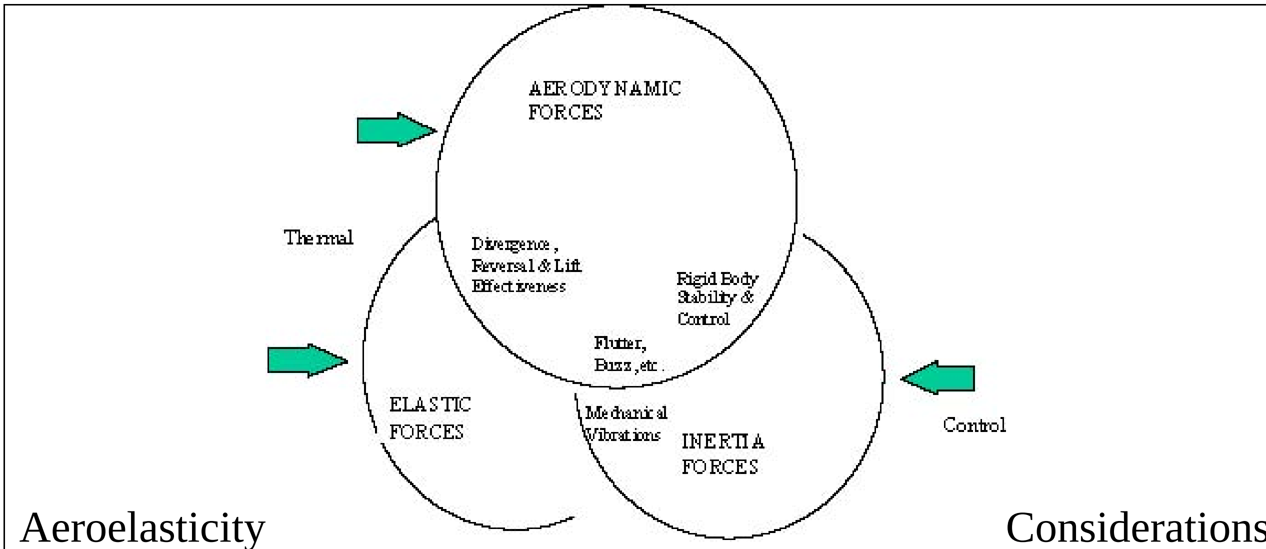

Figure 5 **Physical forces that interact in an aeroelastic analysis and the type of phenomena that may appear.**

3 RESULTS

The aeroelastic stability and response analysis result are presented below The results are presented first for the original model without the dirt build-up layer and then the results for the case with dirt build-up is presented.

The steady flow velocity field around which stability and response of the system was analysed is seen in figure 6.

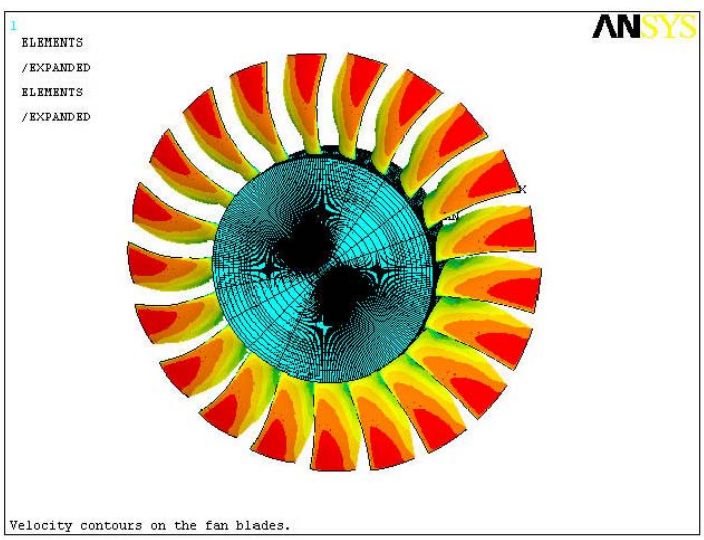

Figure 6 **Steady flow velocity contours on the blade surfaces.**

3.1 Aeroelastic Stability Analysis

3.1.1 Analysis of model with original blade geometry:

An aeroelastic eigenvalue are mathematically complex and include an eigenfrequency and a damping requirement value for a mode to be stable. Figure 7 shows the real part of the aeroelastic eigenvalues, - the frequency as a function of flow velocity - from the analysis with the fan blade model. Figure 8 shows the imaginary part of the aeroelastic eigenvalues, the damping requirement for neutral stability as a function of flow velocity, from the analysis with the fan blade model.

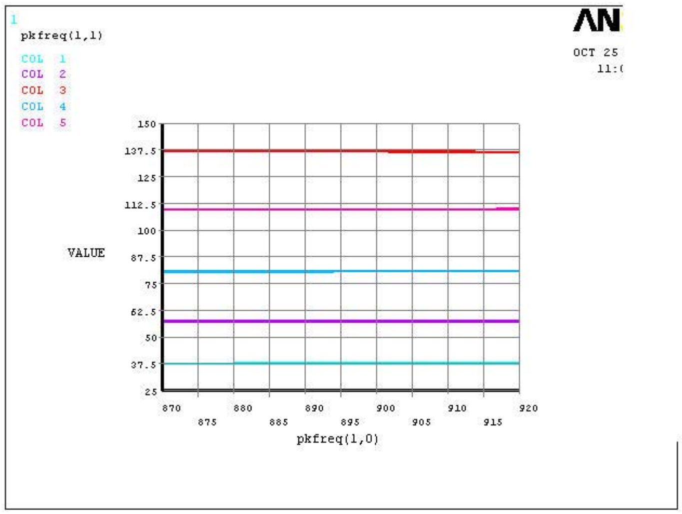

Figure 7 **Aeroelastic mode frequencies a.f.o. flow velocity.**

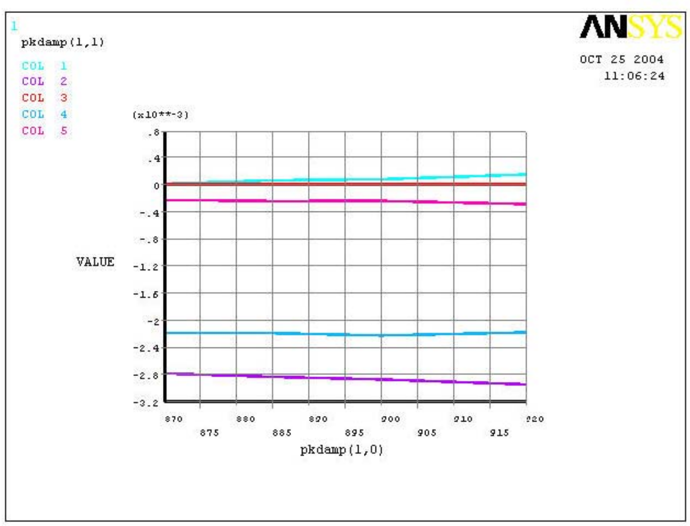

Figure 8 **Damping requirements for neutral stability for the 5 first modes in table 1.**

Figure 7 shows that the aeroelastic modal frequencies are more or less constant within the studied velocity range. Figure 8 show that none of the modes require significant amount of damping for them to be stable. More specifically, only the mode related to the fan axel torsion show positive damping

requirement (these type of modes have not been accurately modelled in this work, due to that the axle system has not been modelled). All other modes show negative damping a requirement, which indicates stable modes.
It should be noted that even if both the structural dynamics and the fluid dynamics is assumed to be linear, the coupled aeroelastic eigenvalue system is non-linear. Due to the non-linear nature of the problem each eigenvalue need to be converged using an iterative procedure.
Table 1 below shows the aeroelastic frequencies and damping requirements for the 5 first modes included in the analysis at 900 rpm.

Mode Number	Frequency Hz)	Damping Requirement	Mode Type
1	37.75	0.7828E-4	Rotor axle torsion
2	57.80	-0.2871E-2	Bending
3	80.86	-0.2189E-2	Radial
4	109.7	-0.2402E-3	Cord dir. Bending
5	136.5	-0.1253E-6	Torsion
Table 1	**Aeroelastic eigenvalues for fan blade model.**		

3.1.2 Analysis of model with blade geometry including dirt build-up

Figure 9 shows the real part of the aeroelastic eigenvalues, the frequency as a function of flow velocity, from the analysis with the fan blade model. Figure 10 shows the imaginary part of the aeroelastic eigenvalues. This is the damping requirement for neutral stability as a function of flow velocity, from the analysis with the fan blade model.

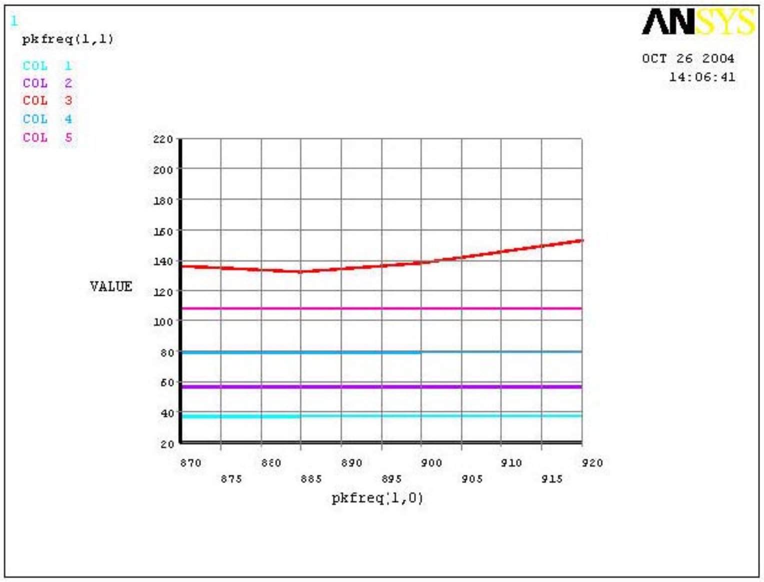

Figure 9 **Aeroelastic mode frequencies a.f.o. flow velocity (dirt build-up accounted for)**

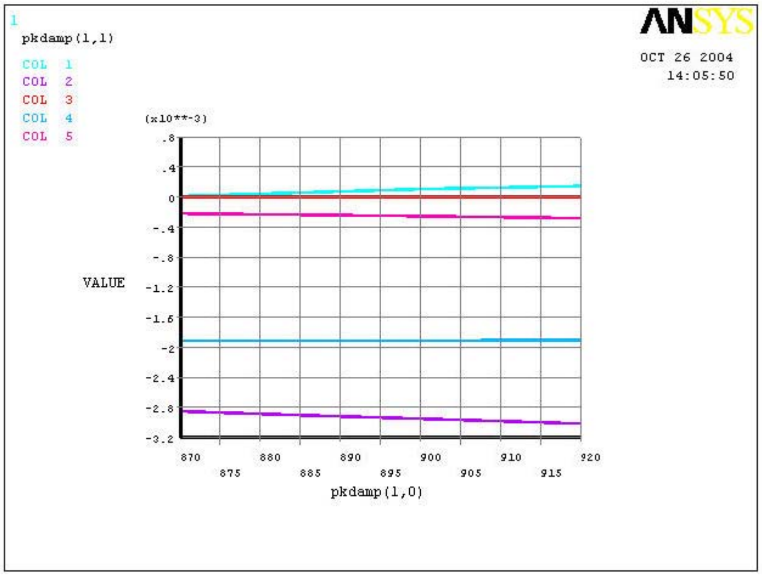

Figure 10	Damping requirements for neutral stability (fan with dirt build-up)

Figure 9 and 10 show results for the same modes as presented in figure 7 and 8 for the original blade. Figure 9 show that most aeroelastic modes are constant as a function of frequency, and that the first torsion mode frequency starts to show some frequency dependency. Figure 10 show that even for the model with dirt build-up included, none of the modes require significant amount of damping for them to be stable. More specifically, still only the mode related to the fan axel torsion show small positive damping requirement (these type of modes have not been accurately modelled in this work). All other modes show negative damping a requirement, which indicates stable modes.

Table 2 below shows the aeroelastic frequencies and damping requirements for the 7 first modes included in the analysis for the fan at 900 rpm.

Mode Number	Frequency (Hz)	Damping Requirements	Mode Type
1	37.47	0.1072E-3	Rotor axel torsion
2	56.01	-0.2949E-2	Bending
3	79.39	-0.1910E-2	Radial
4	107.9	-0.2524E-3	Cord dir. bending
5	108.1	-0.2617E-6	Cord dir. bending
6	128.9	-0.1947E-6	Torsion
7	138.4	-0.7449E-8	Torsion

Table 2 **Aeroelastic eigenvalues for fan blade model including dirt build-up**

The aeroelastic analysis indicates that the dirt build-up on the fan blade does not have any significant negative impact on the aeroelastic characteristics of the system. This conclusion is valid in the operational range that has been investigated in the performed study.

Consequently the pressure oscillations in the flow field will not produce increasing amplitude vibration due to energy picked up by unstable aeroelastic modes. On the other hand, there is significant fluid dynamic forcing in the 50-60 Hz range. In the view of this and that the dirt build-up reduces the bending 57.8 Hz frequency in table 1 to 56.0 Hz in table 2 thus moves the mode frequency in the direction of the frequencies of the forcing functions, this could (and most likely will) of course increase the vibration amplitudes of the blades.

3.2 Aeroelastic response analysis of fan blade model

3.2.1 Analysis of model with original (clean) blade geometry:

By exciting the model with the frequency spectrum presented in figure 4 and summing the contributions using a SRSS (Square Root of Sum of the Squares) method the stress fields shown in Figures 11 and 12 were calculated. Figure 11 shows the Real part of the results and figure 12 shows the imaginary part of the stress field.

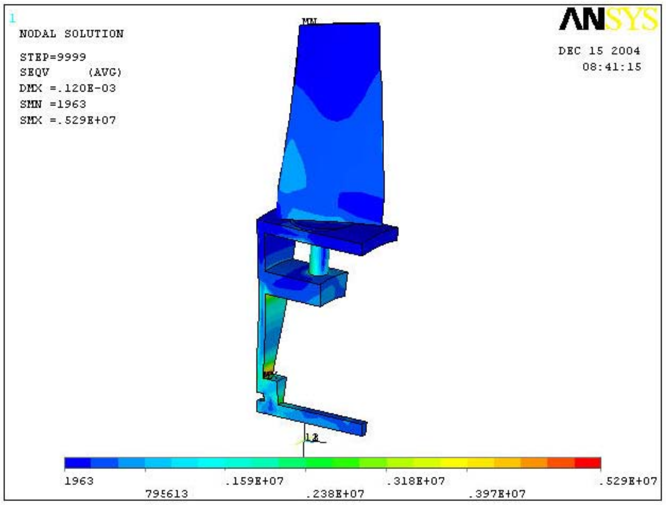

Figure 11	Real part of stress field (clean blade)

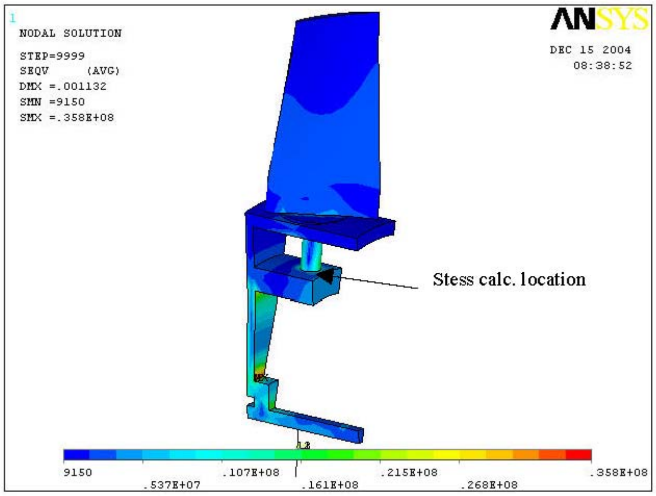

Figure 12	Imaginary part of stress field (clean blade)

Due to the dynamic nature of the model it did not give accurate stress levels at the root of the fan blade shaft. A summation of forces and moments in the location of interest was done and then the absolute bending stress in the shaft was calculated. This procedure gave an absolute value of bending stress amplitude of 19.4 MPa in the location indicated in figure 12. The stress level that were calculated for the blade is close to the 20 MPa experimentally measured level for the clean blade fan and below the allowed stress level for the material of about 27.4 MPa.

3.2.2 Analysis on model with blade geometry including dirt build-up

By exciting the model with the frequency spectrum presented in figure 4 and summing the contribution using a SRSS (Square Root of Sum of the Squares) method the stress fields shown in figure 13 and 14 were calculated. Figure 13 show the real part of the results and figure 14 shows the imaginary part of the stress field.

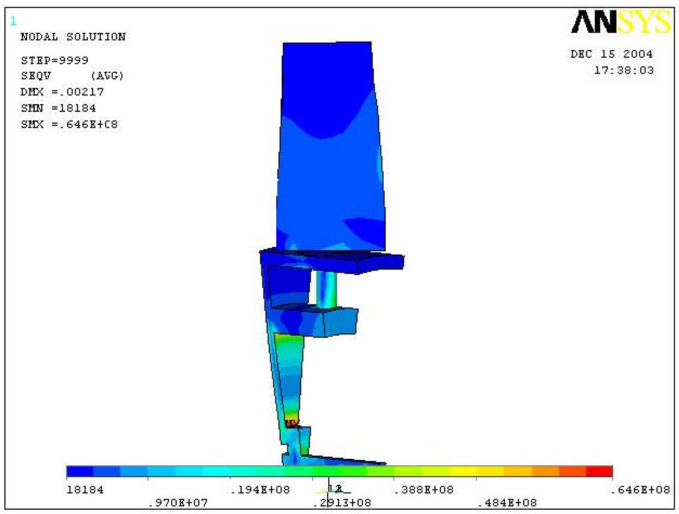

Figure 13	Real part of stress field (dirt build-up)

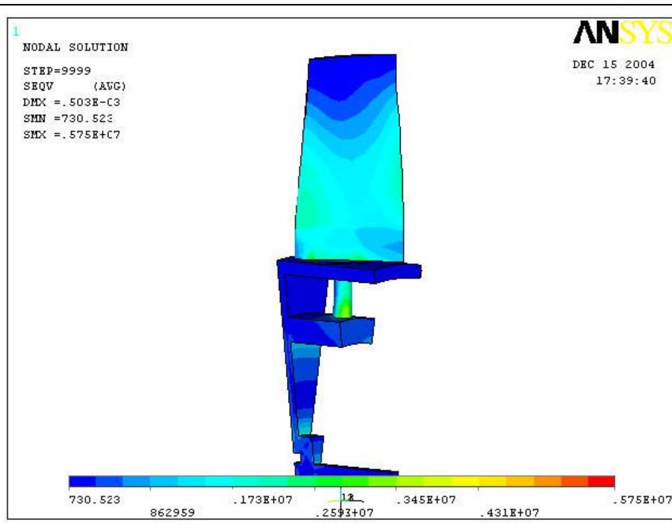

Figure 14	Imaginary part of stress field (dirt build-up)

Due to the dynamic nature of the model (a dynamic model has a coarser mesh and geometry definition then required when studying details in the stress field) it did not give accurate stress levels at the root of the fan blade shaft. A summation of forces and moments in the location of interest was done and then the absolute bending stress in the shaft was calculated. This procedure gave an absolute value of bending stress of about 32.0 MPa in the location indicated in figure 12.
As noticed, the results presented above indicate that the decrease in first aeroelastic fan blade bending mode frequency discussed in the stability analysis part of this work does increase the stress level in the fan blade shaft. This is due to that the bending mode frequency has been moved in the direction of the excitation frequencies with high amplitudes (found in the FFT analysis results, see figure 4).
The stress levels that were calculated for the blade with dirt build-up was hence above the allowed stress level for the material of about 27.4 MPa.
The possibility of a blade failing increases with the increase of stress level in the shaft due to the change in dynamic properties of the fan blade system caused by it the dirt build-up.

4 CONCLUSIONS

The performed aeroelastic stability analysis showed no indications that the fan system had any aeroelastic modes with unstable behavior. The performed analysis also indicates that the dirt build-up on the blades in operation does not have a negative impact on the fans aeroelastic characteristics.

The dirt build-up on the blade does however move the lowest blade bending motion mode frequencies into a frequency range of higher amplitude fluid dynamic pressure oscillations. This is a common cause of increasing amplitude vibrations in systems.
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The performed aeroelastic response analysis and experimental measurements have shown that the stress level in the clean blade case is below the allowed stress level for the material in the fan blade shaft, so there should be no risk for fatigue failure.

It was not possible to perform measurements on the blades with dirt build-up, due to that than fans with the dirt built-up had fail in fatigue, but considering the good agreement between experiments and calculations for the clean blade case, it was possible to rely on analysis for the results. The analysis with the model including the blade with dirt build-up showed an increase of blade shaft stress level. The stress level calculated was above the allowed level for the material, and will increase the risk of fatigue failure. This was most likely the cause for the fan to have a fatigue failure prior to the simulations given above.