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Ambient Vibration Measurement of Ruskin Dam for Seismic Assessment

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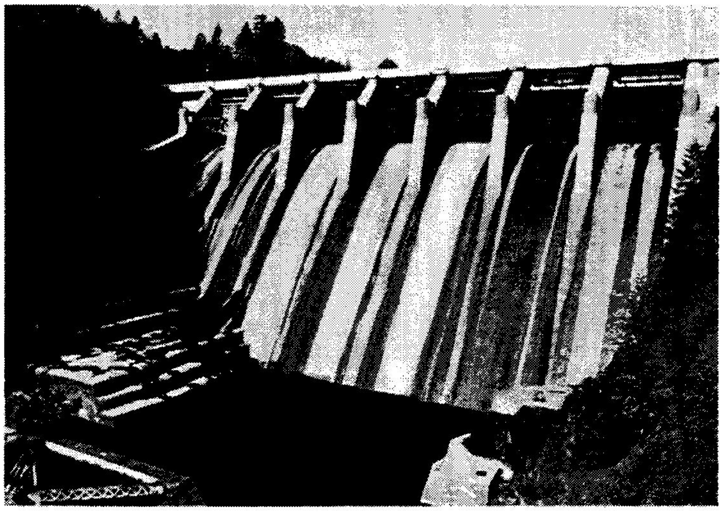
ABSTRACT

To determine the suitability of ambient vibration testing and analysis as part of seismic evaluation studies of concrete gravity dams, a study is being conducted jointly by B.C. Hydro and the University of British Columbia of Ruskin Dam, a 58 m high concrete gravity dam built in 1930 and located near Mission, British Columbia. Ambient vibration testing and analysis techniques were used to identify several natural frequencies and corresponding mode shapes of this dam. As a direct result, there is improved confidence in the finite element model used to assess its seismic response. This paper discusses the preliminary results of this study.

INTRODUCTION

B.C. Hydro's Dam Safety Program has determined that the consequences of failure of Ruskin Dam are high and that dynamic analysis to evaluate seismic response is justified. Numerical modelling and dynamic analysis of Ruskin Dam is in progress using the finite element method.


PHOTOGRAPH 1: DETAIL OF RUSKIN DAM FROM POWERHOUSE ROOF

Confidence in the results of the numerical model are increased if the dynamic properties of the model agree with measured properties, such as frequencies and mode shapes. Vibration testing and analysis techniques are a method by which dynamic properties of concrete gravity dams may be obtained (Cantieni et al 1994, Duron et al 1994, Hall 1988, Paultre et al 1992, Rea et al 1975). This paper presents the preliminary

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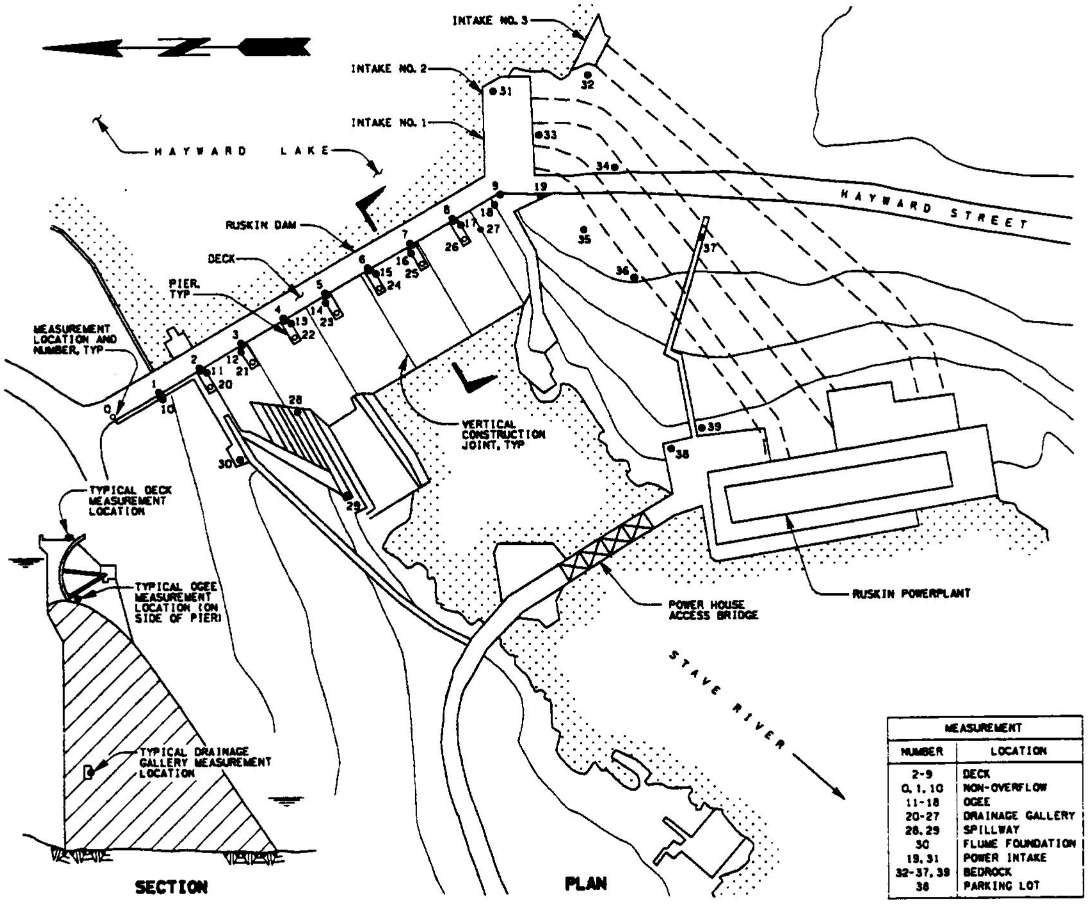
results of an ongoing study to determine whether useful dynamic properties can be obtained via the method of ambient vibration testing and analysis and whether these can be useful for calibration of the numerical model of Ruskin Dam.

This study forms the basis for the first author's M.A.Sc. thesis being completed through the UBC/BCH Professional Partnership Program.

RUSKIN DAM

The dam is shown in Photo. 1 and Fig. 1. There are 3 power intakes on the left abutment (looking downstream), leading via tunnels through bedrock, to a downstream generating station. Atop the entire length of the dam is a public road deck. The dam is 130 m long, including the structure for power intakes 1 and 2. It has an 83 m long spillway section and a 24 m long non-overflow section adjacent to the right abutment. Maximum height from the deepest foundation to the road deck is 58 m. Maximum height of the tallest gravity block is 47 m. The non-overflow section, spillway section and the intake structure are founded on bedrock. The right face of the non-overflow



MEASUREMENT	
NUMBER	LOCATION
2-9	DECK
0, 1, 10	NON-OVERFLOW
11-18	OGEE
20-27	DRAINAGE GALLERY
28, 29	SPILLWAY
30	FLUME FOUNDATION
19, 31	POWER INTAKE
32-37, 39	BEDROCK
38	PARKING LOT

FIGURE 1: RUSKIN DAM - SITE PLAN SHOWING AMBIENT VIBRATION MEASUREMENT LOCATIONS

section is against fill.

The spillway section consists of 6 gravity blocks. The keyed vertical construction joints between these blocks were grouted after 2 winters.

AMBIENT VIBRATION TESTING AND ANALYSIS

Ambient vibration testing and analysis of structures involves no artificial means of excitation. The naturally occurring ambient excitation must be sufficient to excite and yield measurable vibrations of natural frequencies in the frequency range of interest. Ideally, ambient excitation should be broad band white noise over this frequency range. Intuitively, ambient vibrations are of a relatively low amplitude, as a result, measured ambient response vibrations are considered to capture the linear range of behaviour. This is of primary consideration when interpreting and using the analysis results.

Ambient vibrations are stochastic random processes and statistical errors result from their sampling and in the calculation of frequency domain functions using them (Bendat and Piersol 1993). Generally, ambient vibrations are considered to be both stationary and ergodic, meaning that ambient conditions do not change significantly during a sampling period. These statistical errors are also dependent on the total time history record length of signals recorded, the number of individual segments which the time history is broken (or divided) into (for statistical averaging) and on the processing during recording to which they are subjected to. Careful selection of transducers, signal processing and recording equipment is important to ensure the highest signal to noise ratios and least distortion of the data obtained.

The techniques developed at UBC on bridge ambient vibration measurement and analysis (Felber 1993) were used to identify natural frequencies and mode shapes of Ruskin Dam, as generically described in the following paragraphs.

At each measurement point on a structure, a time history of acceleration is obtained and the power spectral density function (PSD) is calculated. For lightly damped structures, frequencies corresponding to local maxima in PSDs, may indicate natural frequencies (Bendat and Piersol 1993). For rapid identification of the potential natural frequencies from the typically large number of signals recorded, an aggregate spectral function of the individual PSDs is calculated. This is termed the "average normalized power spectral density" function (ANPSD) (Felber 1993). Frequencies corresponding to localized maxima in ANPSDs are used to identify potential natural frequencies.

Relative transfer functions are calculated for each measured acceleration with respect to a designated reference location, based on the single input-single output cross-spectral density relationship. They are designated "relative" transfer functions because the magnitude is relative to the reference signal location. By definition, relative transfer functions are complex functions having both a magnitude (gain) and a phase. For a lightly damped system, at a natural frequency, all points on the structure should be vibrating in or out of phase. Therefore, to confirm whether a potential natural frequency identified with the ANPSDs is indeed a probable natural frequency, the phase of relative transfer functions for the majority of measured points should be close to 0 or 180 degrees. This forms the primary test to identify probable natural frequencies.

To quantify the degree to which the individual signals are correlated to the reference signal, the coherence function is calculated. At a natural frequency, the coherence function should have a local maxima (Bendat and Piersol 1993). This is used as a secondary test to confirm probable natural frequencies.

With the probable natural frequencies identified, mode shapes are constructed from the magnitude and phase factors of the relative transfer functions.

In addition to the above described techniques a complimentary signal analysis study was undertaken. This work primarily involved study of the signal captured from the left abutment bedrock, which was found to represent a major source of ambient excitation for Ruskin Dam. Transfer functions were calculated using this signal as input. With this type of transfer function, the phase factor at a natural frequency is near 90 degrees (Bendat and Piersol 1986). This approach yielded a second independent means for identifying natural frequencies. Due to space limitations the details of this study will not be discussed in this paper.

AMBIENT VIBRATION TEST

Ambient excitation at Ruskin Dam originates from wind, waves, deck traffic and vibrations from the foundation. The majority of ambient excitation was expected to come from the left abutment bedrock, where the power intake tunnels are located. Field testing was designed to satisfy the following three objectives:

1. Obtain dam dynamic properties, i.e., natural frequencies and mode shapes.
2. Study hydrodynamic effects on the dam dynamic properties.
3. Study the relevance of the ambient signals originating from the left abutment bedrock.

To describe mode shapes of the dam, a grid of measurement points were located along the deck, the ogee and the drainage gallery, as shown in Fig. 1. Some visible left abutment bedrock outcrops were also selected. In addition, measurements were made on the right side spillway training benches, atop the power tunnel intake structure and on the powerhouse concrete parking lot.

Tests were conducted at two reservoir elevations. One was at the maximum reservoir level (coincident with the top of the radial gates) and the second was with the water at a level 6 m. lower. The tests were conducted during daylight hours on successive weekends in April/May 1994 in order to minimize thermal effects on the recorded data.

UBC's vibration measurement and data analysis equipment was used (Ventura et al 1995), including 8 force balance accelerometers. Measurements were taken in the upstream-downstream (transverse), vertical and cross-canyon (longitudinal) directions. The 8 accelerometers were arranged as two triaxial clusters and one biaxial cluster. The biaxial cluster measured only upstream-downstream and vertical directions and as a result cross-canyon measurements were obtained at only about half of the measurement locations. One of the triaxial clusters remained at the reference location (measurement location 13 in Fig. 1) while the other two clusters were moved from location to location. For each reservoir elevation, testing took two days of approximately 12 hours each day. Generation activity was relatively constant during each test. Bedrock measurement proved to be time consuming as the irregular surfaces presented difficulties in properly mounting and orientating the accelerometers.

The following programs were used to analyse the data:

1. AVTEST to control data acquisition and storage.
2. ULTRA and U2 to calculate frequency domain functions.
3. VISUAL and V2 to animate operating deflected shapes.
4. P2 to calculate ANPSDs.

Programs AVTEST, ULTRA and VISUAL were developed at UBC. Programs U2, V2 and P2 are available from Experimental Dynamic Investigations Ltd. in Vancouver, B.C.

The frequency range of interest was chosen to be 0-20 Hz. To ensure reliable data within the frequency range of interest, the highest frequency able to be resolved from the data, or "Nyquist" frequency, was set at twice the maximum of this range, or 40 Hz. Data acquisition parameters were as follows:

1. Sampling rate: 80 samples per second (80 Hz.).
2. Time history individual segment length: 51.2 seconds.
3. Total time history length: 15 minutes, 22 seconds (16 segments)
4. Filters: low pass 12.5 Hz., high pass 0.1 Hz.

The inverse of the duration of an individual segment length defines the sharpest frequency resolution of the acceleration signals recorded, or 0.0195 Hz.

Typically, accelerations measured varied between 50 and 1000 micro-g's. This compares with the force balance accelerometer resolution of 0.2 micro-g's.

AMBIENT VIBRATION ANALYSIS

ANPSDs calculated for the upstream-downstream direction, for both reservoir cases, are shown in Fig. 2 at a frequency resolution of 0.0781 Hz. Peaks are not always well defined and so the search for probable natural frequencies has involved consideration of frequency ranges.

The phase factor was calculated from the set of relative transfer functions over the entire frequency range of 0-20 Hz. Potential natural frequency ranges which did not yield good results in the phase analysis were rejected from further consideration. For instance, referring to Fig. 2, potential natural frequency ranges corresponding to peaks above 15 Hz. yielded insufficient phase factors and so were not considered to contain probable natural frequencies. A similar conclusion was drawn for the frequency range about the markedly strong peak at 8.5 Hz. for the high reservoir case.

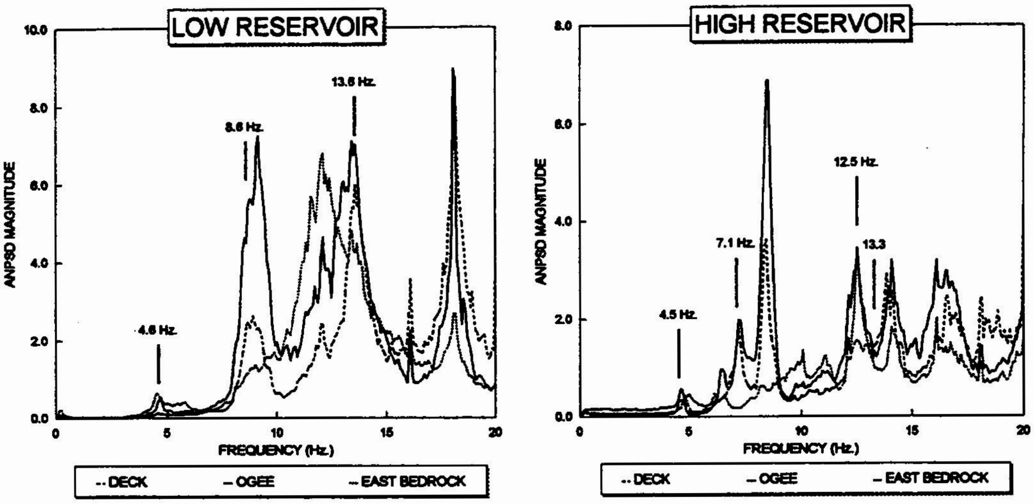


FIGURE 2: ANPSD FUNCTIONS FOR OGEE, DECK AND EAST BEDROCK, UPSTREAM-DOWNSTREAM DIRECTION, LOW RESERVOIR, FREQUENCY RESOLUTION OF 0.0781 Hz.

Probable natural frequency ranges with high phase factors (considered to be 20 degrees for the majority of points measured) were then subjected to coherence function consideration. In addition, transfer functions were calculated with bedrock signals as input and dam signals as output. All of the analyses undertaken yielded an optimum frequency range with a judged median value, for each probable natural frequency. The median values are shown in Fig. 2. All results are summarized in Table 1.

Referring to Table 1, it was found that for the low reservoir case, two probable natural frequencies of the dam and one of the left abutment bedrock were identified. Similarly, for the high reservoir case, three probable natural frequencies of the dam and one of the left abutment bedrock were identified. The most conclusive evidence was found for the first natural frequency of the dam for both reservoir cases, where phase factors of 10 degrees were obtained for most points measured. The weakest evidence was found for the higher natural frequencies, particularly those at 12.1 and 13.3 Hz. for the high reservoir case. For the latter, minimal ANPSD strength is evident in Fig. 2 and selection was based mainly on phase and bedrock transfer function analysis results.

The mode shape corresponding to the first natural frequency range for the low reservoir case is shown in Fig. 3. Only points with phase factors of less than 20 degrees are shown participating in the mode shape. Cross-

TABLE 1: SUMMARY OF AMBIENT VIBRATION ANALYSIS RESULTS

RESERVOIR CONDITION	PROBABLE NATURAL FREQUENCY (Hz.)	MODE SHAPE DESCRIPTION
High	4.5 +/- 0.1	Rigid body motion of left abutment bedrock
	7.1 +/- 0.2	Near single curvature of dam
	12.5 +/- 0.1	Near single curvature of dam (two inflection points)
	13.3 +/- 0.3	Near one and a half curvatures of dam (two inflection points)
Low	4.6 +/- 0.3	Rigid body motion of left abutment bedrock
	8.6 +/- 0.4	Near single curvature of dam
	13.6 +/- 0.3	Near one and a half curvatures of dam (two inflection points)

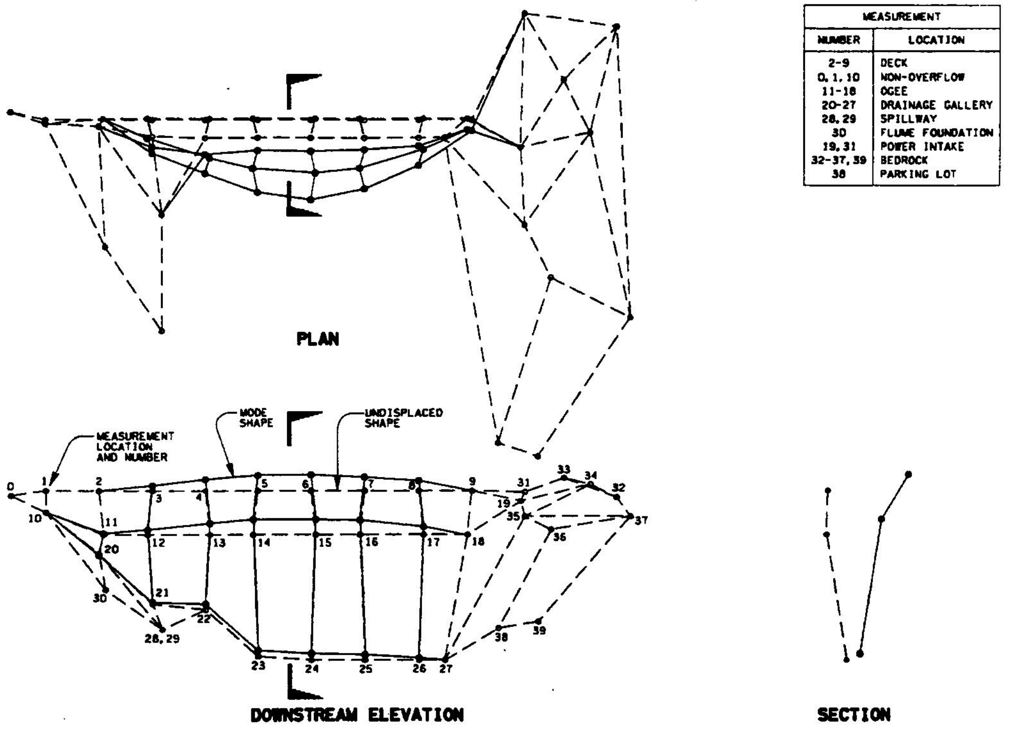


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FIGURE 3: MODE SHAPE OF FIRST NATURAL FREQUENCY, 8.6 +/- 0.4 Hz., LOW RESERVOIR, RELATIVE TO UPSTREAM-DOWNSTREAM REFERENCE SENSOR (MEASUREMENT NUMBER 13)

canyon components are not included. Note that left abutment bedrock points do not participate in the mode shape as most have a phase factor close to 90 degrees.

NUMERICAL MODEL CALIBRATION

In Fig. 4 is shown the finite element model of Ruskin Dam and its foundation bedrock, from the upstream side. The model is currently being calibrated. The dam and bedrock have been modelled with linear 8 noded solid elements with 3 degrees of freedom (DOF) at each node. The bedrock is modelled without mass. Single DOF mass elements have been used to represent hydrodynamic effects with mass computed using Westergaard theory. The deck has been modelled with quadratic 4 noded shell elements with 6 DOF at each node and linear 2 noded beam elements with 6 DOF at each node. A total of 20800 nodes and 7400 elements are in the model.

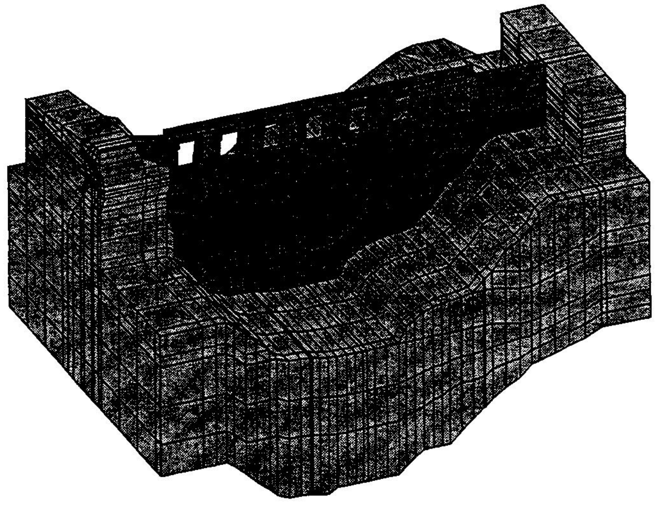

FIGURE 4: FINITE ELEMENT MODEL OF RUSKIN DAM

For efficient solution, Guyan reduction is utilized, yielding a reduced mass matrix. With 1250 master DOF's, approximately 48 hours is needed for the modal analysis using an IBM compatible 486 PC 66 MHz. with 32 Mb. of random access memory, utilizing 96 Mb. of virtual memory.

To date, calibration of the finite element model to the ambient vibration results has incorporated:

1. A monolithic structure across vertical construction joints. For prediction of response to larger amplitude vibrations, such as seismic events, careful consideration must be given to this feature.
2. Bedrock modelled with zones of varying dynamic modulus of elasticity.

Material properties in the finite element model include:

1. Concrete mass density: 2400 kg/m^3
2. Concrete dynamic modulus of elasticity: 35 GPa
3. Bedrock dynamic modulus of elasticity: 5-30 GPa

TABLE 2: COMPARISON OF AMBIENT VIBRATION AND FEM ANALYSIS RESULTS

RESERVOIR CONDITION	1ST NATURAL FREQUENCY (Hz.)		2ND NATURAL FREQUENCY (Hz.)	
	FEM	TEST	FEM	TEST
High	7.5	7.1 +/-	11.6	13.3 +/-
Low	8.6	8.6 +/-	13.9	13.6 +/-

Current modal analyses results for the natural frequencies matching the modes shapes of those measured in the field are shown in Table 2. Not shown but of note, the finite element model yielded more natural frequencies below 20 Hz. than were identified with the ambient testing and analysis. However, as the majority of concrete dam dynamic response is associated with the first natural frequency in the upstream-downstream direction (Chopra 1987), the ambient results remain of significant value. The Ruskin Dam finite element modal analysis has yielded a first natural frequency modal mass in the upstream-downstream direction of 62%.

Hydrodynamic effects on the dam dynamic properties are currently being studied.

CONCLUSIONS TO DATE

The following conclusions have been made to date:

1. Ambient vibration testing and analysis of Ruskin Dam successfully predicted natural frequencies and mode shapes of Ruskin Dam, including the significant first natural frequency.
2. Dynamic properties of Ruskin Dam identified with ambient vibration testing and analysis have proven useful in calibration of the finite element model of the dam.
3. Ambient signals recorded on the left abutment bedrock have proven to be useful as input signals for transfer functions used to identify natural frequencies.

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