Proceedings of ASME Turbo Expo 2011
GT2011
June 6-10, 2011, Vancouver, British Columbia, Canada

GT2011-46857

TESTING OF FULL SPEED NO LOAD OPERATING CONDITIONS IN A SUBSCALE STEAM TURBINE TEST VEHICLE

John Basirico
Bin Zhou
Amir Mujezinovic
GE Energy
Schenectady, New York, 12345, USA

Yuri Starodubtsev
Boris Frolov
GE Energy
Moscow, 107023, Russia

ABSTRACT
During the operation of a power plant, a steam turbine may experience operation at full speed with little or no load (FSNL). Such an operation can take place when power demand is low or during start-up. At such an operation turbine buckets, in particular last stage buckets (LSB), can experience high stimulus coming from unsteady loading due to the flow instability. In those conditions LSBs consume energy rather than produce it. In some cases stimulus can create high alternating stresses in the LSB. As such, operation at those conditions is a particular concern in bucket aeromechanical design. To properly simulate FSNL operation in a stand alone low-pressure (LP) subscale turbine test facility, an external drive motor is normally required due to the unavailability of high and intermediate-pressure sections that would drive the LP turbine at very low load. This work shows that such a simulation can be achieved in the absence of an external drive by running the LP test turbine at higher exhaust pressure and higher mass flow. In those conditions LP exit flow velocity (VAN) similar to an actual FSNL operation will be achieved. This work shows that achieving prototypical VAN is sufficient to simulate operation at FSNL. Measurement data of the test show correlations between bucket alternating stress and turbine operating parameters such as VAN and exhaust pressure. This demonstrates that bucket responses equal or greater than those which would occur in actual FSNL conditions can be tested in a lab setup, In other words, testing at a given combination of VAN and exhaust pressure provides a limiting bucket response case for an operation at the same VAN but lower exhaust pressure. Further, numerical simulations using computational fluid dynamics were performed to prove that steam flow parameters and bucket structural mechanics characteristics in a subscale test turbine are fully representative of its full-scale counterpart, even at low flow or FSNL operating conditions, where broad spectrum of steam stimuli and bucket responses are expected.

INTRODUCTION
Steam turbine full speed no load operation (FSNL) is not uncommon in modern steam turbines. FSNL operation can create high alternating stresses of the LSB and results in High Cycle Fatigue (HCF) issues that reduces bucket service life. Proper understanding of a LSB's dynamic response during FSNL operation typically requires subscale or full scale turbine testing, where actual bucket response are measured. These tests can provide appropriate flow boundary conditions in Computational Fluid Dynamic analysis (CFD), which could then be used to predict the bucket's dynamic response in such operating regimes analytically.

FSNL operation in steam turbines is considered to have zero to very low power output, with a typical averaged steam exit velocity (VAN) of <61 m/s (<200 ft/s) at the LSB, and a typical backpressures at 6,700 to 10,000 Pa (2 to 3 inHgA). GE's Low-Pressure Development Turbine (LPDT) testing facility is used to test the last three or four stages of a steam turbine's low pressure section, often at a subscale. Normally, simulating FSNL operation directly in the subscale steam turbine would require a drive motor to rotate the rotor at low load, since the high-pressure and intermediate-pressure sections are not available to drive the turbine as they would be in an actual FSNL operation.

Three parameters were used to describe FSNL operation, out of which any two are independent: mass flow, exhaust pressure and VAN. In a subscale test turbine, when exact FSNL conditions cannot be achieved due to the lack of drive motor, it is possible to achieve a VAN that is very close to a VAN at

FSNL operation, with a minimum power output. Such a VAN can be achieved by running the subscale turbine at a higher exhaust pressure and correspondingly, a higher mass flow than those that would be encountered during field FSNL operations. There are three assumptions in using such an approach to test the bucket response at FSNL. First, broad-band frequency responses of the LSBs at low load operating condition predominantly depend, on and are approximately proportional to VAN, where VAN is in turn a function of mass flow and backpressure. Such a trend has been observed in a number of turbine tests performed at GE. Secondly, if the VAN achieved in the turbine test, with a higher exhaust pressure, matches that of the field FSNL condition, bucket response would not be lower than that in the field FSNL operation. This was in fact also observed in the LPDT test in the current study, and will be discussed later in more detail. Finally, it is assumed that flow characteristics and major aerodynamic parameters associated with FSNL are captured and all approximately scale (proximity due to not exact scaling of turbine hardware and other uncertainties in test control) in a subscale LPDT test, as compared to the full-scale turbine hardware. This was verified numerically using CFD analysis and is also demonstrated in the following sections. As a result, dynamic response should remain the same between the subscale and full-scale buckets. The main purpose of the LPDT test was to investigate and validate the first two assumptions, and to establish the VAN as a key parameter linked to steam turbine LSB dynamic response. This will in turn greatly assist bucket designers and turbine operators in understanding high LSB dynamic stresses at FSNL and the potential for HCF failures. Further, it is demonstrated that an LPDT without a drive motor can test a more severe unsteady aerodynamic forcing environment that could drive a LSB to high cycle fatigue, and this therefore bounds the upper limit of the response domain. Moreover, validity of using a subscale turbine to test LSB broadband dynamic response is proven with numerical simulations.

TEST MEHTOD

A total of 12 test points were designed for the FSNL study. The 12 test points are broken down into three different VAN series, with various combinations of mass flow and exhaust pressure to achieve a similar VAN within each series. below lists the test points used in the FSNL study where the VAN, backpressure and mass flow where normalized with respect to the lowest value in the test range.

VAN Series	Test Point Label	Actual VAN (normalized)	Backpressure (normalized)	Mass Flow (normalized)
H	H1	3.2	1.0	1.99
	H2	3.3	2.0	3.95
	H3	3.4	3.0	5.93
	H4	3.4	4.1	7.91
M	M1	1.6	1.0	1.00
	M2	1.7	2.0	1.99
	M3	1.6	4.1	3.96
	M4	1.7	5.7	5.52
L	L1	1.0	2.0	1.22
	L2	1.0	3.0	1.96
	L3	1.0	4.1	1.84
	L4	1.1	6.6	3.95

Table 1 – Test Pont Matrix for FSNL Study

Three different gage locations were used as shown in Figure 1. A total of 24 strain gages were used, gage positions one, two and three were repeated circumferentially, around the row, eleven, seven and six times respectively.

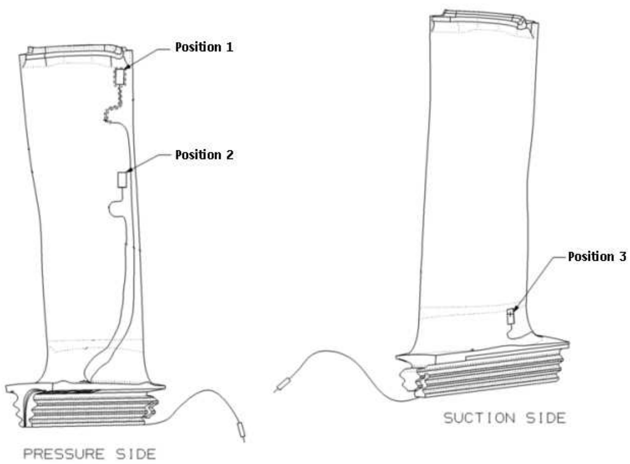

Figure 1 – Instrumentation Locations of LSBs

DATA REDUCTION METHOD

The LSB responses that were analyzed are considered largely non-synchronous, because response frequencies are typically not linearly related to turbine running speed. As the LSB tested is intended for use in a variable speed steam turbine application, FSNL test speed ranges were carefully chosen with sufficient margins from any resonant crossing speeds, as results from this study are intended for non-variable speed steam turbines. Bucket dynamic responses, as measured through bucket-mounted strain gages, were reviewed for three different speed ranges from the low to high end of the speed sweep conducted during test as shown in Figure 2. For each test point, the average and the maximum of measured bucket strains at a particular gage location were derived.

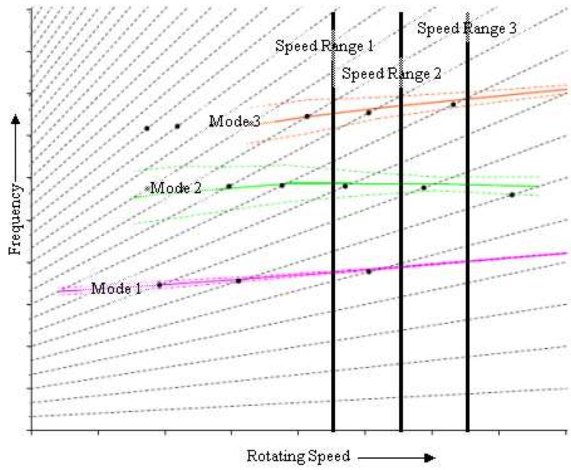

Figure 2 – Campbell Diagram of tested Bucket

Calculation of the average strain gage response is completed in two steps. The first step is to calculate the average strain gage response for a single strain gage. This is accomplished by averaging all the strain gage responses for a particular strain gage over a specific speed and frequency range. An example is shown in Figure 3, where the strain gage data is plotted for all frequencies, within a given speed range, for a particular strain gage. Recognizing the fact that response is broadband though generally higher at lower frequency range, averaging along the entire frequency range provides an overall estimation of the response level for different test flow conditions. The second step is then to take the results from the first step, i.e. the average response of each strain gage mounted on the same bucket location, and further average among multiple instrumented buckets.

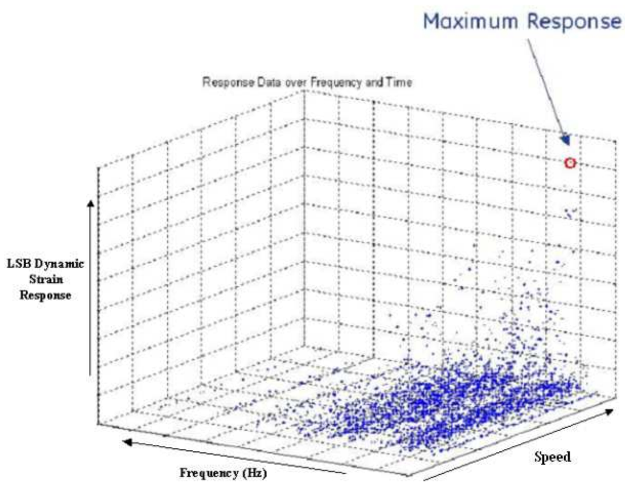

Figure 3 – LSB Dynamic Response vs. Frequency and Speed

The first step of extracting the maximum strain gage response is explicitly shown in Figure 3. The second step then follows the same procedure as the average response method, where averaging is done on the maximum response of each particular strain gage at the same gage location but on different buckets.

It is assumed that such obtained response data will approximately scale between a full-scale steam turbine and a subscale test steam turbine, therefore results and conclusion obtained from subscale turbine can present the true physics of a full-scale turbine.

TEST RESULTS

The results of the test show two clear trends. First, among test points representing different VANs, LSB response is greater for lower VAN. Figure 4, Figure 5, and Figure 6 shows the average normalized strain gage data for all three speed-ranges for the tip gage location. The data shows that the greatest responses occurred in the VAN series L and response decreases with an increase in VAN.

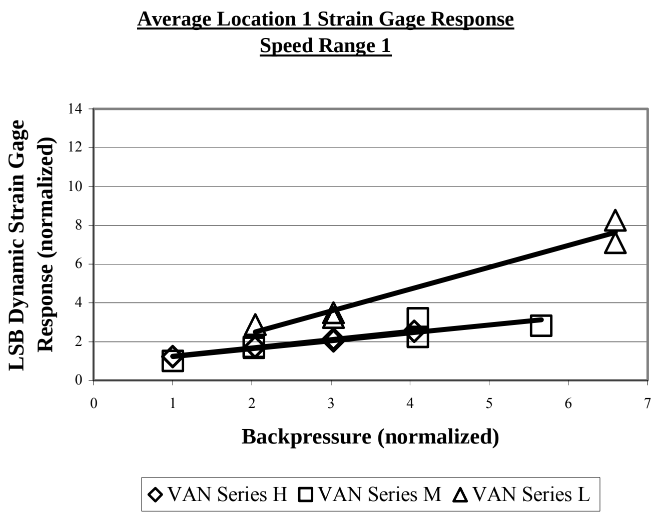

Figure 4: LSB Location 1 Average Dynamic Strain Gage Response for Speed Range 1

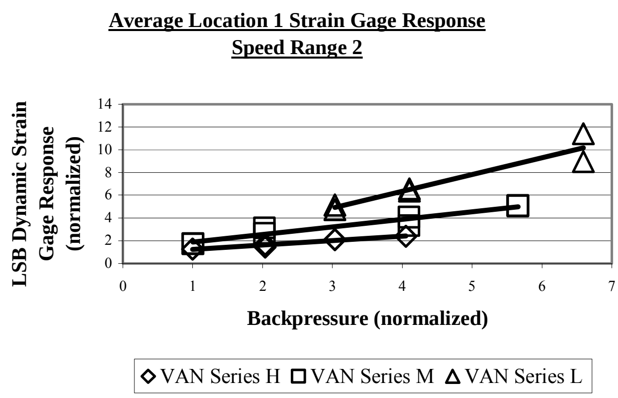

Figure 5: LSB Location 1 Average Dynamic Strain Gage Response for Speed Range 2

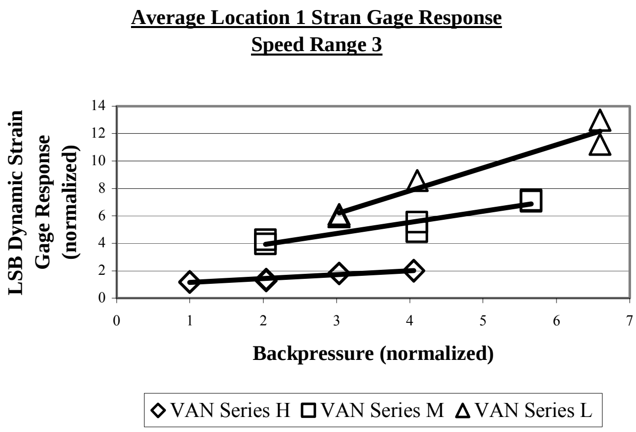

Figure 6 – LSB Location 1 Average Dynamic Strain Gage Response for Speed Range 3

Second, for constant VAN, maximum response is produced at the highest exhaust pressure; this trend is the same for each VAN series.

Both trends observed in the test data validate the two pre-test assumptions that 1) lower VAN leads to higher non-synchronous bucket dynamic response at low load or FSNL condition and 2) non-synchronous bucket response at a given VAN will increase as the backpressure increases. Therefore, if a test point can be run at a VAN that is similar to that of the field FSNL operation, but at a higher exhaust pressure, buckets under testing will experience higher non-synchronous dynamic responses than those of the field FSNL operations.

The maximum strain gage responses conform to the same trends as the average strain gage responses. The trend being an increase in the speed range, decrease in VAN and an increase in backpressure leads to a higher strain gage response.

Figure 7 shows the maximum strain gage responses for speed range 3 at the tip gage locations.

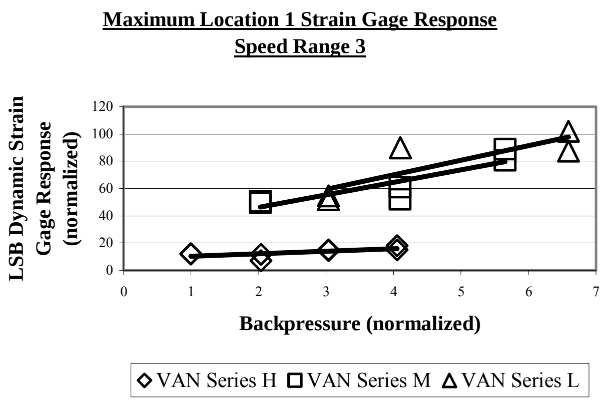

Figure 7 – LSB Location 1 Maximum Dynamic Strain Gage Response for Speed Range 3

Observing the middle and root gage locations, locations two and three, respectively, the same trend of dynamic strain response as seen as the tip section trend observed.

NUMERICAL SIMULATION

3D CFD simulation has been performed to support the 3rd assumption, being that the flow characteristics and major aerodynamic parameters associated with FSNL are captured and all approximately scale in a subscale LPDT test, as compared to the full-scale turbine hardware. The major task of this analysis was to validate that flow parameters at low load or FSNL in subscale (SS) LPDT test are fully representative of its full-scale (FS) counterpart. In other words, this means that unsteady aerodynamic forcing generated by flow separations at FSNL and resulting LSB aeromechanical response are largely independent of the dimensional scaling of a steam turbine. A series of experimental and numerical studies [1-4] were dedicated to investigations of general physics of low flow turbine operating regimes. Detailed studies on aeromechanics aspects of low flow regimes in turbine last stages can be found in [5,6].

An ideal aerodynamics and aeromechanics test with a subscale test turbine assumes two major rules: perfect geometric scaling of the turbine and equivalent aerodynamic boundary conditions or control parameters of the turbine flow. Neither of these two rules can be strictly satisfied in any subscale turbine test. However, in the numerical analysis, the first rule is satisfied by neglecting the structural differences (other then exact scaling) between full-scale (FS) and sub-scale (SS) turbine models, and address the second rule by matching two major aerodynamic control parameters, namely Reynolds number (Re) and Mach numbers (M) for both FS and SS analyses.

Figure 8 demonstrate FS and SS 3D CFD models with scale factor (SF) =1/3.

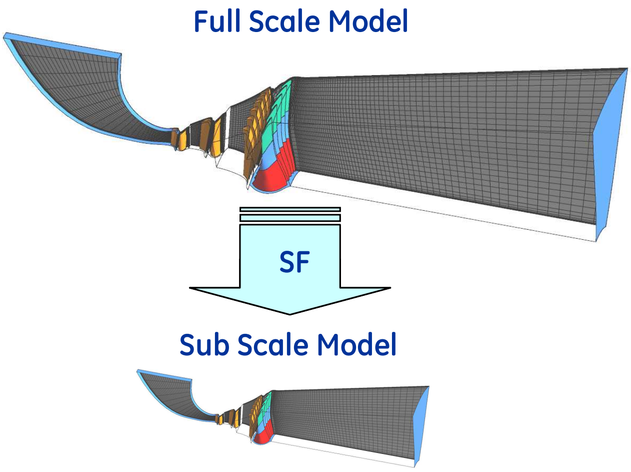

Figure 8 – CFD Model of Full Scale and Sub Scale Turbines

To maintain equivalent Mach numbers, the operational conditions of the model was adjusted so that turbine rotational speed was increased by a factor of 1/SF, inlet steam mass flow was reduced proportional to ratio of cross-section area, while other inlet and outlet boundary conditions were kept the same. Reynolds number calculated for FS and SS models differ proportionally to 1/SF. This difference in Re number was suspected to potentially lead to a deviation in aerodynamic equivalence. The main objective of the current CFD investigation was to find out whether such a deviation exits, and how much it could impact the scalability of dynamic forcing exerted on LSBs at FSNL operating regimes.

All results of numerical simulation in this work have been performed using ANSYS CFX. Grids of FS turbine steam path components have been generated using ANSYS Turbogrid and ANSYS ICEM CFD, and were then scaled with the factor SF to obtain the SS model. The total mesh size of either CFD model amounts to 1.6 million hexahedral cells. Near-wall cells size was adjusted as to provide consequent CFD simulations y+ value less than 2 for blades and less than 10 for end-walls. As the study has been focused on unsteady flow characteristics in LP turbine last stage, CFD model was developed in such manner that it consisted of a last stage sector model of 6 nozzles and 5 buckets passages and single-passage models of all upstream stages. These upstream stages were modeled to provide correct boundary conditions at last stage inlet. Sectors of last stage nozzles, buckets and exhaust diffuser domains have been modeled so that they had the identical angular size.

In both CFD models, mass flow and total temperature were set as inlet boundary conditions, whereas backpressure and exhaust flow temperature were set as outlet boundary conditions.

In unsteady CFD simulations URANS computational scheme with SST turbulence model and 'Automatic' near-wall treatment method applied in ANSYS CFX was used, time step of the SS model was proportionally sized according to that of the FS model by the factor SF. This provides equivalent computational conditions for both models in terms of Courant number.

In accordance with the purpose of this study, turbine operating conditions with a VAN ~ 49 m/s (~160 ft/s, 20% of nominal turbine load) was selected as a typical FSNL condition. Numerical study of the CFD models described above was split into 2 steps: steady and unsteady solutions. The first step had 2 main objectives, preparation of initial guesses for the subsequent unsteady simulation, and comparison of averaged integral parameters such as VAN and aerodynamic force or moment applied on the LSB between FS and SS models. A discrepancy of less than 1% of the absolute values of the integral parameters between FS and SS model proves the scalability of the parameters. Comparisons of radial profiles of flow parameters at various sections of the steam path were also performed. As an example, Figure 9 represents comparative plots of radial profiles of Mach number and flow angle at the exit of the LSB in rotating frame. These plots show good agreement between FS and SS models in steady calculations.

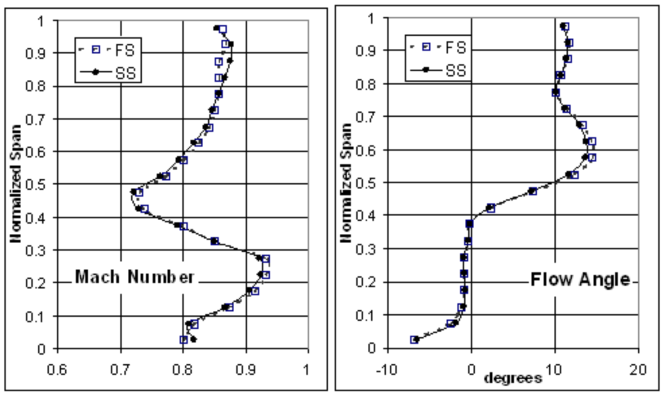

Figure 9 – Radial profiles of Mach Number and Flow Angle at LSB exit in relative frame for FS and SS Models

The main objective of a second step of this study was to validate the scalability of unsteady aerodynamic flow characteristics at FSNL regimes by comparing the frequency spectrum of aerodynamic forces and moments acting on the LSB. In the unsteady solution, progressing time histories of investigated parameters such as LSB integrated forces and moments were recorded for subsequent post-processing and analysis. A typical time history of aerodynamic moment acting on a LSB is presented on Figure 10. This plot shows two separated portions of the data: first one reflects transition process from start point to periodic solution and the second one represents periodic solution itself.

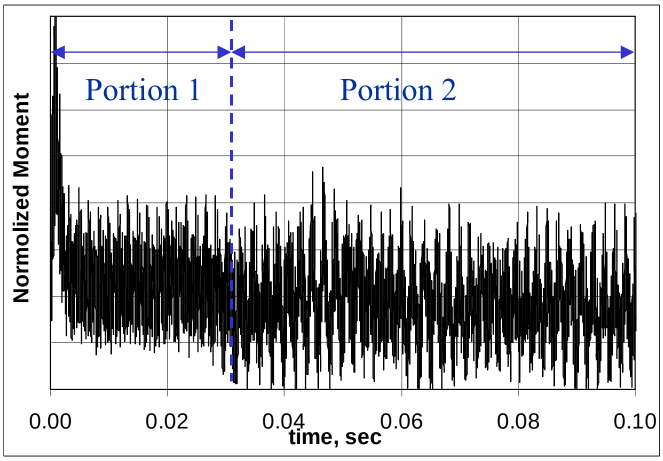

Figure 10 – LSB Normalized Moment time-history of FS Model unsteady solution

In this study the spectral analysis of dynamic characteristics has been performed using Fourier transformation on stabilized periodic portion of the signal.

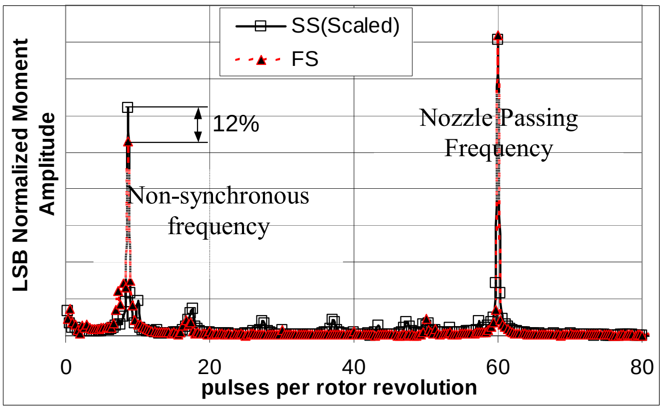

Figure 11 – LSB Normalized Moment Spectra comparison between FS and scaled SS results

Figure 11 presents the comparison of LSB aerodynamic moment spectrum of both FS and SS unsteady CFD solutions. On this plot, SS model data was scaled by a factor of SF ^{3} to be directly comparable with FS data. Spectra range presented on this picture contains two significant peaks. One of them corresponds to a nozzle passing frequency and demonstrates the ideal scalability. The second peak represents a non-synchronous unsteady aerodynamic stimulus on LSB. The peaks of both signals show excellent agreement in frequency, and a reasonably good match in amplitude (12% difference.) This difference in amplitude between SS and FS may be attributed to Re number effect.

CONCLUSIONS

The results of the subscale steam turbine testing show that it is possible to bound the LSB response of the full-scale bucket FSNL conditions in the subscale turbine. The testing satisfied the two assumptions related to the FSNL testing.

The first assumption stating that broad-band frequency response of the LSBs at low load operating condition predominantly depend on and is approximately proportional to VAN, where VAN is in turn a function of flow and backpressure. This assumption is proven to be correct, as shown by the data presented in Figure 4, Figure 5, Figure 6, and Figure 7.

The second assumption stating, if the VAN achieved in the turbine test, with a higher exhaust pressure matches that of the field FSNL condition, bucket response would not be lower than that in the field FSNL condition. This assumption was also validated with the test data presented and can be summarized as follows: if a test point can be run at a VAN that is similar to that of the field FSNL operation, but at a higher exhaust pressure, buckets under testing will experience higher dynamic response than those of the field FSNL operation.

With the objective to validate the scalability of LSB dynamic forces at FSNL operation the detailed 3D CFD unsteady analyses have been performed. CFD simulations were performed at typical FSNL conditions corresponding to VAN 49 m/s (~160 ft/s). As a result of unsteady CFD investigation, spectral content of LSB dynamic forces was obtained and compared for FS and SS LP turbine models. It was shown that both synchronous and non-synchronous unsteady aerodynamic LSB stimuli demonstrates excellent scalability in frequency and good matching in amplitude. However, further detailed investigation of the Re number impact on non-synchronous aerodynamic processes in LSB at FSNL regimes is needed. These results support the conclusions on experimental data mentioned above.

ACKNOWLEDGMENTS

The support of Dr. Victor Filippenko and Dr. Jon Slepski in CFD study results analyses and discussions, as well as the support of the GE Steam Turbine Technology lab to complete the subscale steam turbine testing is kindly acknowledged.
The responsibility for the content of the publication rests with the authors.

REFERENCES

1. Sigg ,R.; Heinz, C.; Casey, M.V.; Sürken, "N. Numerical and experimental investigation of a low-pressure steam turbine during windage", Proceedings of the IMechE, Part A: Journal of Power and Energy, July 6, 2009

2. Wachter, J.; Eyb, G., "Determination of the flow field in LP steam turbines", Proceedings of the ASME Turbo Expo 1986, Düsseldorf, 1986, 86GT-210

3. Herzog, N.; Gündogdu, Y.; Kanh, G.; Seume, J. R.; Rothe, K., "Part load operation of a four stage turbine", Proceedings of the ASME Turbo Expo 2005, Reno, 2005, GT2005-68700

4. Truckenmüller, F.; Gerschütz, W.; Stetter, H.; Hosenfeld, H. G., "Examinations at a three stage low pressure model turbine during ventilation", Proceedings of the IJPG'98 International Joint Power Generation Conference

5. Gerschütz,W.; Casey, M.; Truckenmüller, F., "Experimental investigations of rotating flow instabilities in the last stage of a low-pressure model steam turbine during windage.", Proc. IMechE, Part A: J. Power and Energy, 2005, 219(A6), 499–510. DOI: 10.1243/095765005x31379

6. Zhou, B.; Mujezinovic, A.; Coleman, A; Ning, W; Ansari, A, "Forced Response Prediction for Steam Turbine Last Stage Blade Subject to Low Engine Order Excitation", submitted for publication in ASME Turbo Expo 2011, Vancouver, 2011