VISCOUS HEATING OF FLUID DAMPERS UNDER SMALL AND LARGE AMPLITUDE MOTIONS

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ABSTRACT
This paper summarizes the results from a comprehensive experimental program in an effort to better understand the phenomenon of viscous heating of fluid dampers under small stroke (wind loading) and large stroke (earthquake loading) motions. Two dampers, one with 15 kip and one with 250 kip force output at peak design velocity, have been instrumented and tested under various amplitudes and frequencies. Temperature histories at different locations along the damper casing and within the silicon fluid that undergoes the shearing action have been recorded. The paper shows that the experimental results can be predicted satisfactorily with mathematical expressions proposed previously.

INTRODUCTION
The rapid success of fluid dampers in buildings, in association with the increasing need for safer bridges, has accelerated the implementation of large-capacity damping devices in bridges. The Vincent Thomas suspension bridge, the Coronado Bridge and the 91/5 highway over-crossing (Delis et al. 1996, Zhang et al. 2004, Makris and Zhang 2004), all three in southern California, as well as the Rion-Antirion cable-stayed bridge (Papanikolas 2002) in western Greece are examples of bridges that have been equipped with fluid dampers. Figure 1 (top-left) shows a view of four 250 kip dampers installed at the east abutment of the 91/5 over-crossing (bottom-left), while Figure 1 (top-right) shows a view of fluid dampers and elastomeric bearings installed at the approaching spans of the Rion-Antirion bridge (bottom-right). In addition to the smaller dampers shown, the Rion-Antirion bridge has four large, 350 kip dampers installed between each of the four piers and the bridge deck.

When fluid dampers are installed within the skeleton of buildings to suppress earthquake or wind-induced vibrations, the piston displacements and velocities are relatively small. In contrast, when the fluid dampers are incorporated either in the seismic isolation system of structures or between the towers/peers and the deck of bridges, the piston displacements and velocities can be large. When the dampers undergo large and prolonged displacement histories, the temperature rise

Figure 1. View of the four, 250 kip dampers (top-left) installed at the east abutment of the 91/5 over-crossing in Southern California (bottom-left). View of fluid dampers and elastomeric bearings (top-right) installed at the approaching spans of the Rion-Antirion bridge (bottom-right) recently open to traffic in western Greece.

within the fluid of the damper might be appreciable to the extent that it may damage the end-seals and trigger failure of the damper.

This paper presents selective results from a comprehensive experimental study on the problem of viscous heating of fluid dampers. Two fluid dampers of different size with force-outputs of 15 kip and 250 kip, at their maximum design velocity, have been tested and temperature histories have been recorded at various locations of the damper housing and within the fluid of the damper. Figure 2 shows views of the two fluid dampers mounted on their respective testing frames.

Experimental data under small-stroke motions of the 250 kip damper showed that a single closed form expression derived from first principles is capable of predicting the temperature rise at different locations of the damper with remarkable fidelity. The recorded time histories under long-stroke motions suggest a two parameter cooling law which is an extension of Newton's Law of cooling. The proposed two parameter cooling law allows for a dependable estimation of the internal temperature of the fluid that undergoes shearing action once the external temperature on the damper casing is known. Considering that monitoring of the external temperature of the damper casing is a relatively straight forward task this study develops a valuable formula which esti-

Figure 2. View of the two fluid dampers investigated in this study as they are mounted on their testing frame. Top: 15 kip damper; and bottom: 250 kip damper.

mates the internal fluid temperature of the damper during violent shaking when the external temperature is known.

EXPERIMENTAL STUDIES

Component Testing Under Small-Stroke Motions — Wind Loading

The problem of viscous heating under small amplitude and prolonged duration motions was studied experimentally on a 250 kip damper at the Earthquake Engineering Research Center of the University of California, Berkeley. Figure 2 (right) shows a photograph of the experimental setup with twelve thermocouples—six internal high-temperature thermocouple probes in contact with the internal oil, and six external thermocouples. The setup comprises a self-equilibrating reaction frame, a 340 kip trunnion-mounted actuator with a stroke of ± 12 in. and a 1000 gpm proportional servo-valve.

The 250 kip damper has a mid-stroke length of 72 in., and a maximum stroke of ± 8 in. Unlike the 15 kip damper, the 250 kip damper has been designed to deliver the nonlinear force-velocity relation $P(t) = C|\dot{u}(t)|^{\alpha}\,\mathrm{sgn}[\dot{u}(t)]$, where $C = 965.2\,\mathrm{kN(sec/m)}^{\alpha} = 60\,\mathrm{kip(sec/in)}^{\alpha}$ with $\alpha = 0.35$. The 250 kip damper considered in this study was originally one of two spare dampers provided for the 91/I5 overpass in the greater Los Angeles area. The overpass uses a total of eight dampers, four at each end, to dissipate energy and control the displacement of the bridge deck during a seismic event. A photograph showing the four dampers installed at the south end of the overpass is shown in Figure 1 (top). The seismic response of the 91/I5 overpass has been studied by Zhang and Makris (2004).

Figure 3 shows a detailed photo of one row of thermocouples and a schematic of the thermocouple locations, respectively. The thermocouples labelled by the circled 1 through 6 are internal thermocouple probes. Thermocouples 1 and 4 are at the mid-stroke location (separated by $90°$ along the circumferential direction), thermocouples 2 and 5 are at +4.5 in, and thermocouples 3 and 6 are at the end of the stroke location (+8 in.). The thermocouples labelled by the circled 7

through 12 are external thermocouples located at roughly the same locations as the internal thermocouples, with 7 and 10 at mid-stroke, 8 and 11 at +4.5 in., and thermocouples 9 and 12 at the end of the stroke (+8 in.).

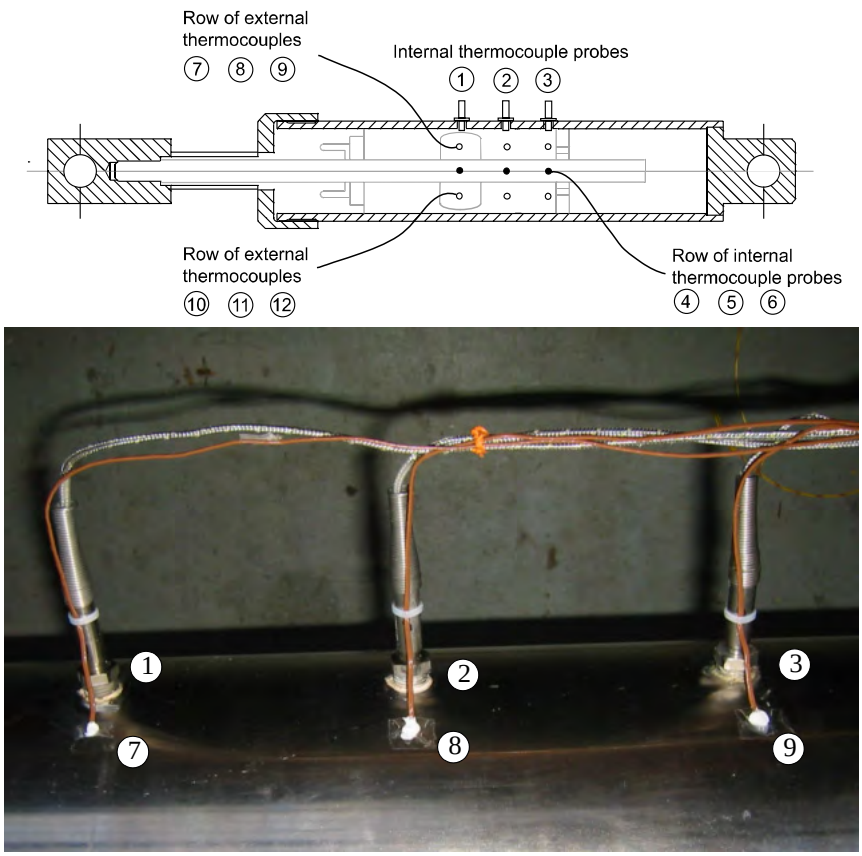

Figure 3. Top: Schematic of the 250 kip fluid damper indicating the locations of the six internal thermocouple probes ((1) through (6)) and the six external thermocouples ((7) through (12)). Bottom: Close-up showing one row of internal thermocouple probes and one row of external thermocouples.

Figure 4 plots the recorded temperature histories at the mid-stroke position under harmonic loading with amplitude $u_o = 0.5$ in. and frequency $f_o = 0.666$ Hz for a duration of loading equal to 23 minutes (920 cycles). The recorded temperature histories with thermocouples No. 1 and No. 4 shows that the temperature rise is not axisymetric. The temperature measured by thermocouple No. 1 increases much faster at the beginning of loading and subsequently the temperature measured from both thermocouples rise at approximately the same rate. Upon termination of loading the temperature homogenizes and the two thermocouples indicate the same temperature within five minutes (300 sec). The experimental data shown in Figure 4 are used to examine the validity of an analytical expression derived previously by the senior author (Black and Makris 2005). Figure 4 (left) shows that the analytical solution with x=0 offers a very satisfactory prediction for the temperature history at mid-stroke. Figure 4 (center) plots the recorded temperature histories at x=4.5 in. under the same loading. Now the recorded temperature histories from the two thermocouples separated by 90 degrees are almost identical while the temperature rise at mid-stroke (x=0) since the location x=4.5 in. is away from the localized heat source. The analytical expres-

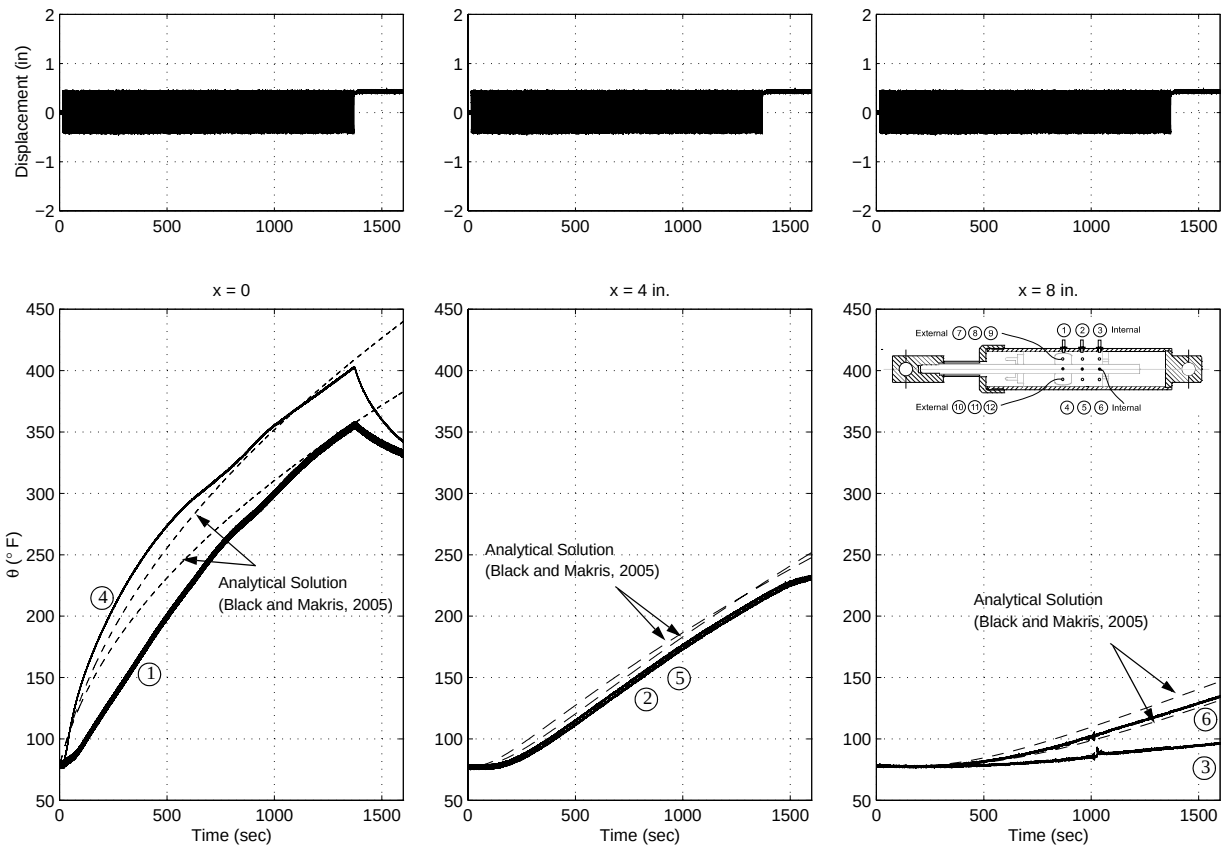

Figure 4. Comparison recorded temperature histories (thin lines) at x = 0 (left), x = 4.5 in. (center) and x = 8.0 in. (right) with the analytical predictions under harmonic loading with U_o = 0.5 in. and f = 0.66 Hz.

sion offers a good prediction for x=4.5 in not only for the peak values but also for the entire shape of the temperature curve through the history of loading. An equally good prediction is achieved when x=8.0 in. which predicts the temperature rise at the end-stroke locations. At the end-of-stroke location the temperature rise is not axisymetric; however, the prediction is in close agreement with the history of the hotter thermocouple. The temperature rise prediction at the end-of-stroke location is of prime interest since we are concerned with the temperature that the end-seals will experience.

Component Testing Under Large-Stroke Motions — Earthquake Loading

The problem of viscous heating under large-amplitude motions was investigated experimentally with two dampers — a small 15 kip damper and the 250 kip damper introduced in the previous section.

15 kip Damper

The experimental setup for the testing of the 15 kip damper is shown in Figure 2 (left). The force developed in the damper is measured through a stationary load cell that is connected between the damper and the reaction frame. The imposed displacement history is measured with a linear variable differential transducer (LVDT) located at the right end of the actuator.

Temperature histories are recorded at two internal and two external locations. The temperature at the two internal locations was measured via high-pressure, high-temperature thermocouple probes (labelled by the circled 1 and 3) installed directly through the damper housing. The probes were installed near the end of the stroke, (+6 in.) and separated by $90°$ in the radial direction. The external temperature was measured using 2 Type-K thermocouples placed to coincide with the internal probes (labelled by the circled 2 and 4). The internal and external thermocouples could not be placed at the mid-stroke location as they would impede the movement of the outer sleeve of the damper housing which moves in line with the piston head.

Figure 5 plots the recorded and predicted temperature histories when the damper is subjected to long-stroke harmonic loading. The top plot in each figure shows the input time history, while the bottom plots shows the recorded internal and external temperature histories together with predicted internal temperature history. The lines with the circled numbers are the recorded temperature histories at the positions indicated on the inset damper schematic and Figure 3. In both Figures 5 (left) and 5 (right), the anlytical solution offers a dependable estimate of the internal temperature of the fluid recorded near the end-seals of the damper (Black and Makris, 2005). While there is a small difference between the readings of thermocouples No. 1 and No. 3 in Figure 5 (left); the internal and external temperatures recorded at different radials are nearly the same indicating that the 15 kip damper exhibits a nearly radially symmetric temperature rise. This conclusion does not hold for the 250 kip damper.

250 kip Damper

A comprehensive testing program was conducted with the 250 kip damper in order to characterize its performance under long-stroke motions and study the force-temperature relationship of the damper. Experimental tests at four different amplitudes ($\pm$ 4, 5, 6 and 7 inches) were performed reaching piston velocities up to 17.5 in/sec. Figure 6 plots the recorded and predicted temperature histories when the 250 kip damper is subjected to long-stroke harmonic loading. As in Figure 5, the top plots in Figures 6 show the input time history, while the bottom plots show the recorded internal and external temperature histories together with the predicted internal temperature history (dashed line). Figure 6 reveals that the analytical solution for the internal oil temperature given the external temperature provides a satisfactory prediction (Black and Makris 2005). In addition, it is also clear that the heat distribution is not axisymmetric and that the temperature rise at the end-of-stroke locations is relatively small compared to the temperature rise at mid-stroke.

CONCLUSION

This paper presents selective results from a comprehensive experimental program that investigates the problem of viscous heating of fluid dampers during small and long-stroke motions. Temperature histories at various locations along the damper casing and within the silicone fluid that undergoes the shearing action have been recorded and used to validate closed form expressions which estimate the internal temperature of the damper fluid during wind and earthquake loading.

Under small-stroke motions (piston stroke is a fraction of its head diameter) the temperature rise is more intense in the vicinity of the piston head and there is an appreciable temperature gradient along the longitudinal direction of the damper. Experimental data under small-stroke motions on a 250 kip damper showed that a single closed-form expression that was derived from first principles

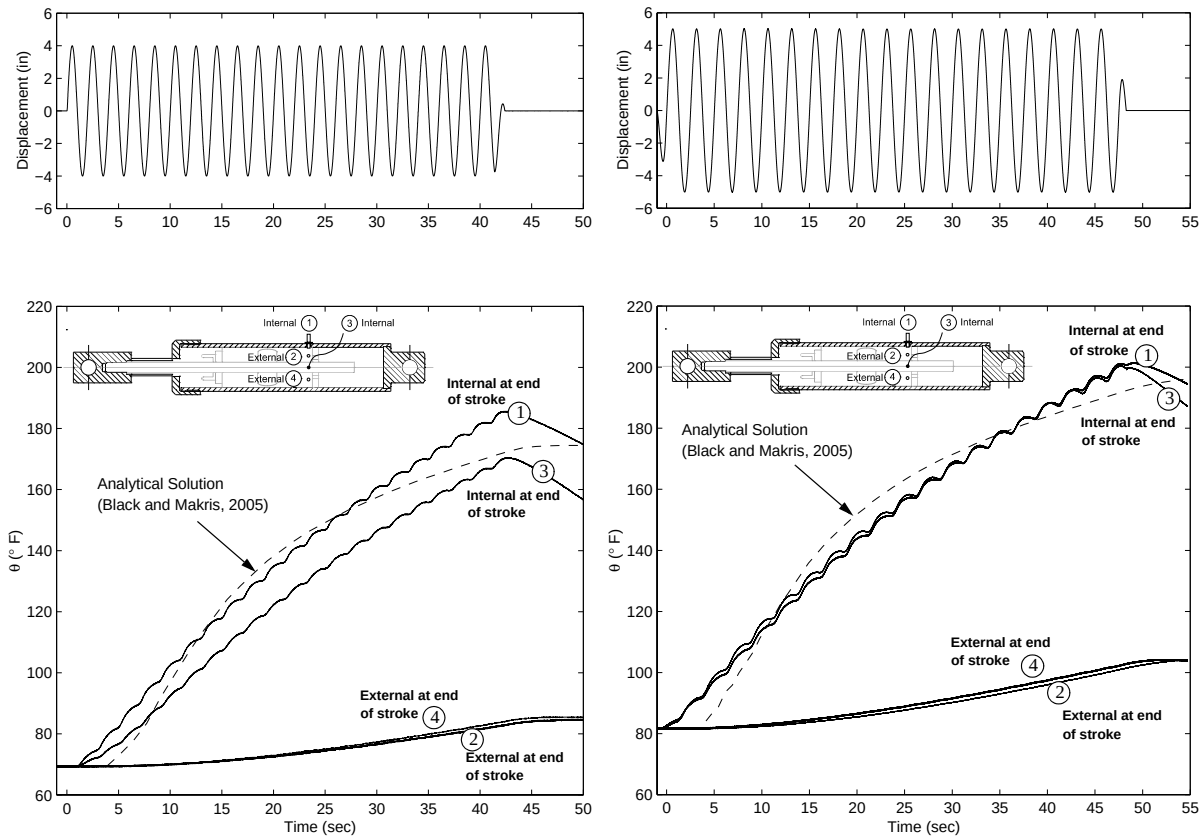

Figure 5. Top: Plots showing the harmonic inputs with amplitude, U_o = 4.0 in., f = 0.5 Hz (left) and U_o = 5.0 in., f = 0.4 Hz (right) imposed on the 15 kip damper. Bottom: Comparison of the measured temperature histories with the analytical solutions (dashed lines).

is capable of predicting the temperature histories at all locations of the damper with remarkable fidelity.

Under long-stroke motions (more than two times the piston diameter) few cycles (four to six) are sufficient to raise the temperature of the internal fluid of the damper by approximately 100°F near the center where the piston experiences the highest velocity while the temperature rise at the end-of-stroke location—the location of the internal seals—is relatively small. More specifically, the temperature increase at the mid-stroke location is more than an order of magnitude greater than that at the end of the stroke. The study also showed that the force-output of the 15 kip dampers was unaffected by increasing internal fluid temperature, whereas, the force output of the 250 kip damper exhibit a 2 kip drop for each 10°F increase in the internal fluid temperature.

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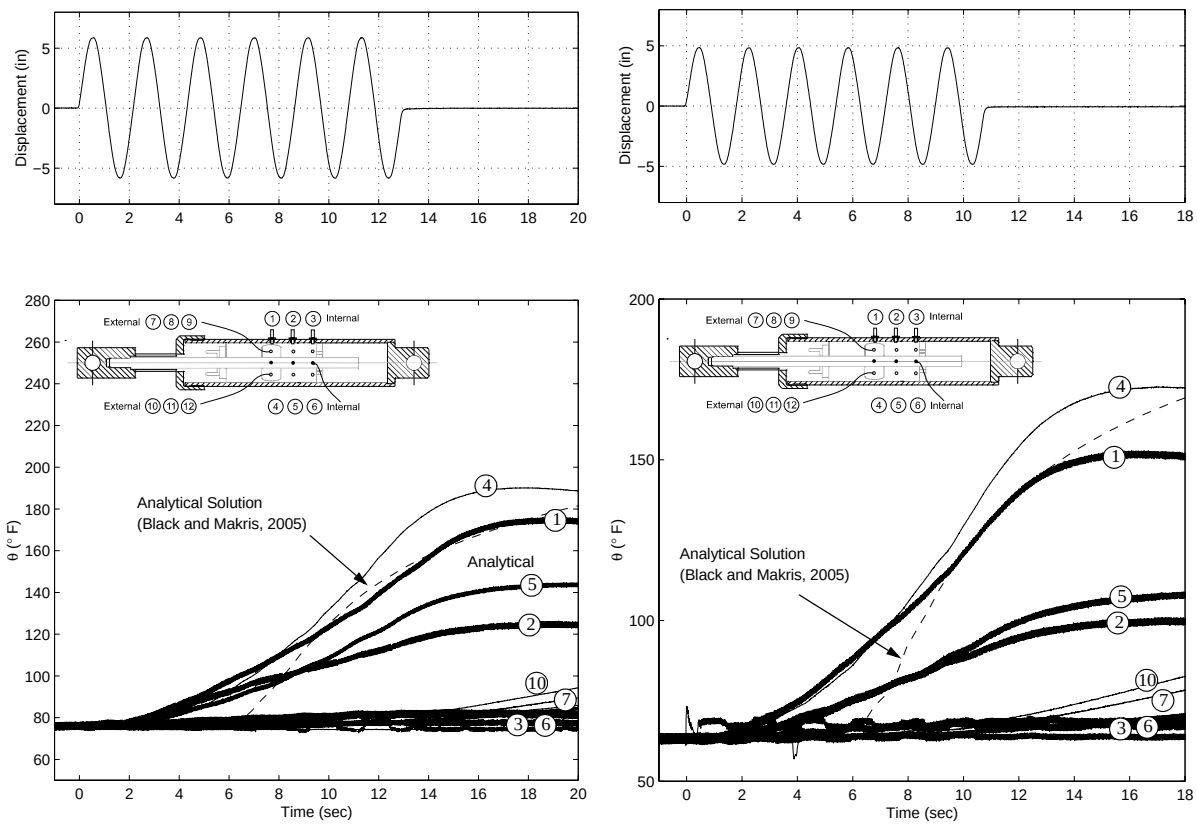

Figure 6. Top: Plots showing the harmonic inputs with amplitude, U_o = 6.0 in., f = 0.464 Hz (left) and U_o = 5.0 in., f = 0.557 Hz (right) imposed on the 250 kip damper. Bottom: Comparison of the measured temperature histories with the analytical solutions (dashed lines).

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