CHAPTER 9
CONCLUSIONS

What we call the beginning is often the end
And to make an end is to make a beginning.
The end is where we start from.
- *T.S.Elliot*

This research focussed on the development of the next generation of liquid dampers for mitigation of structural response. Two type of liquid dampers, namely the sloshing dampers (TLDs) and the liquid column dampers (TLCDs) were considered. Firstly, a new sloshing-slamming analogy was presented for sloshing type dampers. It was noted that the existing models neglect the effect of impact of liquid on the container walls. The first approach proposed by the authors is to consider a sloshing-slamming analogy of TLD. This involves modeling the TLD as a linear system augmented with an impact subsystem. This analogy captures the essence of the underlying physics behind the complexity of the sloshing phenomenon at higher amplitudes. The second approach uses certain nonlinear functions, described as *impact characteristic functions*, which can succinctly describe the phenomenological behavior of the TLD. The parameters of this model are derived from experimental studies. Experiments were also conducted to study the local pressures on the walls of the container and to better understand the nature of the impact process. It was observed that the peak pressures occur at the static liquid height. The pressure-time integration shows that the contribution of the impact pulse to the overall sloshing pulse is approximately 20-25%. This feature may play an important role in future modeling studies on TLDs.

Next, analytical modeling of tuned liquid column dampers (TLCDs) was considered. Optimum absorber parameters (i.e., tuning ratio and damping ratio) were derived for a variety of loading cases ranging from white noise excitation to filtered white noise cases. The theoretically obtained optimum absorber parameters were compared with experimental results and the match was found to very be good. The optimum absorber parameters were also determined for the case of multiple TLCDs (MTLCDs). These parameters include number of TLCDs, the frequency range and the damping ratio of each damper. MTLCDs are more robust as compared to single TLCDs with respect to changes in the primary system frequency. Moreover, the smaller size of MTLCDs offers convenient portability and ease of installation at different locations in the structure.

The beat phenomenon is very common in combined systems like structure-damper systems. This involves transfer of energy from one system to another and in some instances could be harmful to the structure. It has been observed that beyond a certain level of damping in the secondary system (i.e., the damper), the beat phenomenon ceases to exist. A mathematical and experimental study of the beat phenomenon was conducted. It was noted that the disappearance of the beat phenomenon is attributed to the coalescing of the modal frequencies of the combined system. Experimental validation of the beat phenomenon in combined structure-TLCD system was shown in the laboratory.

Various semi-active strategies were developed for the optimal functioning of TLCDs. These include gain-scheduling and clipped optimal system with continuously-varying and on-off control. Gain-scheduled control is useful for disturbances which are of long-duration and slowly-varying (e.g., wind excitation) and where the steady-state response is the control objective. The headloss coefficient is changed adaptively in accordance with a look-up table by changing the valve/orifice opening. This type of semi-active system leads to 15-25% improvement over a passive system. The application of these systems for offshore structures was also considered. Experimental validation of the gain-scheduled system was done in the laboratory using a prototype TLCD equipped with a valve controlled by a electro-pneumatic actuator and positioning system.

A different semi-active algorithm was also examined, which requires a controllable valve with negligible valve dynamics and whose coefficient of headloss can be changed by applying a command voltage. This type of control is more suited for excitations which are transient in nature, for e.g., sudden wind gusts or earthquakes. The efficiency of the state-feedback and observer-based control strategy was compared. Numerical examples showed that semi-active strategies perform better in terms of response reduction than the passive systems for both random and harmonic excitations. In the case of harmonic loading, the improvement was about 25-30% while for random excitation, the improvement was about 10-15% over a passive system. It was also noted that *continuously-varying* semi-active control algorithm did not provide a substantial improvement in response reduction over the relatively simple *on-off* control algorithm.

An experimental technique, namely the hardware-in-the-loop technique, was developed for testing liquid dampers. The main advantages, namely the cost effectiveness and repeatability of the test, is realized due to the fact that a virtual structure simulated in the computer interacts in real-time with the damper.

Finally, the design, implementation, cost and risk-based decision analysis for the use of liquid dampers in structural vibration control was laid out. Comparisons were made between different dynamic vibration absorbers (DVAs), namely the TMDs, TLDs and

TLCDs. It was estimated that the cost of a fully functional TLCD system has been estimated to be 1/10 times the cost of a TMD system with a similar level of performance. The risk-based decision analysis framework presented would facilitate building owners/ designers to ensure adequate life-cycle reliability of the building from serviceability viewpoint at a minimum cost. It was concluded that when the probabilities of failure are low, choosing semi-active dampers over passive dampers is not cost effective. However, in critically unserviceable structures, the semi-active scheme delivers better cost/utility benefits.

The following future studies in this area are recommended:

1. In the sloshing-slamming analogy of TLDs, the mass exchange parameter was determined from empirical relationships obtained through experiments, which relate the change in the hardening frequency as a function of excitation amplitude. This analogy could be further refined should it be possible to quantify more accurately the mass exchange between the sloshing and slamming modes from theoretical considerations.
2. The sloshing pressures and forces obtained during experiments should be compared to numerical sloshing studies which incorporate the slamming/impact action of the liquid.
3. Hardware-in-the-loop studies can be experimentally verified by conducting a full-scale test of the structure-damper system and then verifying it using a HIL simulation.
4. Experiments concerning semi-active TLCDs were done on band-limited white noise type excitations in order to provide proof of concept for the damping schemes. A more elaborate experiment in the wind-tunnel using a structure attached to a semi-active TLCD is needed before installing these dampers on actual structural systems. This will however, pose serious modeling concerns.