Experimental and Analytical Study on Application of Variable Fluid Damper in Base Isolation System

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URL	http://hdl.handle.net/10097/61518

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授　与　学　位	博士（工学）			
学位授与年月日	平成２１年９月９日			
学位授与の根拠法規	学位規則第４条第１項			
研究科，専攻の名称	東北大学大学院工学研究科（博士課程）都市・建築学専攻			
学位論文題目	Experimental and Analytical Study on Application of Variable Fluid Damper in Base Isolation System（性能可変オイルダンパーの免震構造物への適用に関する実験解析研究）			
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論文内容要旨

ABSTRACT

Decoupling buildings from the damaging effects of the ground motion produced by a strong earthquake, which is generally referred to as “base isolation”, has now achieved recognition as a practical design alternative. This technique is based on shifting the fundamental period of the superstructure sufficiently away from predominant period of most earthquakes so that the behavior of the entire structure can be governed by its first mode where the deformations are concentrated at the isolation level, while the superstructure moves almost rigidly.

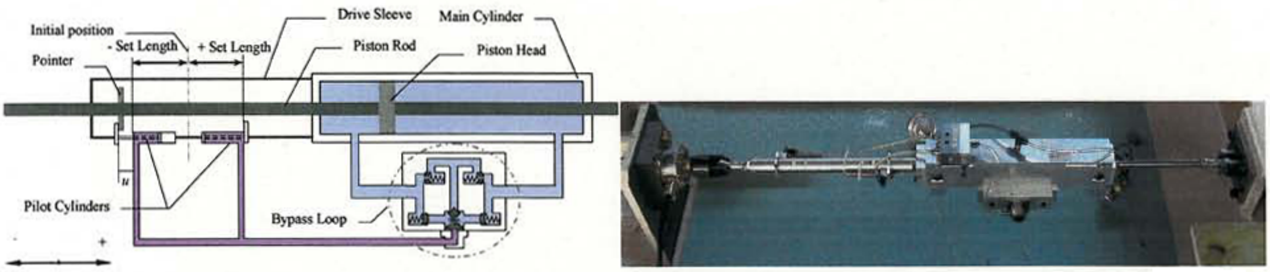
Even though the impulsive aspect of the near-fault ground motion records was originally identified more than three decades ago, the lack of adequate number of near-source ground motions has hindered quantifying near-fault ground motions. Recently, obtaining records from near-source sites has raised serious question about efficiency and viability of base isolation technique for seismic protection of buildings. Impact of these rare strong pulses on base-isolated systems can lead to large isolator displacement. It is a common practice to reduce displacement demand on the isolators by means of high damping in the isolation system. The supplemental damping does control displacement, but at the expense of increasing transmitted acceleration and interstory drift.

Although design of isolator and superstructure is based on Design Basis Earthquake (DBE) level, safety of isolation system should be confirmed at Maximum Capable Earthquake (MCE) level. Displacement control at MCE level, which represents a very large and very rare event, may result in a too stiff and heavily damped system. The solution to this dilemma is how provide control displacement for large input earthquakes while maintaining good performance for more frequent minor to moderate events.

Variable Fluid Damper has been proposed and small-scaled prototype device has been fabricated at Tohoku University to decrease base displacement of isolation system especially under extreme excitations (see Figure 1). The Variable Fluid Damper

(VFD) has been developed to control base displacement of seismically isolated structure by providing linear damping to minimize counter effect on superstructure at moderate ground motions and enhancing energy dissipation capacity through nonlinear behavior when base isolated system is subjected to extreme event such as near-field excitation. Motivated by control of isolator displacement under severe condition and providing functionality of seismic isolation at design level, a systematic experimental and analytical study on application of Variable Fluid Damper in base isolation system has been carried out in this dissertation.

The research activities to achieve the objectives involved the following steps: Behavior and mechanism of Variable Fluid Damper was discussed; Properties of the VFD were identified through harmonic loading test; Performance of the small-scaled VFD was investigated experimentally and analytical model was developed to simulate response of the VFD; A series of shaking table test were conducted on base-isolated single-story test structure incorporating VFD to verify analytical simulation; Thus numerical model reasonably was employed for assessment of VFD response; Comprehensive analytical and parametric study was conducted to investigate performance of the VFD within different isolation system; and, Application of the VFD was considered for base isolation system of full-scale relatively high-rise building.



(a) (b)

Figure 1 Variable Fluid Damper: (a) Schematic diagram; (b) Photograph

Distinctive features of the proposed Variable Fluid Damper are as follow: VFD is regulated by an internal mechanism independent of power supply, sensor, and monitoring; VFD normally behaves as a linear viscous damper to provide functionality at frequent events; and When displacement overreaches preset value energy dissipation is increased through nonlinear behavior to reduce isolator displacement at extreme condition.

The configuration of the VFD consists of a run-through fluid damper combined with a bypass loop (Figure 1a). The bypass loop is connected to two pilot-cylinders. The bypass loop has an orifice and a valve that is adjusted by a control mechanism. A pointer is installed on piston rod of the damper. The pilot-cylinders are fastened with appropriate distance, referred to as set length, from initial position of the pointer. As soon as damper's displacement exceeds set length, the pointer dislocates piston of the pilot-cylinder. Consequently, spring is compressed proportional to volume of fluid discharged from the pilot-cylinder, thus valve is obstructed. Damper response has two modes, when valve is open and when valve is close.

In normal mode, valve is open and damper forced is proportional to relative velocity of the damper rod with respect to the damper cylinder (Figure 2b). Linear viscous behavior, even though fluid can flow across orifice and valve, is mainly due to valve effect. In nonlinear mode when maximum displacement overreaches set length, valve is closed by valve-spring interaction; damper force is proportional to square of velocity (Figure 2c). When internal pressure of the damper surpasses spring-valve interaction, which is equivalent to a limiting force for nonlinear behavior (F_l), then valve is pushed back. The limiting force defines upper bound of nonlinear response of the damper.

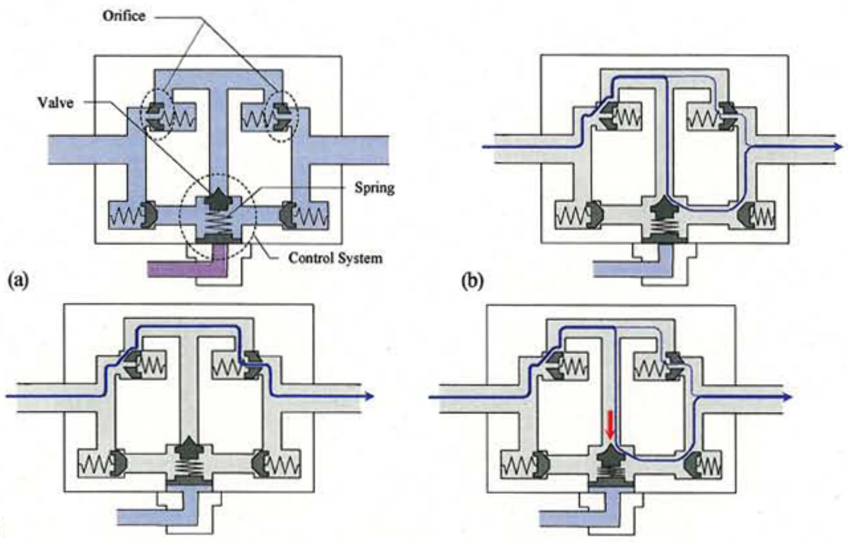


Figure 2 Bypass loop: (a) Detail; (b) Linear stage (c) Nonlinear stage

The damper response in different stages was expressed by simple mathematical formulas. The ideal mathematical simulation of the VFD in linear and nonlinear stages is illustrated in Figure 3.

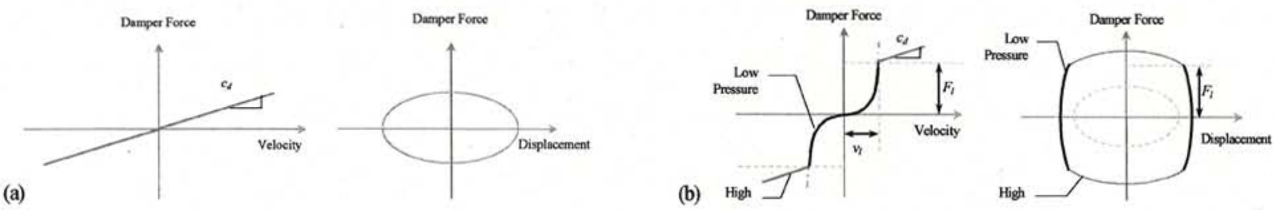


Figure 3 Damper force versus velocity and displacement: (a) Linear stage (b) Nonlinear stage

To identify dynamic properties of the VFD, response of the prototype damper was studied experimentally subjected to sinusoidal motion over a range of frequencies. Damper configurations consisted of using different set length, changing type of pilot-cylinder, and replacing of the control system. Results of harmonic loading test on prototype damper were compared with values predicted by formulas developed for numerical model of the damper behavior. Numerical simulation of the damper force agreed reasonably well with experimentally measured results, so accuracy of simulation model for damper force was validated.

Shaking table test was conducted on single-story isolated test structure incorporating the prototype VFD to investigate performance of VFD experimentally and to assess validity of numerical simulation. Details of the test structure is depicted schematically in Figure 4a. Structural properties of the test structure were identified through quasi-static loading, free vibration, harmonically forced vibration, and white noise excitation in different conditions.

Lumped-mass models was used for simulation of the test structure. The simulation model of bare frame (without bracing) was a two degree of freedom (2-DOF) system. When the frame was braced, relative displacement of the mass respect to the base was so small that corresponding degree of freedom could be disregarded; therefore, simulation model was a single degree of freedom (SDOF) system, to which attributed mass was equal to total mass.

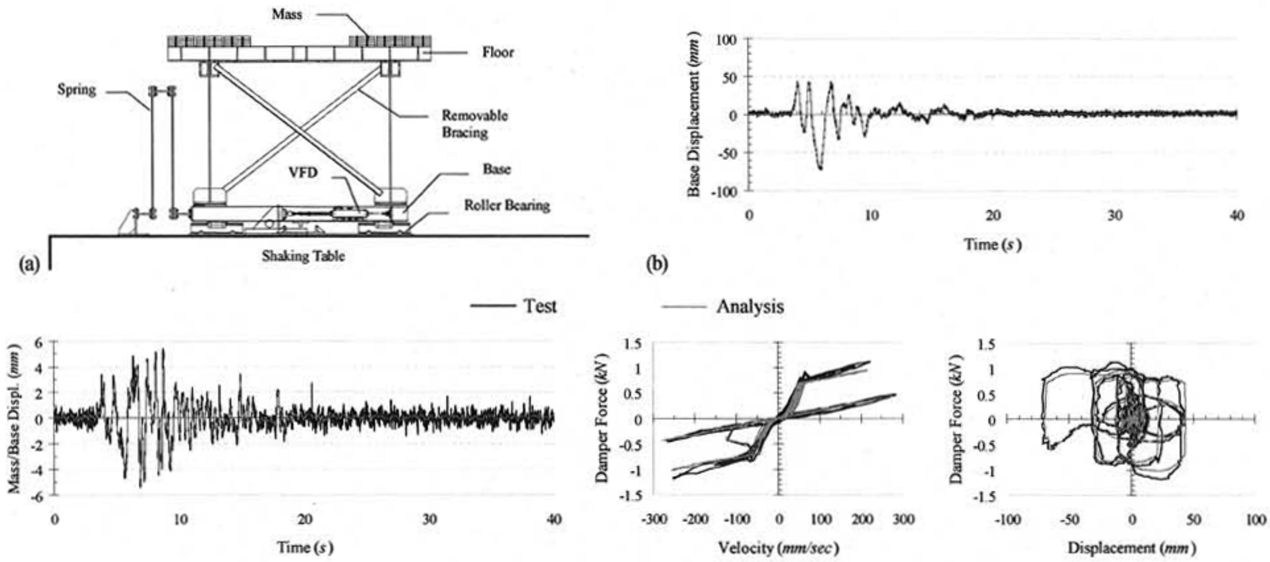


Figure 4 Shaking table test on isolated structure incorporating VFD: (a) Detail of test structure
(b) Sample of experiment results for 2-DOF system under scaled Kobe ground motion compared with analytical simulation

Experimental investigation of the VFD utilized in base isolation demonstrated that the developed damper could reduce maximum base displacement through increasing energy dissipation while transmitted acceleration might be increased. Numerical simulation of the damper was verified by carrying out shaking table test on isolated test structure incorporating VFD, so performance of the VFD within isolation system can be evaluated adequately by analytical study. For instance, comparison of experiment with analysis is presented in Figure 4b.

Performance of the Variable Fluid Damper incorporated into base isolation system was evaluated through comprehensive analytical study. To understand influence of the VFD, response of a mid-rise isolated building was investigated utilizing lumped-mass, shear-building model subjected to different ground motions. Superstructure was an eight-story reinforced concrete moment-resisting frame building, while simple isolation system (including linear spring and damping elements) and sliding isolation system were considered for seismic isolation. A parametric analytical study was carried out to recognize influence of properties of the VFD on response of base-isolated building. The main goal was recognizing effect of the VFD on the response of isolation system under near-fault and far-fault earthquake records.

Among parameters, that control response of the VFD, nonlinear stage limiting force and set length had major role. Limiting force represents amount of additional damping force provided by VFD when maximum base displacement exceeds preset value. Set length regulates response of the VFD in different stages. Analytical study results revealed that VFD could be recommended to be applied as a safety (supplementary) device within isolation system, where this damper normally has small contribution in total damping of isolation system.

Application of the VFD within base isolation system of relatively high-rise building was investigated by means of analytical survey. Physical properties of the full-scale building were estimated for simulation model. Superstructure was an eighteen story RC frame building. To include nonlinear behavior of the superstructure, bilinear origin-oriented model was adopted for shear-drift constitutive law to take effect of cracking into account. The isolation system, which had bilinear load-deformation relationship, was a hybrid passive energy dissipation system consisting of Sliding-Elastomeric Bearings and Laminated Rubber Bearings. In addition, properties of base isolation system were determined to find isolation system similar to the isolated building.

Three far-fault records (Hachinohe, El Centro, and Tohoku), four near-fault records (Kobe, Sylmar, Tabas, and Imperial Valley), and one artificial record (Sannomalu recommended for design of isolation systems) were utilized for analytical study. As the common design practice of Japan implies, ground motions were scaled to have 0.25 *m/s*, 0.5 *m/s*, and 0.75 *m/s* PGV as service criterion, design criterion and safety criterion respectively. Design requirements were considered to ensure safety of building content at service level (L1), functionality at design level (L2), and isolator performance at safety level (L3).

Two cases were considered for application of VFD in base isolation: Main element of isolation system and safety device that is added to isolation system. Analytical study on application of the VFD for both cases revealed that at over-design loading level, supplementary damping was necessary that might be provided by the proposed damper. Appropriate properties of the VFD that met design requirements of base isolated system at safety loading level were found. Effectiveness of the VFD to keep base displacement bellow allowable limit was confirmed subjected to over-design ground motions. It was shown that using VFD as supplementary device was advantageous.

Experimental study on prototype damper and analytical study based on modeling VFD showed that the proposed idea and objective could be achieved. The VFD enhanced robustness of base isolation system at extreme events while performing well at design level earthquakes.

論文審査結果の要旨

兵庫県南部地震の後、免震建物が大いに普及しているが、長周期成分を含む巨大地震が到来すると、免震層のクリアランス以上の応答変位が生じ、擁壁に建物が衝突することが懸念されている。本論文では、電気を使わずに変位に応じて機械的に減衰性能を変化させることができる性能可変オイルダンパーを開発し、その縮小試験体を作成して振動実験により基本性能を確認し、さらに高層の弾性すべり支承鉄筋コンクリート造免震建物にその装置を設置したモデルで地震応答解析を行って、その有効性を示したもので、全7章よりなっている。

第1章は序論である。

第2章では、性能可変オイルダンパーの機構を概説するとともに、製作した縮小性能可変オイルダンパーを振動台により定常波加振して、その性能を表す諸値を明らかにしている。さらに、その結果を整理して、変位が大きくなると比例的にダンパーの減衰係数が大きくなり、想定通りの機構を有することを示している。

第3章では、免震建物の地震応答解析手法を概説し、本研究における考え方を示している。

第4章では、第2章で性能を確認した縮小性能可変オイルダンパーを、1層鉄骨造の縮小試験体に設置して、記録地震動を入力した振動台実験を行った結果を示している。検討において、入力波は海洋型として 1968 年十勝沖地震の八戸波を、直下型の兵庫県南部地震として神戸波を対象とし、ダンパーの初期設定クリアランスをパラメータとしてさまざまなケースを設定している。得られた結果から、本ダンパーを使用することにより、応答加速度をあまり増大させずに応答変位を低減できることを明らかにしている。さらに、このダンパーの特性を適切に表現できる解析モデルを提案し、それを用いれば、実験結果をよくシミュレーションできることを示している。

第5章では、8層の鉄筋コンクリート造免震建物を想定して、性能可変オイルダンパーを設置する場合に、ダンパーのどの性能が応答低減に対して有効であるかを明らかにするためにパラメトリックスタディを行っている。その結果、ダンパーの初期設定クリアランスの大きさと、性能可変して減衰係数が増大した後にその性能を元の小さい値に復帰させる荷重の2つが最も重要であることを明らかにしている。

第6章では、実在する 18 階建の弾性すべり支承鉄筋コンクリート造免震建物を対象として、性能可変オイルダンパーを設置した場合の有効性を検討している。解析における建物の諸値は、検討用に簡略化して設定し、上部建物は鉄筋コンクリートの性状を表すためにひび割れを考慮した弾塑性モデルとしている。弾性すべり支承の摩擦係数と、性能可変オイルダンパーの減衰係数の設定においては、性能可変オイルダンパーを主体的に稼動させる場合と、巨大地震時の過大応答変位を抑制するために補足的に稼動させる場合の2ケースを設定している。得られた結果としては、上部建物の応答加速度・応答変位が過大にならないようにするためには、後者の補足的な使用が望ましいと結論つけている。

第7章は結論である。

以上を要するに、本論文は、地震応答変位に応じて減衰性能を機械的に大きくすることができる性能可変オイルダンパーの性能を明らかにし、さらに、弾性すべり支承を有する鉄筋コンクリート造高層免震建物に適用した場合の有効性を示すものであり、長周期成分を持つ巨大地震に対する免震建物の安全性を向上させることに寄与するところが少なくない。

よって、本論文は博士（工学）の学位論文として合格と認める。