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MACHINE FOUNDATION DESIGN: EXPERIMENTAL AND ANALYTICAL SOIL STRUCTURE INTERACTION

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ABSTRACT

A comprehensive dynamic testing program has been undertaken to establish the dynamic characteristics of existing fan foundations in order to evaluate their suitability to support new variable speed fans. The dynamic testing program encompassed two sets of tests: pull tests and steady-state vibration test. In addition, dynamic soil-structure interaction analyses were performed to evaluate the response of the foundation to the dynamic operating loads of the new fans.

INTRODUCTION

Many gas/coal fired energy plants are undergoing upgrades that include installing gas cleaning equipment on their boilers that will necessitate higher pressure requirements for the induced draft (ID) fans in employed in the operation. Thus, these fans are to be retrofitted/replaced to meet the new operation requirements. As part of the upgrade, the ID fans in operation at an existing plant have to be replaced by variable speed fans. The new variable speed fans would be situated on top of the foundations of the existing fans. Hence, there is a need to assess the suitability of the fans and motor foundations in existing configurations to support the new equipment, and to evaluate the need for any retrofitting of the foundations.

In order to perform a thorough and efficient assessment of the foundation suitability, two steps that involve physical and analytical aspects of soil-structure interaction (SSI) have to be conducted. Often, the first step in this assessment is to conduct vibration response tests on the existing foundations to establish their dynamic response characteristics, including evaluating the dynamic properties of the supporting foundation soil and the foundation stiffness and damping constants. The second step in the assessment involves analytical soil-structure interaction analysis in order to: evaluate the response of the existing foundation to the dynamic loads stemming from the normal operating conditions of the new equipment; and devising retrofitting scheme in case the dynamic performance of the existing foundation is found to be unsatisfactory.

Two types of pile dynamic tests can be conducted: forced (steady state) vibration test and free vibration pull out (plucking) test. In the forced vibration test, an exciter is mounted on top of the foundation to generate a harmonic force of variable frequency. The foundation response at different frequencies is measured using either vibration pickups or accelerometers. Such tests were conducted for both vertical and horizontal vibrations by many researchers. Gle and Woods (1984) conducted steady state dynamic lateral load tests on piles and compared their observations with findings from analytical solutions. Puri and Prakash (1992) conducted full-scale vibration tests on a 17 m single driven pile. They compared the observed responses with those obtained from the plane strain solutions attributed to Novak (1974). Blaney et al (1987) conducted large amplitude, but low frequency, vertical vibration tests on a full-scale pile group installed in overconsolidated clay.

Sy and Siu (1992) performed a field study involving forced vertical vibration testing of a foundation. They used an electromagnetic shaker to generate random broadband and sinusoidal excitations to excite the foundation along the vertical, horizontal, and rocking modes. The measured response frequency functions from the subsequent sinusoidal frequency sweep tests were compared to the theoretical results calculated based on a plane strain approximate solutions and measured in situ shear were wave velocity data.

In the plucking (pull out) tests, free vibration of the foundation is triggered by an initial deflection or impulse and the response is recorded and analyzed. Chandrasekaran et al.

(1975) conducted free vibration tests of pile foundation. Zhu et al. (1992) executed plucking field test to determine the dynamic characteristics of pile foundations. The results obtained from the field test data were used to establish theoretical solutions for the dynamic stiffness and damping of the piled foundation.

OBJECTIVES AND SCOPE OF WORK

This paper presents the comparison between the full-scale vertical and horizontal vibration responses of large ID fan foundations, which is considered necessary to qualify and quantify the dynamic performance of these foundations to the dynamic operating loads of new fans. Two types of testing programs are described herein. In the first testing program, quadratic type harmonic load tests were conducted by employing the existing fan to produce force amplitudes applied within a frequency range that covered the resonance frequencies of the tested foundation system. In the second testing program, a plucking test was conducted to establish the dynamic characteristics of the existing foundation.

The dynamic properties of the subsurface soil adjacent to the test foundations were determined considering the information furnished in the geotechnical reports corresponding to the subject foundations. The paper compares the field observations against the theoretical predictions using the program DYNA6 (El Naggar et al, 2011) and provides an insight into the role of pile-soil interaction in theoretically matching the field observations.

The foundation vibration velocity, displacement amplitude and phase measurements were carried out with the objective to identify any resonant frequencies of the foundations, and to provide vibration data to help validate/calibrate the dynamic analysis models for the proposed upgrade. To achieve these objectives, vertical and horizontal vibration data were collected at different locations and elevations on the surface of subject foundations.

Two different tests were performed on each foundation:

- The pull test which allows us to determine the frequency resonances for the lower vibration modes of the complete structure including foundations, pedestals, motors, fans, and air ducts attached to the fans.
- The standard ramping-up and coasting-down test to establish natural resonant frequencies and damping factors of the fans' foundations including pedestals and motor-fan assemblies.

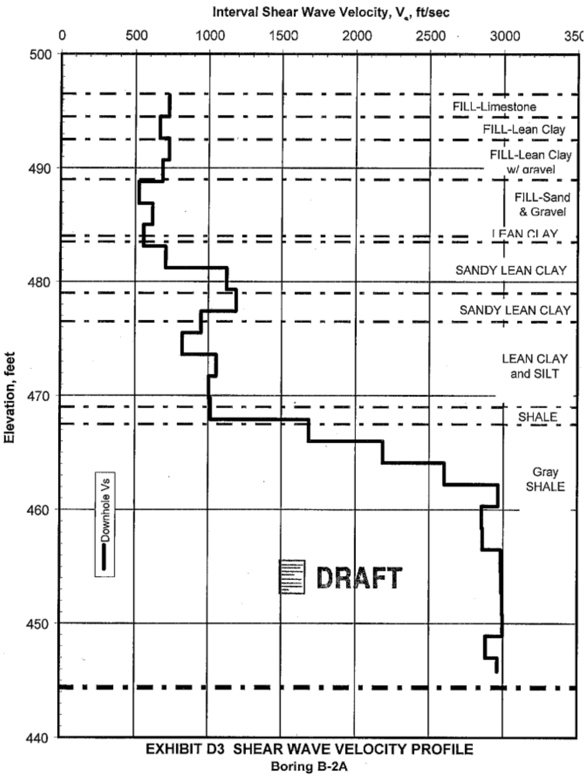
Data was collected using consecutive pull-out and ramping-up and coasting-down tests at selected measurement locations. The pull-out tests were performed by application of the impact elastic rebound force after the breaking of a rupture member. The Ramping/Costing tests were accomplished by changing the working frequencies during spinning up and shutting down modes of operation of the fans. The working frequencies of both fans were increased from almost 0 RPM to the maximum achievable working frequency of around 600 RPM.

SOIL CONDITIONS

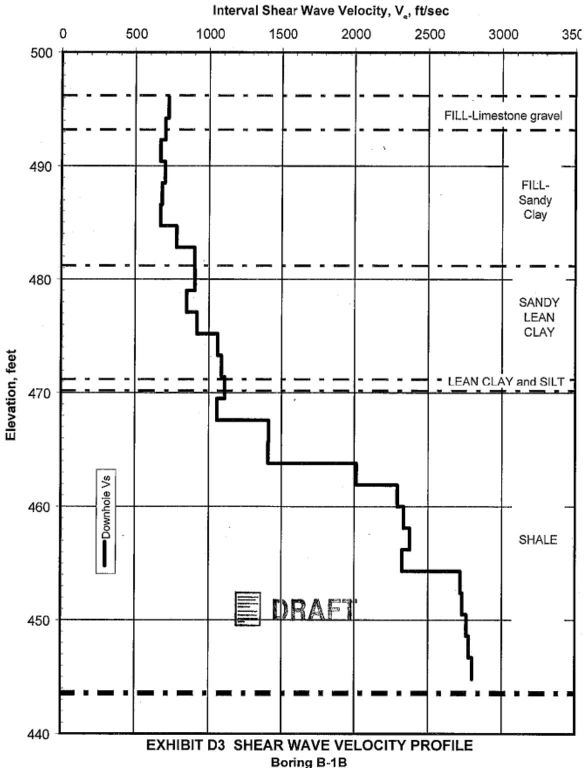
In order to establish the dynamic soil properties of the soil profile at the site of the subject foundations, two seismic down-hole tests were conducted near the foundations. The site soil profile established from these tests is composed of approximately 20 ft of layers of variable fill, underlain by layers of sandy clay and lean clay and silt. These soil deposits are underlain by shale that appears in the borehole at an elevation of about 40ft below existing ground level as shown in Figures 1. The measured soil shear wave velocity profiles are also provided in Figure 1.

A careful review of the geotechnical report and the construction drawings for the existing fans foundations revealed that the foundations are founded on backfill of unknown quality underlain by native overconsolidated Paleozoic sediments (shale), referred to as bedrock. The existing foundation details show that the thickness of the backfill underneath the foundation is 12-14 ft. There was considerable uncertainty about the stiffness (i.e shear modulus) of the backfill and the relative stiffness between the backfill and the underlying much stiffer shale. The presence of this much stiffer material at a shallow depth relative to the width of the foundation affects the dynamic characteristics of the foundation.

The commonly used halfspace model (e.g. Veletsos and Verbic, 1973; Veletsos and Nair, 1974) may not be appropriate for the calculation of the stiffness and damping values of the foundation in such conditions. In addition, inspecting the existing foundation details revealed that the foundation has some voids filled with fill of unknown quality and the existence of retaining wall "bins" with embedment on one side only. These unusual foundation conditions necessitate evaluating the natural frequency of the existing foundation from dynamic testing to help establish the proper analytical model that can be used for calculating the response of the foundation to the new ID Fan operating loads and the design of its retrofit if necessary.



(a)



(b)

Figure 1 Soil layers and soil shear wave velocity profile from Seismic down-hole testing, a) B-2A; and b) B-1B

MEASUREMENT AND TEST PROCEDURE

Vibration data was collected at three locations on the fans' concrete foundations as shown on Figure 3. The data was collected using velocity sensors installed on the surface of the concrete foundation using a fast setting epoxy compound. The selected locations were: the ground level in line with the center of gravity (CG) of whole structure; the fan bearings; and adjacent to the support feet of the fan motors. These locations are summarized in Tables 1A and 1B and are shown schematically on Figures 2 a and b.

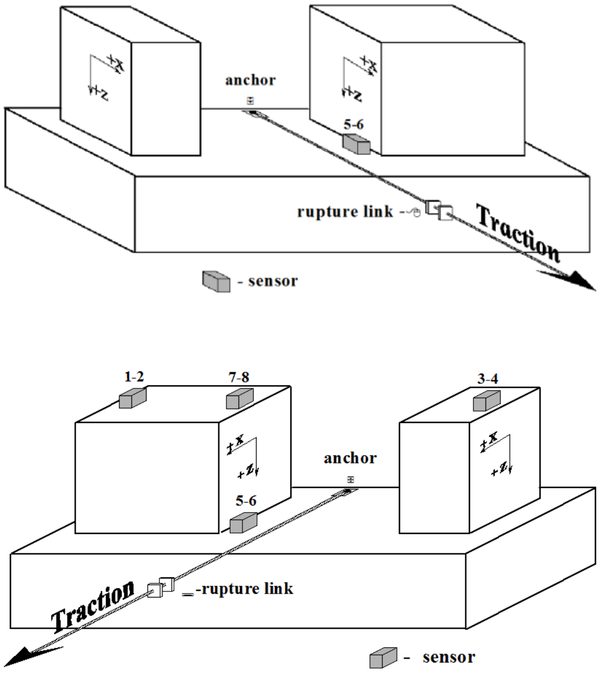
Table 1A. FAN 1-A Sensors locations and orientations

Channel #	Orientation	Location
1-4	-	Not connected
5	Vertical	Fan Concrete Base, In line with CG
6	Horizontal	Fan Concrete Base, In line with CG
7-8	-	Not connected

Table 1B. FAN 1-B Sensors locations and orientations

Channel #	Orientation	Location
1	Vertical	Motor Bearing, Non Drive End
2	Horizontal	Motor Bearing, Non Drive End
3	Vertical	Fan Bearing, Non Drive End
4	Horizontal	Fan Bearing, Non Drive End
5	Vertical	Fan Concrete Base, In line with CG
6	Horizontal	Fan Concrete Base, In line with CG
7	Vertical	Motor-Fan Bearing, Drive End
8	Horizontal	Motor-Fan Bearing, Drive End

Figure 2 shows the location and orientations of the two-component velocity sensors. The channel ID numbers are shown above the sensors (same for both pull and Ramping/Coasting tests).



(a)

(b)

Figure 2 Locations and orientation of the velocity sensors on, a) Fan 1-A; b) Fan 1-B.

Test Equipment

The waveforms for both the Pull test and the standard Ramping-Up and Coasting-Down tests were collected using two-component velocity sensors and a multichannel data acquisition system connected to a notebook computer.

Sensors Installation

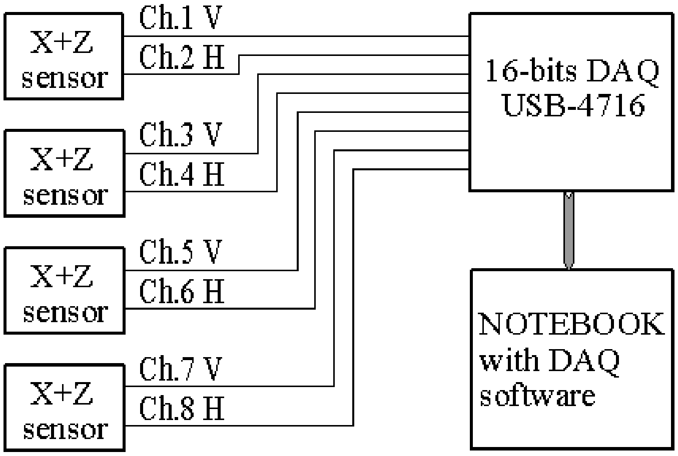
All sensors were bound to the thoroughly cleaned concrete surface using a compound of epoxy resin. An additional support retained the cable in a stable position in order to eliminate possible cable vibrations close to the sensor. An example is shown in Figure 2.

Figure 3. A sensor installed at the driving end of Fan 1-B

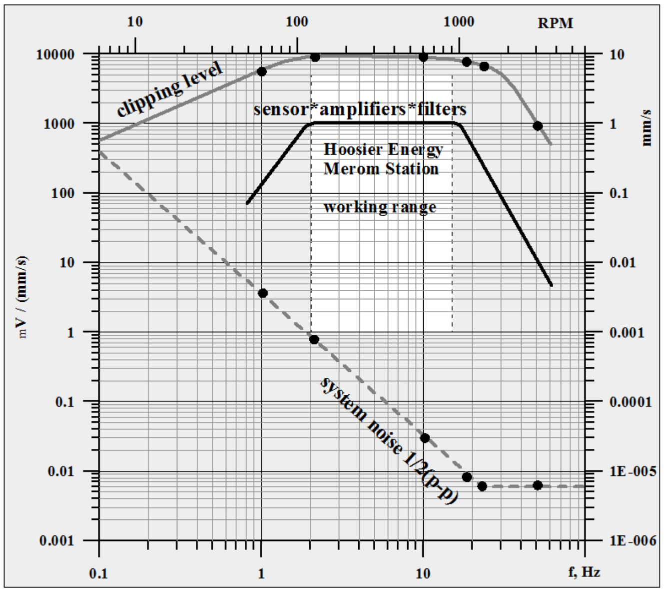
All sensors were connected to the data acquisition system using shielded cables. The shielding of each cable was connected to a common grounding point at the data acquisition system side to ensure the electromagnetic compatibility (EMC) with electromagnetic fields around the motors and because of high intensity electromagnetic disturbance present in the power generation station. This measure was used to keep all those side effects under reasonable control, to reduce the electrical induced noise and to enhance the immunity of the data acquisition system.

Data Acquisition System

Measurements were acquired and analyzed using a multichannel data acquisition and analysis system using VBA and C++ software. A simplified block-diagram of data acquisition system is shown in Figure 4a, on which, V and H denote vertical and horizontal orientations of the sensors. The data acquisition system includes four two-component velocity sensors, six channel analog to digital converter using USB-DAQ-4716, USB stack and notebook computer with data acquisition and analysis software. The system recorded eight velocity channels at a rate of 200 Hz or samples/second/channel, allowing the analysis of vibration spectra up to 100 Hz. The sensitivity chart of the data acquisition system, and its noise and clipping levels are shown in Figure 4b.



(a)



(b)

Figure 4. a) Data acquisition system with eight two-component velocity sensors multi-channel analog to digital converter ; b) sensitivity chart of the data acquisition system

PULL TEST

Background

The pull test (impulse test) is used to establish the frequency resonances of the lower vibration modes of the complete multistory residential and industrial buildings, piles and pile foundations, and other tall or slender structures. A pull force is applied to an anchor point at the top level of the structure. The pull is suddenly released after breaking a rupture link, which forces the whole structure into free vibration. The movement mainly involves the first vibration mode in a case of a symmetric structure. Usually, the first vibration mode consists of a free coupled horizontal-rocking of the structure. In case of an asymmetric structure, the second and higher vibration modes appear. In addition, torsional movements may contribute to the free vibrations.

Application of Pull Test for Machine Foundation

The pull test is not commonly used in the case of a shallow foundation with pedestal and machinery on top. In the current case, the test was adapted in order to reduce the rocking vibrations and to establish the horizontal component of the vibration with higher resonant frequency at the foundation surface. The traction (pull) force used in testing was applied to an anchor attached to foundation surface in such a way that the pulling cable passed close to the center of gravity of the foundation-machinery structure (see Figures 2 and 5).

Pull Test Implementation

The arrangement for the Pull test is shown schematically in Figure 5. The test arrangement was executed and the test was operated by the staff of Sterling Boiler and Mechanical Inc. The rupture link and the anchor point are shown on Figure 6.

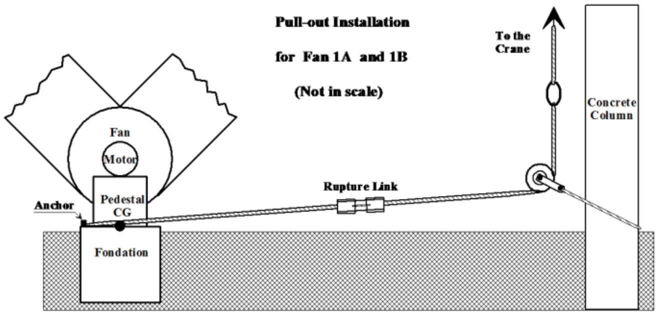
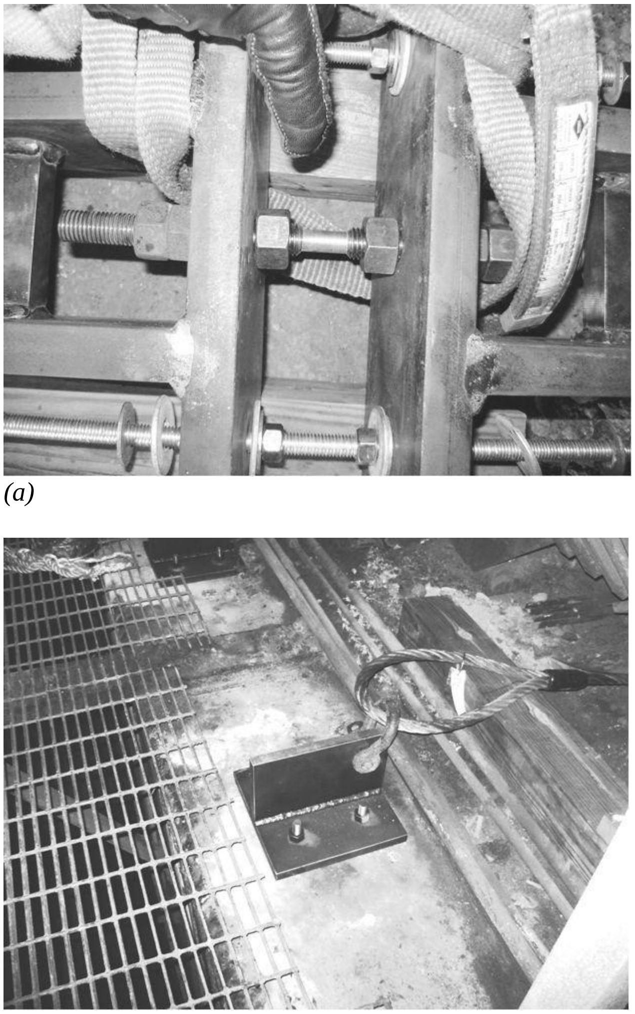


Figure 5. A sketch of the Pull test installation



(a)

(b)

Figure 6. a) rupture link (breaking rod connected between two jaws); b) anchor connection at the end of the pulling cable.

The pulling force used in the test varied between 15 1nd 25 kips. It was exerted by a hoist crane and redirected horizontally using 1 ½”steel cables and a pulley (Figure 5). The rupture link (Figure 6a) was connected in the middle of the horizontal portion of the pulling cable, dividing it into two segments. The free jumping of the jaws of the rupture link was limited by two threaded dowels with nuts located symmetrically with respect to the breaking element. The dead end of the cable is attached to the foundation surface by an anchor shown in Figure 6b.

Only the pulling force acts on the structure before the breaking of the rupture link. This force bends the structure in its direction and causes accumulation of potential elastic energy before breaking. Two main forces act on the released structure after the breaking of the rupture element. The elastic rebound force moves the middle part of structure into the opposite direction of the previously applied traction. The reactive inertial force opposes this movement at the upper part of the structure trying to keep it in rest. The bottom part of the structure is embedded in the ground and exhibits small movement after the breaking compared to the over-ground parts. The movements of different parts of the structure are illustrated in Figure 7.

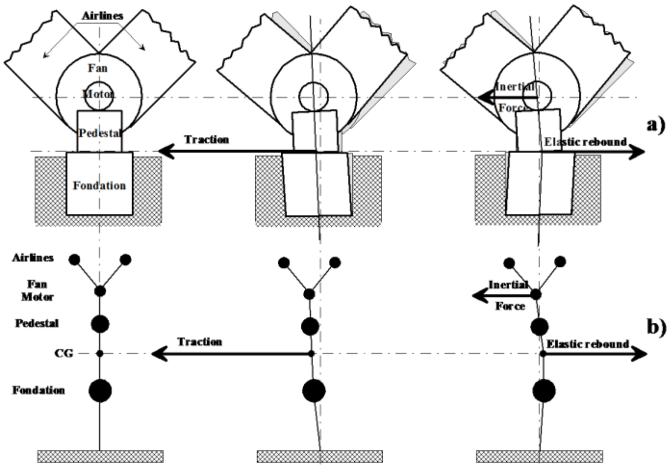


Figure 7. a) Unloaded pulled-horizontally and released structure; b) lumped mass model.

The existence of the inertial force causes a time delay before the upper part of the structure is involved in a horizontal movement in the direction of the elastic rebound. This time delay gives rise to a phase difference between the displacement of the middle and upper part of the structure. This effect predetermines the existence of the second vibration mode for the whole structure. On the other hand the released structure will reach the same position it had before being bent under the pulling force due to of the elasticity of the structure. The original shape can be restored if the free oscillations involve the first vibration mode of the structure.

The first two bending modes involved in the free oscillations are dominant. The movement is mainly in the horizontal direction with a small rocking component. Higher than second vibration modes will have very small part in the free oscillations of the whole structure because:

- The air lines (ductwork) have high flexibility and significantly lower mass compared to the sum of other parts;
- The bolted connections with gaskets between the airlines (ductwork) and the fans are flexible and absorbent, which causes significant damping and phase shifting of the vibrations at higher frequencies, which have reduced amplitudes.
- The high frequency vibrations have very small intensity because the energy after impact is distributed mainly between the first two vibration modes. The result is that the intensities of higher vibration modes are equal to or below the ambient noise level.

If there are higher resonances, they will be associated with the foundation structure (and supported machinery) without the ductwork. The pull test was implemented after Ramping-up and Coasting-Down tests for both fan foundations. These sequences did not allow for a probable disturbance in the embedment during the intense pulling test.

RAMPING-UP AND COASTING TESTS

The Ramping-up and Coasting-Down tests were performed on the fans excited forced vibrations in the whole structure with increasing and consecutively decreasing frequencies equal to the changing rotational speed. This method utilizes the vibrations due to admissible unbalances of the fan and motor rotors. The range of excitation frequency in this test is limited to the rotating machine speed.

Execution of the Pull and Ramping-up and Coasting Tests

Pull and Ramping/Coasting tests were performed initially on Fan 1-B with all sensors of the data acquisition system collecting velocity waveforms. After a preliminary analysis of the field data from Fan 1-B tests, a decision was made to reduce the number of working channels to channels #5 and #6, which recorded test vibrations close to the CG of the structures. At this test point we had minimal influence from the torsional and rocking reactions on the waveforms of interest. The field analysis of the ambient vibration noise after both tests on Fan 1-B did not show significant influence of the pulling force on the aftermath noise spectra. This result allowed conducting the Pull test before Ramping/Coasting test on Fan 1-A.

Fan 1B was ramped-up from 0 to 630 RPM smoothly. After the maximum speed of 630 rpm was reached, the fan speed was reduced immediately without keeping a steady maximum speed. Fan 1A was ramped-up from 0 to around 500 RPM smoothly. At 500 rpm, the airflow was changed, which affected the test conditions significantly. This effect is discussed later.

Test Sequence

The tests summarized in Table 2 were carried-out consecutively using arrangements shown in Figures 2 a and b as follows:

1. Ambient vibration noise recording with all eight channels at Fan 1-B;
2. Ramping-Up and Coasting-Down test with all eight channels recording, and running-up and shutting down Fan 1-B while Fan 1-A was shut down;
3. Pull test on Fan 1-B with all eight channels recording;
4. Ambient vibration noise recording at Fan 1-B with all eight channels.
5. Ambient vibration noise recording with channels #5 and #6 at Fan 1-A;
6. Pull test on Fan 1-A with channels #5 and #6 recording;
7. Ramping-Up and Coasting-Down test with channels #5 and #6 recording, and running-up and shutting down the Fan 1-A while Fan 1-B was shut down;
8. Ambient vibration noise recording at Fan 1-A.with channels #5 and #6.

A sample of the vibration measurements obtained from these tests is presented in Figures 8-18.

Table 2. Vibration tests arrangements

Data	Fan 1-A		Fan 1-B		Ramping-up / Coasting		P
set	TEST	Data	TEST	Data	Fan 1-A	Fan 1-B	Pull Force
Test #1	n/a	n/a	Noise	Ch. #1-8	Still	Still	n/a
Test #2	n/a	n/a	R/C	Ch. #1-8	Still	0-630-0 RPM	n/a
Test #3	n/a	n/a	POT	Ch. #1-8	Still	Impulse	26000 N
Test #4	n/a	n/a	Noise	Ch. #1-8	Still	Still	n/a
Test #5	Noise	Ch. #5-6	n/a	n/a	Still	Still	n/a
Test #6	P data	Ch. #5-6	n/a	n/a	Impulse	Still	17000 N
Test #7	R/C data	Ch. #5-6	n/a	n/a	0-540-0 RPM	Still	n/a
Test #8	Noise	Ch. #5-6	n/a	n/a	Still	Still	n/a

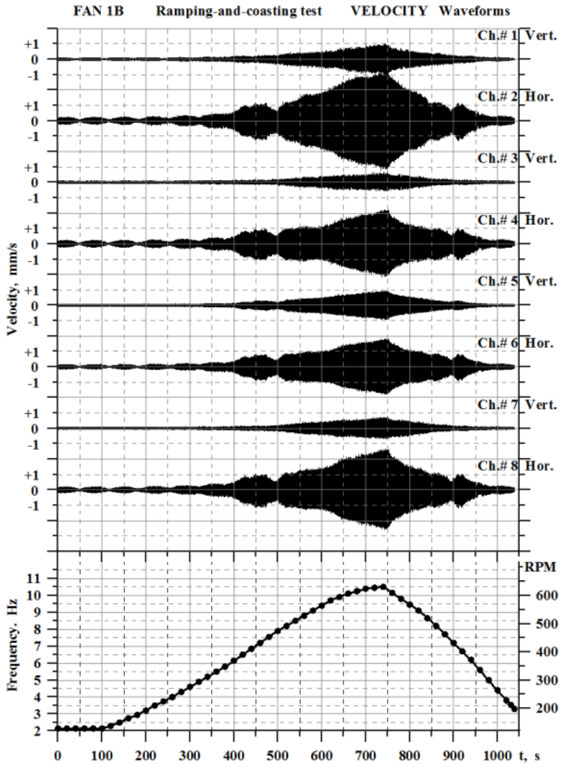


Figure 8. Test 2: Ramping/Coasting test of Fan 1-B - unfiltered velocity waveforms

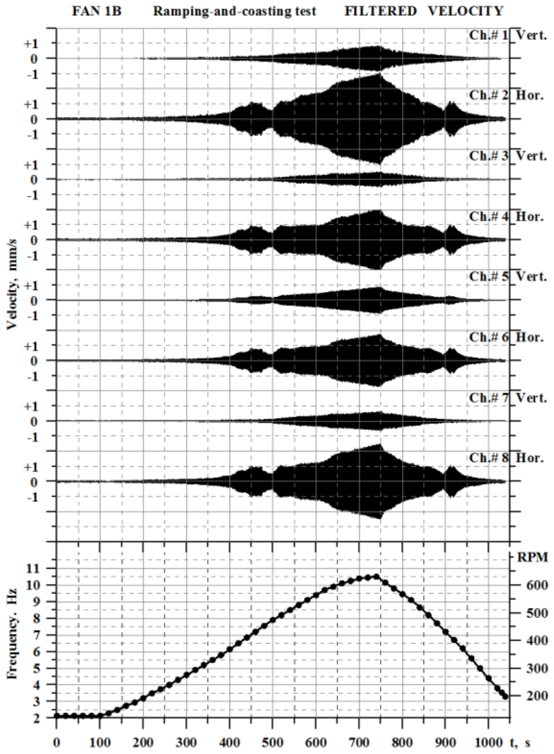


Figure 9. Ramping/Coasting test of Fan 1-B - filtered velocity waveforms

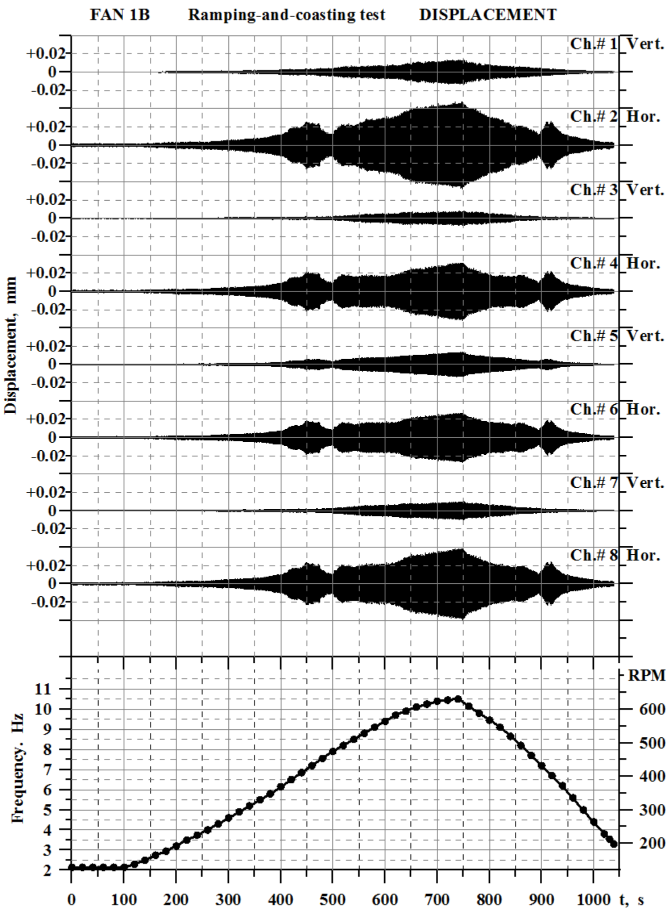


Figure 10. Ramping/Coasting test of Fan 1-B – displacement

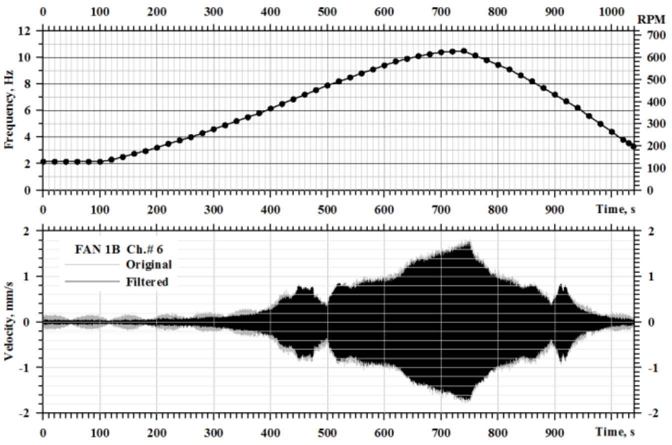


Figure 11. Ramping/Coasting test of Fan 1-B – Ch.#6 comparison of original and filtered waveforms

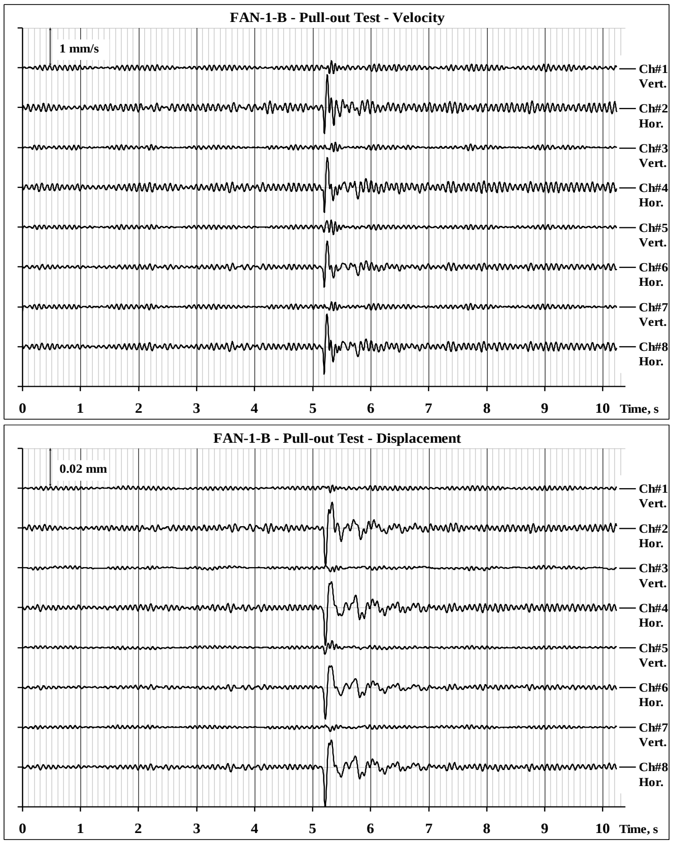
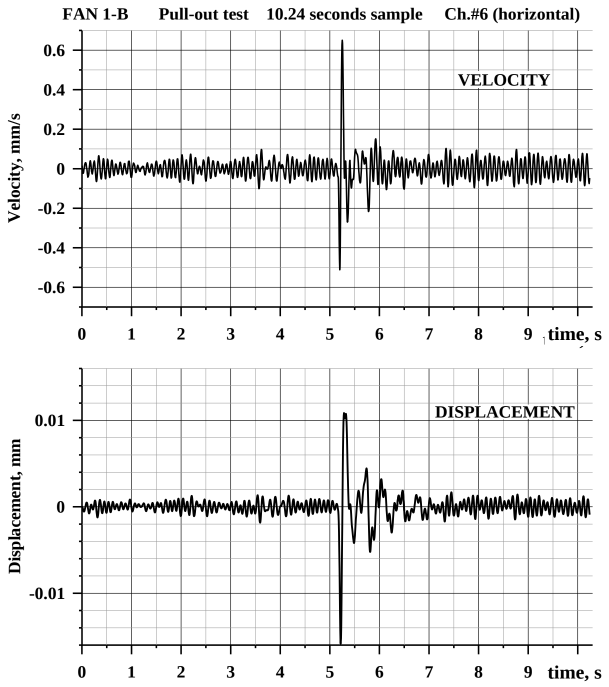
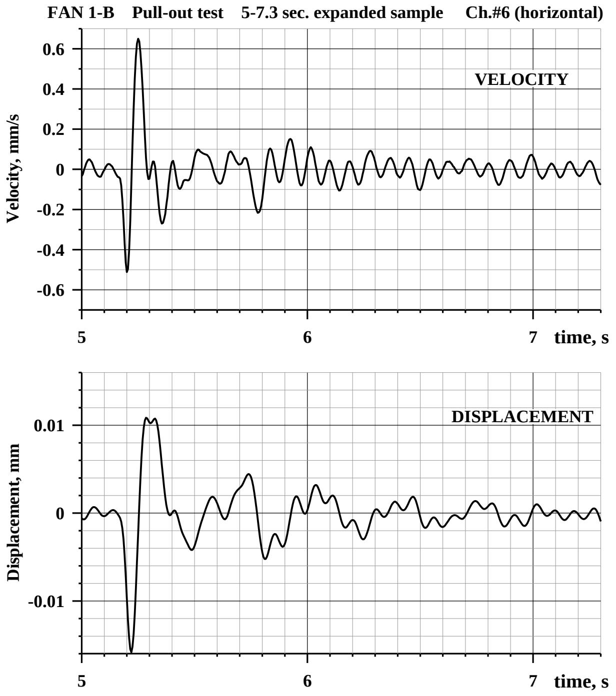


Figure 12. Pull test on Fan 1-B – velocity and displacement waveforms



(a)



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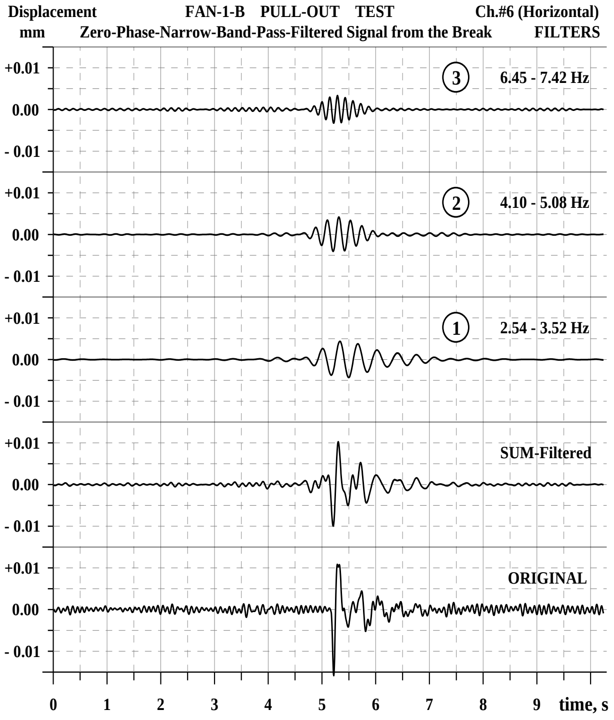
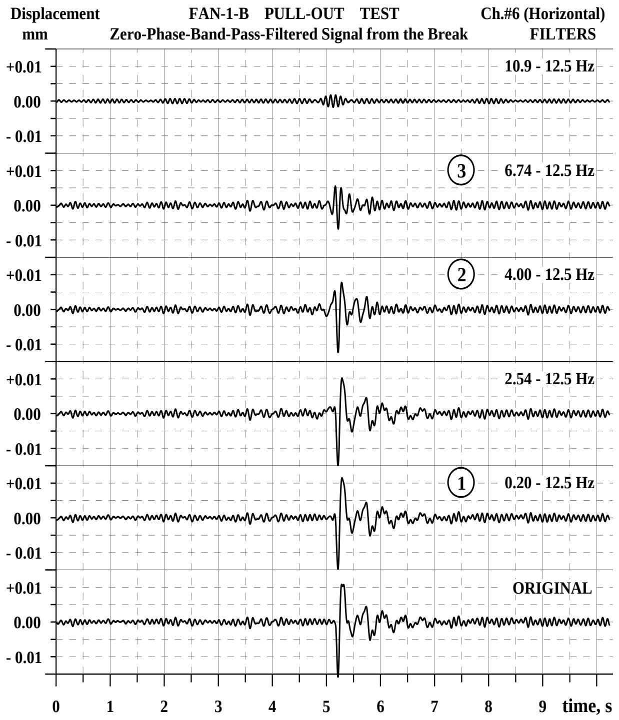


(c)



(d)

Figure 13 Pull test on Fan 1-B – Ch.#6 – velocity and displacement waveforms, a) 10 sec record; b) expanded 2-sec record; c) filtered by narrow band-pass filter; d) filtered by BP filters with constant high cutting frequency

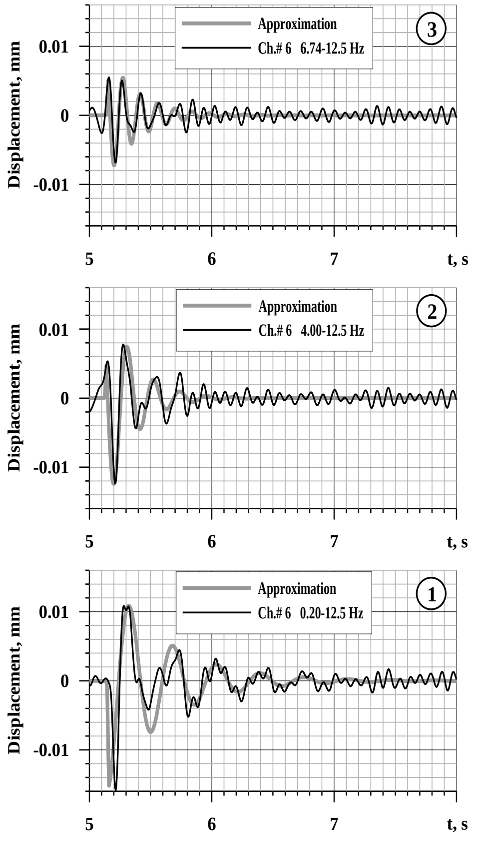
The SUM Filtered graph is obtained by summing the narrow BP filtered waveforms. It is free of high frequency oscillations and close to the shape of the ORIGINAL waveform. The filtered waveforms are used to determine the damped resonant frequencies, but cannot be used for calculation of the damping factor because of the “ringing effect” of the narrow band-pass filters. The 0.20 - 12.5 Hz filter is used to remove the trend and offset of the ORIGINAL waveform. It is close to the shape of the ORIGINAL waveform. This type of filtering ensures consecutive elimination of the resonances starting from the lowest frequency. The resulting waveforms can approximate all visible resonances with a suitable function, i.e.

$$x = X_0 e^{-D\omega_o t}\cos\left(\omega_D t + \varphi\right) \qquad (1)$$

where index “0” marks undamped and index “D”- damped frequencies f, ω and RPM.

φ is an operational phase angle, which is used to adjust the rising slope of the impact with the time. Figure 14 shows the approximated resonances with the function given in Eq. 1. Similar results and analyses were accomplished for Fan 1A, but not presented herein due to space limitations.

FAN 1-B Pull-Out Test Approximation of the Impact Reaction



f_o, Hz	7.11
ω_o, rad/s	44.7
RPM_o	427
φ, rad.	3.87
D	0.09
f_D, Hz	7.08
ω_D, rad/s	44.5
RPM_D	425

f_o, Hz	4.72
ω_o, rad/s	29.7
RPM_o	283
φ, rad.	4.28
D	0.16
f_D, Hz	4.66
ω_D, rad/s	29.3
RPM_D	280

f_o, Hz	2.82
ω_o, rad/s	17.7
RPM_o	169
φ, rad.	0.35
D	0.12
f_D, Hz	2.8
ω_D, rad/s	17.6
RPM_D	168

Figure 14. Analytical approximation of the resonances for the Pull test on Fan 1-B – Ch.#6

DISCUSSION OF RESULTS

Results from Pull tests for ID Fans 1A and 1B

The summary of the findings of the pull tests is provided in Table 3 in terms of observed natural frequencies and damping ratios. The system dynamic characteristics listed in Table 3 are extracted from the tables appended to Figure 14 (and same for Fan 1A). The frequencies $\mathbf{f_{0i}}$ are for undamped resonances. The errors for the frequencies are <5 %, and for the damping they are +/- 0.02.

The first observed natural frequency, $\mathbf{f_{01}}$, gives the frequency of the first vibration mode of the ductwork (airlines) (see Figure 11). This natural frequency can be observed from the records of the pull tests but can't be observed from the coast-down tests because it is very lightly excited (centrifugal load amplitude at 184 rpm is very small) and it has sufficient damping. The second observed natural frequency, $\mathbf{f_{02}}$, gives the frequency of the second vibration mode of the whole structure with ductwork (airlines) and is associated with the horizontal vibration mode. Again, this frequency could be observed from the pull test data, but not from the coast-down data because the centrifugal dynamic load is relatively small, and this mode is relatively damped. The third natural frequency, $\mathbf{f_{03}}$, gives the frequency of the first resonance of the structure without ductwork (airlines), which is associated with the horizontal vibration mode of the foundation structure. This natural frequency can be observed from the results of the coast-down tests because it is sufficiently excited and is relatively lightly damped.

Table 3 Natural frequencies and damping ratios established from Pull tests

Fan #	f_{01}, Hz	RPM	D_1	f_{02}, Hz	RPM	D_2	f_{03}, Hz	RPM	D_3
1A	3.07	184	0.11	5.38	323	0.12	6.72	403	0.08
1B	2.82	169	0.12	4.72	283	0.16	7.11	427	0.09

Results from Ramping/Coasting tests for ID Fans 1A and 1B:

Figure 15 shows vibration RMS level vs. frequency (rotational speed) of Fans 1A and 1B. Fan 1A was ramping-up from 0 to around 500 RPM smoothly. At this speed, the airflow was changed, which affected the test conditions by changing the forcing function as it introduced a lateral force acting on the foundation due to the overpressure (or vacuum),. Accordingly, the foundation has changed suddenly, which was observed in the measured vibration amplitudes in real time. The determination of foundation the natural frequency from the vibration measurements requires a well defined forcing function characterized by non-fluctuating amplitude. Hence, the change in the forcing function due to the change in the airflow rendered the vibration amplitudes and RMS velocity values measured at speeds above 500 RPM unreliable for determination of the foundation resonant behavior. In addition, the fan speed was limited to 540 RPM due to the additional overpressure or vacuum (decision was made by the operators to minimize the overpressure). It is noted from Figure 15 that the foundation has possible resonance near 7.5 Hz (450 rpm).

Fan 1B was ramped-up from 0 to 630 RPM smoothly. After the maximum speed of 630 rpm was reached, the fan speed was reduced immediately. The vibration had a clear resonant pattern within both the ramping-up and coasting-down branches of the response curves. This resonance occurred at around 7 Hz (420 rpm), as can be noted from Figure 15. This is consistent with the findings from the pull test. It is also noted from Figure 15 that the response dropped right after the resonant peak, demonstrating what could be termed "anti-resonance". This dipping in response can happen due to opening of tiny gaps between the foundation walls and the embedment due to the presence of embedment backfill from only one side, as observed onsite and indicated on the as-built construction. Another explanation could be the presence of a hollow section within the foundation with the inner backfill not occupying the void fully. This will allow the fill to have a lagging out of phase movement, which can cause this “anti-resonance”. The presence of such hollow section filled with backfill material is also indicated on the construction drawings.

Figure 15 also shows that the response curves exhibit some plateau past the first resonant peak then continues to increase afterwards, indicating the presence of another possible peak. This peak would be associated with the foundation rocking vibration mode. It should be noted that the rocking vibration mode was not excited during the pull test because the pulling force was intentionally applied very close to the C.G. of the machine-foundation system such that no rocking moment occurs, and hence the system behaved more like a single degree of freedom in the horizontal direction. However, establishing an accurate value of the horizontal natural frequency helps identify, calibrate/verify the proper analytical model to describe the dynamic characteristics of the foundation. This model can then be used to accurately calculate the rocking natural frequency as will be explored further in the following section explaining the theoretical geotechnical model.

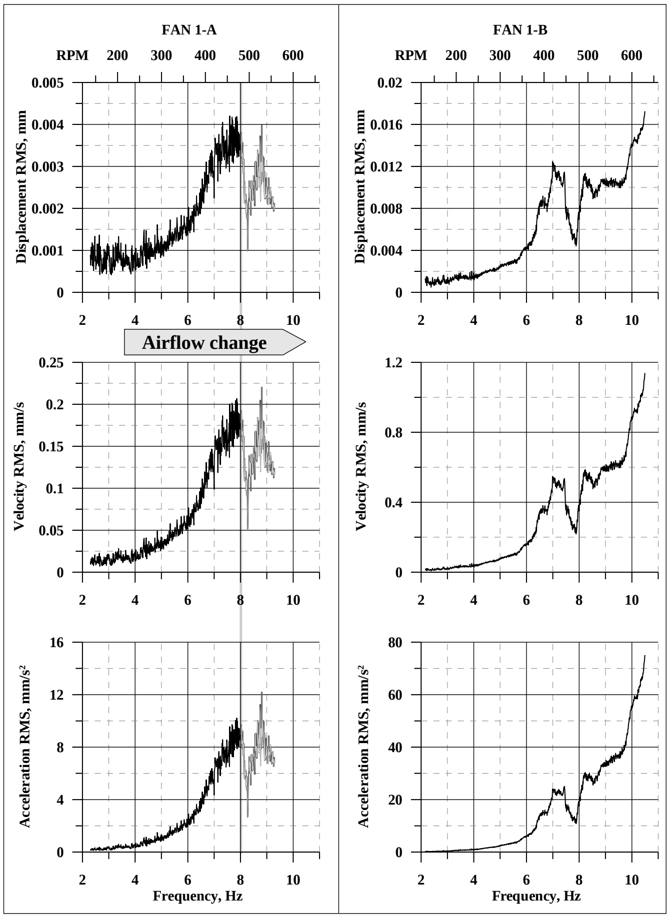


Figure 15. Fan 1-A and 1-B – The vibration RMS vs. frequency

GEOTECHNICAL MODEL AND FOUNDATION RESPONSE ANALYSIS USING DYNA6

The analysis of the pull test and coast-down tests indicated that the foundation has a natural frequency around 420rpm with a total damping ratio around 9% along the horizontal vibration mode. In addition, the observed response graphs show that the peak indicating the location of the horizontal natural frequency is followed by a plateau followed by an increase in the response indicating the presence of another peak at a frequency higher than the maximum frequency reached during the test (i.e. greater than 10.5Hz). This peak is likely associated with the rocking mode and thus showed more in the readings taken at the top of the foundation (especially channels 7 and 8), but did not show at the lower point (1 and 2). Also, this behavior showed more in the horizontal response than in the vertical response (both are affected by the rocking vibration).

The magnitude of the horizontal resonant frequency and the associated low damping ratio are not representative of the behavior of a shallow foundation resting on homogeneous halfspace. In addition, the observed plateau followed by an increase in the response (indicating another peak) is not indicative of the response of a shallow foundation resting on halfspace. As mentioned earlier, the existing foundation details show that the foundation is underlain by about 12-14 ft of backfill underlain by the overconsolidated sediments (shale). The presence of this very stiff material (shale) at a shallow depth relative to the width of the foundation, affects the dynamic stiffness and damping constants of the foundation as it increases the stiffness and reduces the damping. The commonly used halfspace model is not suitable for simulating the response of such soil profile. It is better represented as a soil underlain by a much stiffer soil (Wong and Luco, 1985), which is referred to as composite medium in the program DYNA6 (El Naggar et al., 2011).

The existing foundation setup involves embedment of 14 ft around the foundation except for a 35 ft section along the south wall, which has an embedment of only 4 ft. In addition, there are two steel bin retaining walls on the south side of the foundation. Furthermore, the foundation block includes three large voids filled with fill. Each void is about 8 ft wide and 7 ft deep and spans across the foundation width. These unusual arrangements have contributed to the observed behavior in the dynamic testing, and should be considered in the response analysis for the new fan conditions. Additionally, some or all of these arrangements could be revised as part of any retrofit of the foundation to ensure satisfactory performance for the new ID fans.

In order to reproduce the observed response pattern during vibration monitoring testing using the program the DYNA6, the option of Composite Medium is selected. Adjusting the thickness of the soil layer and the shear wave velocity of the soil backfill and underlying shale appropriately can produce a match between DYNA6 prediction of the resonant frequency and the response trends that were observed from the vibration monitoring. The damping safety factor in DYNA6 is then adjusted such that the amplitude at resonance calculated by DYNA6 is close to that observed from the vibration monitoring. By doing so, the theoretical soil model is calibrated to match the observed behavior. The results obtained from the calibrated DYNA6 model are shown in Figure 16.

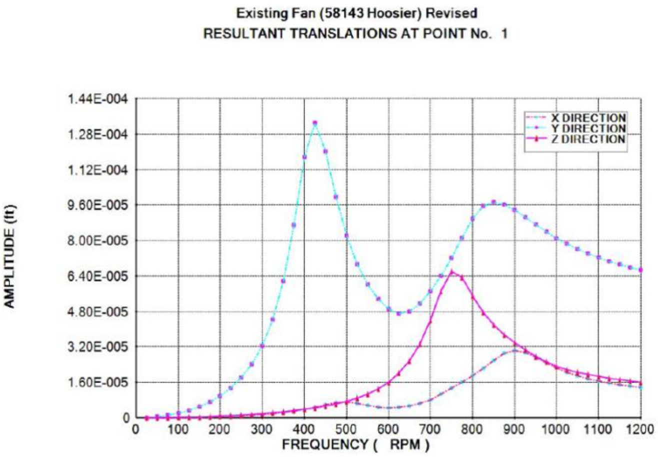
Following the establishment of the geotechnical model from the previous step, the steady state behavior predicted by DYNA6 should be adjusted to match that observed from the vibration monitoring program. Given that the geotechnical model is now calibrated to the actual observed behavior, the remaining parameter to match the observed steady state behavior is adjusting the unbalance force in the DYNA6 analysis. Thus, the unbalance force obtained from matching the steady state behavior with the observed behavior is deemed to be representative of the actual unbalance (centrifugal) force due to the rotation of the fan impeller. This unbalance force can be multiplied by a factor of safety to arrive at the design unbalance force for the design of the new machine. Any change in the mass of the rotating part and operating speed of the equipment will also have to be accounted for in calculating the unbalance force for the new equipment.

Discussion on Comparison between Calculated and Measured Response

The program DYNA6 was used to analyze the response considering the Composite Medium option, with 14 ft deep soil layer (representing the backfill), Vs = 800 ft/sec and the ratio for Vs of the backfill to that of underlying shale as 0.3. The Poisson's ratio of the fill is considered to be 0.33 and its material damping ratio is considered to be 0.02. The damping safety factor used is 3. To account for the fact that embedment depth is not uniform around the foundation (i.e. 14 ft on 3 sides and 4 ft on a 35 ft section along the south wall), a weighted average embedment depth of 10.3 ft is considered in the analysis. The calculated response, shown in Fig. 16, has the same patterns observed during the vibration monitoring. However, the dipping (anti-resonant behavior) that appears in the observed behavior is due to the voids existing in the foundation structure (filled with fill with unknown quality), which cannot be reproduced by DYNA6 due to the adopted rigid body assumption. Also, the calculated responses do not show the resonant peaks associated with the vibration of the ductwork because they are not modeled in DYNA6. However, this resonant peak is not important for the normal operating conditions because the dynamic load at this frequency is very low and the damping ratio is high, so the associated response amplitudes are very small.

The data collected and the analytical approximation identified lightly damped resonances in the horizontal direction at around 6.7 Hz to 7 Hz for ID Fans 1A and 1B. In addition, a potential resonance is likely to exist between 11 and 13 Hz and would have low damping. The spectra of the vibration background noise shows a very sharp peak around 11.3 Hz at both foundations. If there is no equipment operating permanently at this frequency, it should be considered as the potential resonant frequency of the machine-foundation system, including soil structure interaction.

The low frequency resonances (between 2.8 and 5.4 Hz) were provoked by the impulse from the lateral loading during the Pull test. In normal working conditions, these resonances will not affect the structure because the normally balanced motor/fan will produce very small dynamic lateral loads at these rotational speeds. Thus, for the consideration of the new fan foundation response, only resonances between 6.7 and 12 Hz that can affect the structure because of their low damping and higher frequency (i.e. higher centrifugal load). The response of the existing foundation to the new ID fan loading conditions should be calculated using the analytical model established herein. If the calculated response is found to be unsatisfactory, the foundation should be revised taking advantage of the existing conditions. For example, the existing voids can be exploited to add an additional section to the foundation connected rigidly to the foundation by integrating the new section with the existing foundation through concreting the voids with reinforcement extending into the new added section. The size and configuration of the added section, if any, should be established based on the response analysis of the new fan. Additionally, the steel bin arrangement can be altered to provide a more conventional embedment along the entire perimeter of the foundation.



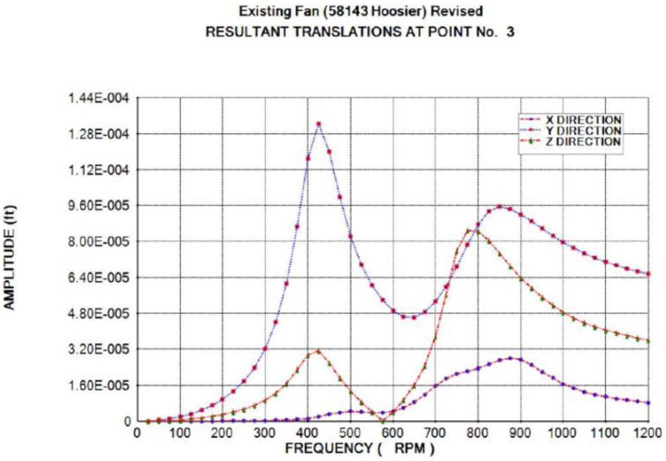


Figure 16 Calculated response using DYNA6 for the Composite Medium. Points 1 and 3 are about 5ft from Channels 5 and 6 measurement point (1 near the edge and 3 near the centre of footing)

CONCLUSIONS

A comprehensive dynamic testing program was conducted to establish the dynamic characteristics of existing fan foundations in order to evaluate their suitability to support new variable speed fans. The dynamic testing program encompassed two sets of tests: Pull tests and steady-state vibration test. Based on the analysis of the tests results, the following conclusions may be drawn:

1. The pull tests revealed the first 3 natural frequencies of the fan-foundation-ductwork system and the associated damping ratios. The first two natural frequencies involve the ductwork and have relatively high damping. These vibration modes are not excited during the normal operating conditions of the fan (low speed) and their response is insignificant. The third natural frequency, around 7 Hz, is associated with the horizontal vibration mode of the fan-foundation system. This is an important natural frequency and has to be considered in the dynamic analysis for the new fan-foundation response as it falls within the normal operating frequency range.
2. The steady-state vibration tests indicated a horizontal resonant peak at around 7.5 Hz for fan 1A and 7 Hz for fan 1B. These values are similar to the results obtained from the pull tests, thus confirming that the horizontal natural frequency of the foundations 1A and 1B is around 7Hz.
3. The Steady-State vibration tests indicated the presence of another resonant peak at a frequency between 11 and 13 Hz. These frequencies fall outside the range of frequencies considered in the testing but they were discerned from the vibration noise measurements, and corroborated by the trends of the observed response curves in the steady state testing, and that obtained from the analytical model. The analysis of the noise measurements indicated a resonant peak at 11.3 Hz. There were no equipment running at this frequency at the time of the measurements, thus this is a likely value for the resonant frequency associated with the rocking vibration mode of the fan-foundation system. This resonance must be considered in the response analysis for the new fan loading conditions and their response.

The analytical model for the existing foundation model was established in the DYNA6 environment considering the “Composite Medium” option. The results obtained using this model exhibit the same trends and range of values as those observed during the dynamic testing. The model has been calibrated using the measured response and can be used to analyze, or design the retrofit if needed, for the new fan foundation system.

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