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STATISTICAL ENERGY ANALYSIS OF A HIGH SPEED ELEVATOR CAB AND FRAME

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ABSTRACT

An analytic prediction model was developed to identify the dominant paths of broadband (100 - 5000 Hz) acoustic energy transmission into an elevator cab enclosure. Statistical Energy Analysis (SEA) was used as the method, including analytical SEA, test based SEA, and panel transmission loss experiments. The model was validated statically with vibration and acoustic measurements made in Otis' Ride Quality Evaluation Facility, and operationally with measurements made in Otis' Bristol Research Tower. The validated AutoSEA model has provided a new means of identifying and quantifying the dominant noise sources and paths for vibro-acoustic energy flow through the elevator cab. This analysis has also demonstrated potential as a design tool for evaluating cab enclosure noise reduction concepts.

1. INTRODUCTION

An SEA model of a high speed elevator was developed to predict the performance of design concepts for reduction of elevator interior noise. The basic approach was to experimentally characterize the important vibro-acoustic energy sources and identify the dominant paths of broadband (100 - 5000 Hz) acoustic energy transmission to the cab interior. Statistical Energy Analysis (SEA) was particularly well suited to this complex problem which involved modeling multiple sources and paths of structure-bore and airborne noise. The basic system of interest comprised an aerodynamically shrouded cab enclosure mounted through sound isolation pads to a rigid frame comprised of steel beams.

The main premise of SEA is to model the flow and power balance of vibro-acoustic energy paths in the subsystems which comprise the structure of interest. In SEA terminology, a subsystem is a structural or acoustic region used to model a uniform noise or vibration field, e.g. the cabin interior space or a beam in the car frame. In order to calculate the energy flow and power balance in an SEA system, three types of information are required: subsystem damping loss factors which describe the rate of energy dissipation from the subsystems, coupling loss factors which quantify the rate of energy exchange between two connected subsystems, and the vibro-acoustic power inputs to the SEA system. The cab and car frame were modeled with representative AutoSEA subsystems, each of which was treated as a lumped mass. Test based SEA measurements were used to define the subsystem damping loss factors. The coupling loss factors between physically connected subsystems were modeled by representative connections within AutoSEA, and these connections were validated using test based SEA measurements. The test based SEA estimates of damping and coupling loss were based on measurements of acceleration and sound pressure resulting from impact hammer and acoustic excitation of the various subsystems. Accelerometer and microphone data obtained under operational conditions in the test hoistway were used to generate forcing functions to simulate the ambient hoistway noise, cab exterior panel vibration, and frame vibration. These forcing functions were applied to constrain the energy of the "boundary" subsystems, and the resulting energy balance provided predictions of cab interior noise.

The statistical concepts inherent in SEA are particularly appropriate for modeling elevator enclosure noise as the assembly of the components can vary from installation to installation. Because of these variations, any robust prediction technique must be insensitive to these variations. Alternate techniques such as finite element modeling or modal analysis are not equally well suited to addressing the problem at hand because the frequencies studied are too high to be modeled practically. While this paper focuses on the validation of the AutoSEA model using data acquired on an elevator running at 9 m/s and 5 m/s, the utility of the model stems from the capability of identifying and addressing dominant sources and paths of cab interior noise. Having validated the basic SEA model, design changes and noise control concepts have been evaluated quantitatively without the need for extensive experimentation. For example, once the contribution to interior noise from a particular path can be evaluated, the effect of changing a component along this path can be predicted. Similarly, knowing the dominant paths focuses re-design efforts on problem components and enables cost/performance tradeoffs. This capability reduces the overall product development lead time and improves the product performance.

2. AutoSEA MODEL

As illustrated in Figure 1, multiple sources and paths of vibro-acoustic energy must be included in the AutoSEA model in order to rank the dominant energy sources and paths. Structure-borne noise enters the cab/car frame system as vibration energy induced at the roller-guides and hitch. This energy propagates through the car frame assembly, across the sound isolation pads, to the platform and then into the cab enclosure. The airborne noise enters the cab enclosure from many potential paths including the ventilation system, transmission through the wall panels, and acoustic leakage around the doors.

Using AutoSEA, the cab and car frame assembly was divided into more than one hundred representative subsystems. These subsystems included an acoustic cavity to model the cab interior; flexural panel elements to represent the exterior and interior wall panels, the ceiling, roof, and floor panels; beam elements to represent the frame members; and a rib-stiffened plate to model the platform. Within each subsystem, an experimentally estimated damping loss factor determined the rate of energy dissipation. The coupling between connected subsystems was modeled by representative connections within AutoSEA. The coupling loss factors were compared to experimentally estimated values for the subsystems in question and the parameters within AutoSEA which determine the coupling loss factor were adjusted if necessary to achieve agreement with experiment.

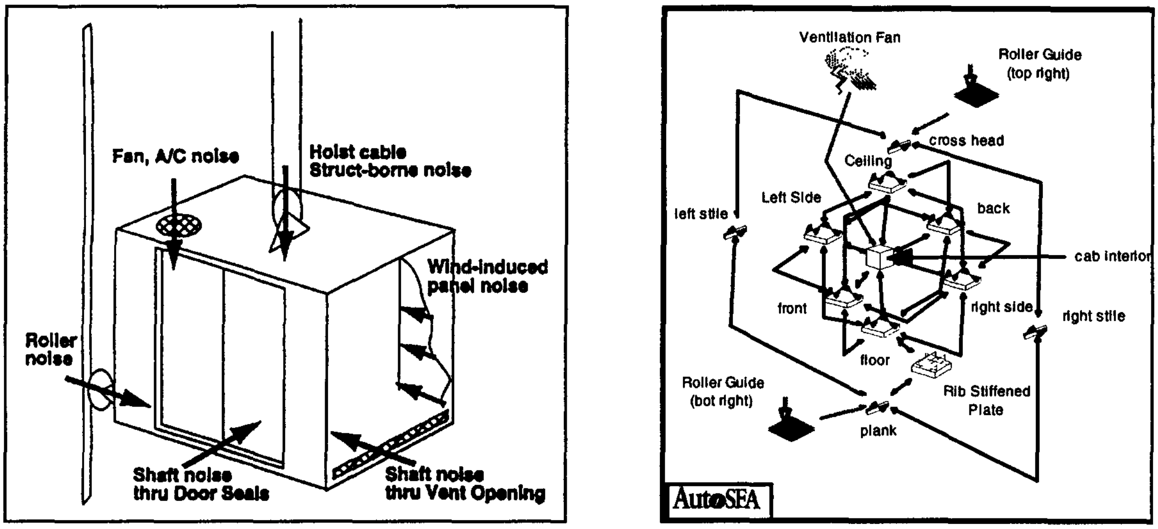

Figure 1. Schematic of Vibro-Acoustic Sources and Paths for an Elevator.

The experimental data used to estimate and validate the parameters in the SEA model was derived from a variety of sources. The response of the various components to structural excitation was determined by impact hammer testing in the Otis Ride Quality Evaluation Facility. These measurements were used to characterize the coupling and damping of the components (or subsystems) in question in the SEA model and to statically validate the model for structural excitation. The transmission of sound from the hoistway to the cab interior was also characterized experimentally in this facility by acoustically exciting the cab interior and the hoistway with a speaker system and measuring the resultant sound transmission. The modeling of sound propagating through the double wall ventilation ducts was validated against the results of transmission loss tests of the wall panels. A leakage model simulating the air gaps around the doors was incorporated into the model to achieve accurate prediction of the sound transmission from the hoistway to the cab interior, using experimental data.

The purpose of the static simulations was to validate the prediction of both the structure-borne noise transmitted through the stile/upright to the remainder of the cab/car frame system and the airborne noise which transmitted into the cab through the walls, the ventilation ducts, and the leakage areas. Based on these results, it was concluded that the SEA model can be utilized to simulate the flow of vibro-acoustic energy in an elevator cab/car frame system under operational conditions.

3. OPERATIONAL DATA

Validating the model under operational conditions required quantifying the vibro-acoustic energy entering the system. In AutoSEA, an energy input can be in the form of a known point force acting on a structure, a known power input to either a structural or acoustic subsystem, an acoustic field incident on a structure, an unsteady pressure field on a plate subsystem, or a defined energy level in a particular subsystem. The predictions described here utilized the latter approach. Measurements of various component energy levels were made at Otis' Bristol Research Test Tower. In short, it was assumed there were four dominant vibro-acoustic sources:

1. Upright vibration caused by the roller guide and rail interaction or hitch and cross head interaction
2. The acoustic field incident on the exterior of the cab
3. The acoustic field in the shroud cavity
4. Exterior panel vibration induced by aerodynamic loading

These four source excitations were measured directly and the energy levels computed from the measurements were used to constrain the vibration or sound pressure spectrum of the corresponding subsystem in the model. AutoSEA was then used to calculate the energy balance in the rest of the system. Note that these sources were not truly independent. For example, the sound pressure inside the shroud was largely due to that in the hoistway; however, it was more expedient to measure the sound pressure inside the shroud than to characterize the coupling of the shroud cavity to the hoistway. Similarly, the vibration of the exterior wall panels, though largely due to aerodynamic excitation, includes some content due to the vibratory energy being transmitted through the frame. Applying the constraint as a "user-defined energy" for the subsystem in question avoids these complications.

The acquisition of operational data was accomplished by recording the output signals of a set of microphones and accelerometers on two 16-channel TEAC DAT recorders. The data were acquired with a bandwidth of 5 kHz per channel with the elevator running at speeds of 9 m/s and 5 m/s. One channel of each recorder was dedicated to a vertical acceleration signal which was integrated to provide elevator velocity as a function of time. The resulting thirty-two channels of data were then downloaded from tape to computer storage for analysis with Matlab signal processing software. To insure that the experimental data used for the validation represented a statistically stationary system, only data from the constant velocity region of the elevator motion was used. One-third octave spectra were calculated from the data traces and used as inputs to the AutoSEA model, as described in the following sections.

3.1 UPRIGHT VIBRATION

The uprights (or stiles) of the car frame are critical subsystems from the SEA point of view in that all of the vibration energy input to the system from the roller guide/rail interaction and rope/hitch interaction propagate to the cab interior through the upright. If one neglects aerodynamic inputs on the cab exterior, all of the structure-borne vibro-acoustic energy flows through the uprights. Hence, measuring the vibration levels of this subsystem provides a means of quantifying the structure-borne vibro-acoustic energy entering the system. Eight accelerometers were used to obtain a space-averaged measurement of the upright vibration under operational conditions. Four accelerometers were used to measure front-to-back vibration and four were used to measure side-to-side acceleration. One-third octave spectra calculated from each accelerometer were combined to generate a space-averaged measurement.

3.2 ACOUSTIC FIELD INCIDENT ON CAB EXTERIOR

Another important source of interior noise was the direct propagation of the ambient sound field to the cab interior. The sound field incident on the cab was measured by microphones incorporating a novel approach to blend them into the contours of the cab so as to screen them from flow induced noise which would otherwise contaminate the measurement. These microphones were used to measure the sound levels at central locations on the two sides, back, and front of the cab. These individual measurements were then combined to generate a space-averaged sound field incident on the cab.

3.3 ACOUSTIC FIELD IN UPPER SHROUD CAVITY

Based on prior experience, a quantifiable amount of acoustic energy entered the cab through the ceiling ventilation ducts. While the ventilation fan noise itself was not considered because the fans were not running during the experiments, the propagation of noise from the shroud cavity through the ceiling ducts to the cab interior was modeled. Two microphones were placed in the upper shroud cavity to measure the sound pressure level within the shroud.

3.4 EXTERIOR PANEL VIBRATION

The transmission of vibratory energy from the exterior panel of the double wall enclosure to the inner wall and radiation into the cab interior was also modeled. By applying the measured energy level of the panels as a constraint on the AutoSEA model, the actual source of the excitation on the exterior wall (e.g. incident turbulent flow, impulsive aerodynamic forces resulting from the cab interaction with the hoistway, or structure-borne noise from the platform) need not be known. In order to characterize the vibration of the exterior panels, three accelerometers were located on each of three different exterior panels, the two right exterior panels and the center rear exterior panel. The space-averaged one-third octave spectrum of panel vibration over the rated speed region was used to define the subsystem energy constraint in the AutoSEA model.

4. SEA MODEL VALIDATION AND RESULTS

The operational measurements were applied to the SEA model of the elevator cab by setting the vibration energy levels of the upright and exterior panels, and the acoustic energy level of the external sound field (hoistway) and upper shroud cavity to the measured values. AutoSEA solved the system of energy balance equations resulting in predictions of the vibro-acoustic energy levels of all the subsystems which comprise the model, including the cab interior sound level. The predicted subsystem vibration and acoustic spectra were compared to measured spectra obtained over the rated speed region of the elevator operational measurements. In general, good agreement (± 3 dB) between predicted and measured spectra were obtained.

The measured subsystem vibration and acoustic spectra used to validate the model (which were obtained during the same set of hoistway experiments used to define the subsystem vibration and acoustic levels) include:

- *Cab interior sound level* - one cab center microphone
- *Interior panel vibration* - three arbitrarily placed accelerometers each on the rear center panel and the right side center panel
- *Floor panel vibration* - three arbitrarily placed accelerometers attached directly to the wood floor inside the cab by removing sections of the carpet
- *Sub-frame beam vibration* - four arbitrarily placed accelerometers measuring vertical vibration

Measurements from multiple sensors on a single subsystem were combined to yield a space-averaged measure of the response. Comparisons of measured and predicted spectral levels are illustrated in Figures 2 through 5 for the elevator running at 9 m/s. Figure 2 illustrates the good overall agreement between the SEA model predicted interior noise levels and the measured interior noise levels. The model predicts the experiment within 2 dB at all frequencies. The importance of this positive result stems from the fact that interior noise was the main figure of merit for the SEA modeling effort described here; hence, the good agreement lends confidence that the model is capturing the relevant physics and can be used to identify and quantify the dominant noise sources and paths.

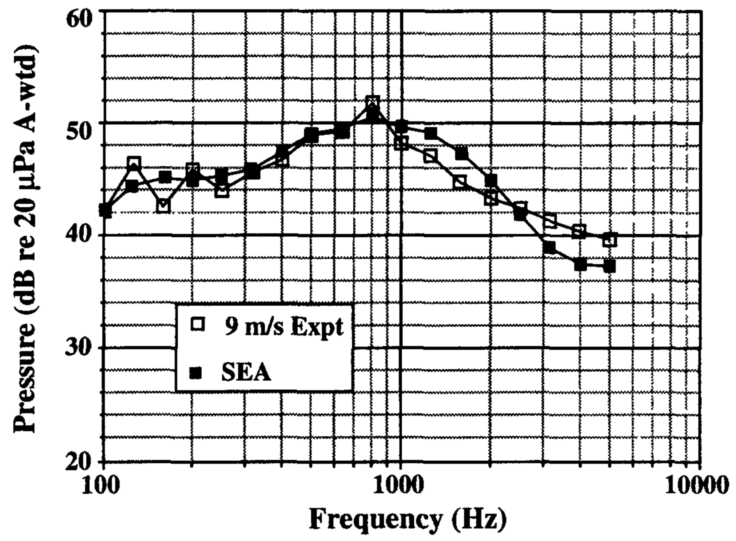

Figure 2. Cab Interior Noise Level

The model for the flow of energy through the double wall path (exterior panel vibration propagating to interior panel vibration) was validated by the comparison of measured and predicted inner panel vibration levels in Figure 3.

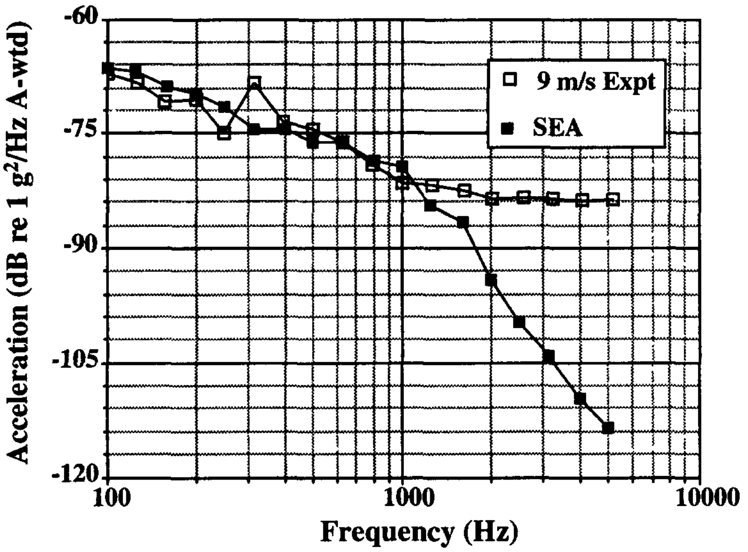

Figure 3. Response of Interior Wall Panel

Good agreement was observed both in terms of spectrum shape and level over the frequency range of 100 Hz - 1250 Hz. The deviation between the measured data and the prediction above 1250 Hz is due to the signal dropping below the noise floor of the instrumentation system. The good agreement between prediction and measurement within the 100 Hz to 1250 Hz range indicates that the AutoSEA model of the coupling between the interior and exterior wall represents the physics. Accelerometer measurements were also obtained on the support frame (a structural element which supports the platform via six sound isolation pads). A comparison of the predicted and measured vibration levels is presented in Figure 4. The good agreement between the model and experiment indicates that the SEA methodology correctly models the flow of vibration energy from the upright, through the frame, and to the support frame structural members.

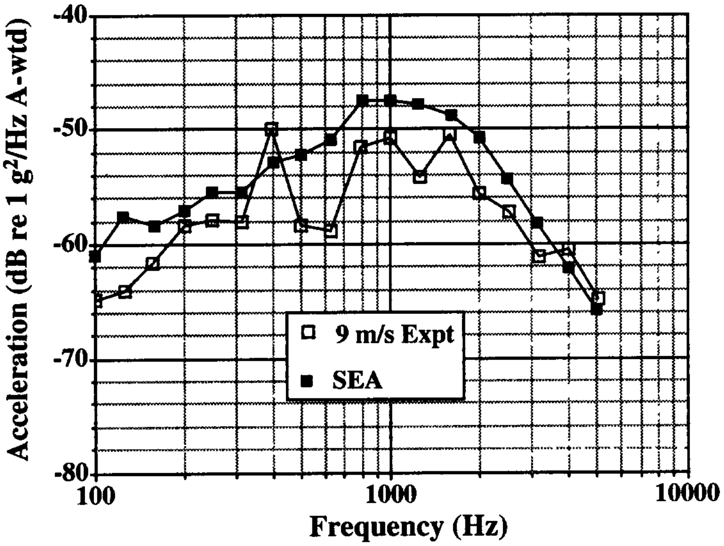

Figure 4. Response of Support Frame

This agreement was an important result because it implied that setting the vibration level of the uprights was an appropriate approach to specifying the structure-borne vibration energy due to the roller-guides and hitch, and it also implied that the vibration energy incident on the cab structure (via the sound isolation pads and platform) was accurately predicted and hence lends confidence to the prediction of structure-borne vibro-acoustic energy. The variations in the measurement at low frequencies (for example, between 300 Hz to 500 Hz in Figure 4) are common for components which are not modally dense within a particular third-octave band and are the failure of AutoSEA to predict such modal behavior does not indicate any deficiencies in the modeling.

The predicted vibration levels on the cab floor (Figure 5) were on the order of 4 - 6 dB lower than the measured levels for the 9 m/s operational case. The floor subsystem was problematic from the SEA model point of view as well as from the experimental measurement of vibration. The floor and platform are tightly coupled subsystems which violate some of the assumptions inherent in the experimental SEA parameter estimation algorithm used. The net effect is that the damping of these subsystems tends to be over estimated leading to predicted vibration levels which are lower than would otherwise be the case. The experimental estimation of SEA parameters for closely coupled subsystems is an area requiring further investigation.

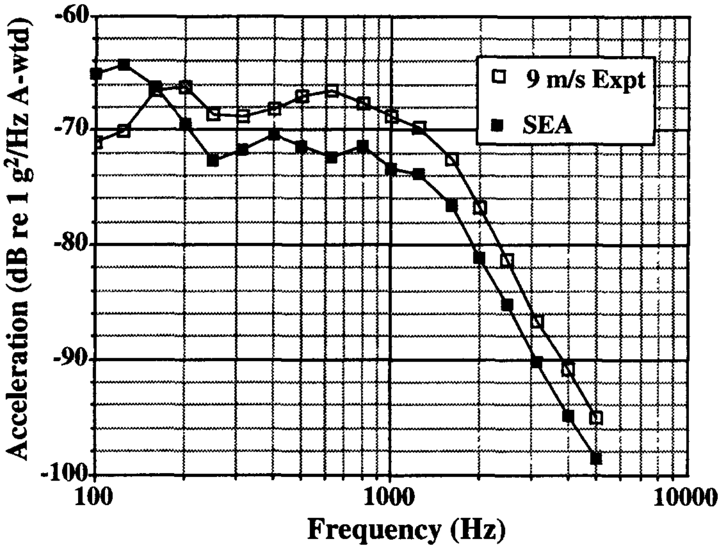

Figure 5. Response of Floor Panel

The AutoSEA model of the elevator operating at 9 m/s was found to simulate the noise and vibration physics of the system well enough to be useful for guiding design alternatives analysis. The primary benefit obtained from the modeling effort was that the importance of the various noise and vibration sources and paths could be quantified, thereby indicating which components of the system design should be addressed in order to reduce the cab interior sound levels. The relative contribution of the dominant paths by which sound power may enter the cab enclosure is illustrated in Table 1 for the 9 m/s and 5 m/s operational cases.

Table 1. Contribution of Dominant Noise Paths into Cab Interior (dB re Total Interior Noise Level)

Speed	Airborne	Floor	Ceiling Ducts	Walls
9 m/s	**-2 dB**	**-6 dB**	**-10 dB**	**-19 dB**
5 m/s	**-4 dB**	**-4 dB**	**-12 dB**	**-17 dB**

The data displayed in Table 1 is the sound pressure contribution of each path relative to the overall interior sound pressure level at that speed expressed in dB. At 9 m/s, the airborne path was the most significant (2 dB(A) less than the total) and the structure-borne path through the double walls was the least significant. At 5 m/s, the airborne path and structure-borne path through the floor were of equal magnitude (4 dB(A) less than the total).

5. CONCLUSIONS

Based on the good agreement between the predicted and measured response of several subsystems including the interior acoustic sound levels, it was concluded that the AutoSEA model captures the important physics of the vibro-acoustic energy flow in the cab and car frame system. Having demonstrated the accuracy of the model, one can proceed to delve into the power balance calculation results which indicate the dominant noise paths to the cab interior and their relative contribution to the overall noise level. The significant conclusions based on this analysis are as follows.

1. At 9 m/s, the dominant path was airborne noise radiating through the acoustic leaks and non-resonant energy transmission. The secondary path was structure-borne noise emanating from the floor. This path radiated only 3 dB less energy than the airborne path and was still significant from the point of view that *eliminating* the airborne noise would only reduce the interior noise by 5 dB (assuming the floor contribution remained the same.)
2. At 5 m/s, the contributions to interior noise were the same for the floor and airborne paths, so the greatest interior noise reduction possible by treating only one path was 3 dB.

Clearly, this type of information highlights focus areas for reducing the cab interior noise. Not only were the dominant paths identified, but the reduction required along a given path to achieve a particular cab interior noise target can be predicted. The model also illustrates how dramatically improving a single component can have only a minimal impact on the noise because the benefit is masked by a secondary source or flanking path of noise. A sequential build and test approach to noise reduction might overlook this point. Further analysis and SEA simulations have offered valuable insights into various noise reduction concepts which are currently being incorporated into Otis' high speed elevators.

The interior noise predictions presented herein were based on setting the SEA subsystem energy levels to those measured under operational conditions. Measurements of various component energy levels were made in a high rise test tower, both to describe the energy going into the system and to validate the SEA predictions. The measured data was used model constrain the subsystem energy to match the experimentally determined values in the AutoSEA. Although adequate for the current validation study, in general this approach has the limitation that any modification which would change the power flow through the subsystems in question would require re-testing to determine the new energy level to be imposed. Conversion of the measured energies to equivalent input powers and application of the "user-defined power" condition in the AutoSEA model would circumvent this limitation.

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