# FEED-FORWARD COMPENSATION FOR ENHANCED REPRODUCIBILITY OF EMULATOR-TYPE LOAD-BASED TESTS

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## ABSTRACT

This study adopts a feed-forward compensation method and provides evidence of its effectiveness for responding to the need for ensuring minimum levels of trackability of the return air condition in testing facilities to achieve standardized result reproducibility during dynamic tests. A linearized model of the thermal and transport delay within the testing environment forms the basis for a feed-forward recalibration of the temperature and humidity control signals from the room emulator to the reconditioning unit. Its implementation in interlaboratory tests on a 10kW-ceiling-type unit demonstrates advanced trackability, leading to delays and deviations of the test results limited within 60 s and 2% of the recorded COP, respectively, at different testing conditions. The proposed method does not require additional equipment and is therefore proposed for enhancing the capability of current testing equipment in conducting precise dynamic tests.

**Keywords:** Dynamic operation, Delay compensation, Feed-forward control, Reproducibility

## INTRODUCTION

To mitigate global warming the global energy sector strives for technical solutions to approach carbon neutrality, requiring a fundamental transformation of the energy supply and demand system. In this context, heating and cooling account for nearly 50% of the global energy demand [1], making a reliable and realistic assessment of indirect emissions due to the energy consumption required by the system operation essential for a comprehensive evaluation of the environmental impact of air conditioners and heat pumps.

The emulator-type load-based tests [2,3] respond to the necessity to reproducibly assess the operation performance of air conditioners and heat pumps while accounting for the thermal interaction with the building characteristics. The method relies on the integration of current testing equipment with a virtual building software – the room emulator – that calculates the modulations of the temperature and humidity within the conditioned space in response to given load characteristics and the supplied cooling/heating capacity from the tested unit.

Results should maintain a certain degree of reproducibility across a complete set of test conditions in different laboratory environments. A previous set of round robin tests (RRT) demonstrated the possibility to achieve result reproducibility with a maximum 5% [4,5] deviation in the recorded cooling COP. The main source of discrepancy was attributed to the limitations in the trackability of the calculated indoor condition by the reconditioning equipment of the psychrometric chamber, resulting in deviations and delays of the measured return air condition to the indoor unit from the target values of the room emulator.

To address this issue and define reliable reproducibility tolerances, Giannetti et al. [6,7] developed a new technique called *Feed-Forward Compensation* (FFC), which uses a linearized model to account for the deviation, delay, overshoot, and undershoot characteristics between target and actual conditions, and consequently compensate for these discrepancies.

This paper presents the results of a round-robin test conducted using the same air conditioner across our testing equipment and a second institution's facility to validate FFC as a beneficial tool for dynamic performance evaluation of air conditioners.

## ROUND-ROBIN TEST

The benefit of integrating this software tool in the emulator-type load-based testing methodology is investigated in interlaboratory tests on a 10kW-ceiling-type unit.

### TESTED UNIT

The air conditioner tested in this study is a ceiling-type commercial unit. Its specifications are listed in Table 1, and its external appearance is shown in Fig. 1. To assess dynamic operation performance, the unit was instrumented within an air-enthalpy testing equipment.

### TEST EQUIPMENT

Tests were conducted in two laboratories; at Waseda

University and at Company A, with Company A's test room being larger than that of Waseda University. Table 2 provides the specifications of the two test setups.

Table 1 Specifications of package air conditioner

| Item | | *Value* | Unit |
|---|---|---|---|
| Cooling | Rated capacity | 10000 | W |
| | Power consumption | 2410 | W |
| | COP | 4.15 | - |
| Heating | Rated capacity | 11200 | W |
| | Power consumption | 2350 | W |
| | COP | 4.77 | - |
| Refrigerant | | R32 | - |
| Mass charge | | 3.10 | kg |

Fig.1 Appearance of the tested unit (left) outdoor unit, (right) indoor unit.

Table 2 Specification of indoor test room

| Characteristic | Waseda | Company A |
|---|---|---|
| Dimensions (mm) | W3800×D6800 ×H3000 | W3800×D6800 ×H3000 |
| Volume ($m^3$) | 77.5 | 87.6 |
| Capacity (kW) | ~12.5 | ~15.0 |

Details on Waseda University's emulator-type load test device are available in [2,3], and additional information on the round-robin testing procedure refer to [4,5].

## EVALUATION METHOD

To evaluate test results, with a focus on reproducibility, it was observed whether corresponding test conditions on the same tested unit produce consistent results in different testing environments. COP was evaluated following JIS standards [8], which define it as the ratio of the average cooling capacity to average power consumption, measured over a 35-minute period for continuous operation, or over three operational cycles for intermittent operation. The Partial Load Ratio (PLR) is defined as the ratio of actual cooling capacity or cooling load to the rated capacity. For instance, a PLR of 25.0% corresponds to a test performed at a cooling load of 2.5 kW. In fact, the test condition discussed here focused on cooling operation at 25.0% PLR (representing intermittent cycling operation). Tests were conducted while comparing the methodology described in [2,3] with a second test run conducted while integrating the FFC method. Further technical details on the FFC are provided in [6,7] and are hereby omitted.

## TEST RESULTS

In a previous publication [5], it was demonstrated that settlement to nearly stationary operation at 50% PLR condition exhibit a result reproducibility level of approximately 2.2% in terms of recorded COP. While intermittent and cycling on-off operation at 25% PLR could be affected by result deviations approaching 5% in the recorded COP (Table 3). To analyze this discrepancy, Fig. 2 shows the corresponding test results at 25% PLR, while Fig. 3 compares the emulator-indicated temperature, actual indoor air temperature, and compressor speed for Waseda University and Company A, respectively. In both cases, the actual indoor air temperature lagged behind the emulator's indicated value. Differences in such delay and over/under-shoot characteristics led to different operation response in terms of compressor speed modulations according to the embedded control logic.

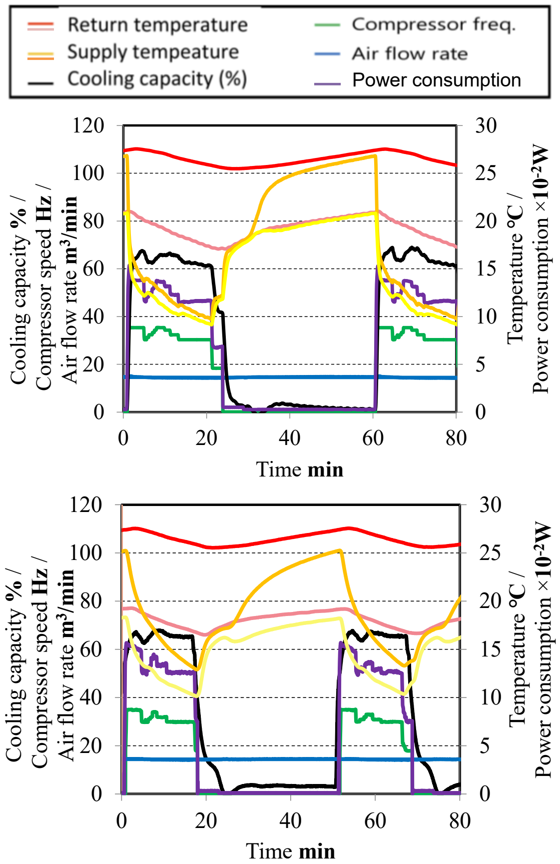


Fig.2 Test results without FFC at 25% PLR and 29°C outdoor temperature (top) Waseda University (bottom) Company A.

Table 3 Test results without FFC at 25% PLR and 29°C outdoor temperature.

| COP (Waseda) | COP (Company A) | Deviation |
|---|---|---|
| 5.34 | 5.57 | 4.3% |

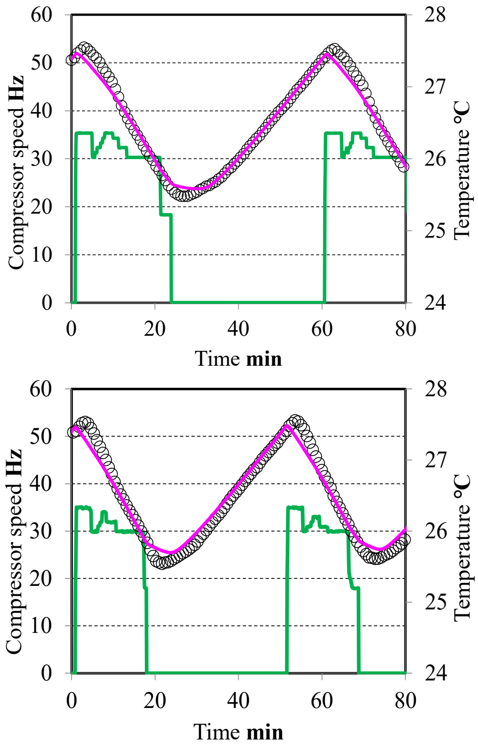


Fig.3 Emulator room temperature (purple line), measured room temperature (black markers), and compressor frequency (green line) results without FFC (top) Waseda University (bottom) Company A.

Table 4 summarizes the COP values obtained when the FFC method is integrated in the testing methodology. Figures 4 and 5 depict the operational behaviors and the testing facility trackability recorded at Waseda University and Company A, respectively. The results indicate that, with FFC, the COP difference between the two sites remained within 2%.

Figure 5 shows the emulator-indicated temperature (purple line), actual indoor air temperature (black markers), and compressor speed (green line) for Waseda University and Company A. In both cases, the delay between the emulator output and the actual indoor temperature was effectively compensated. As a result, the rate of temperature change aligned more closely with the emulator's target, allowing the compressor speed to decrease gradually in both testing environments, leading to consistent cycling time intervals, hence confirming that FFC enables more reproducible tests.

Table 4 Test results with FFC at 25% PLR and 29°C outdoor temperature.

| COP (Waseda) | COP (Company A) | Deviation |
|---|---|---|
| 5.88 | 5.80 | 1.4% |

Figure 6 illustrates the adjustments introduced by the FFC to compensate for delays during the test. Consequently, the FFC system rapidly adjusted the emulator-indicated temperature.

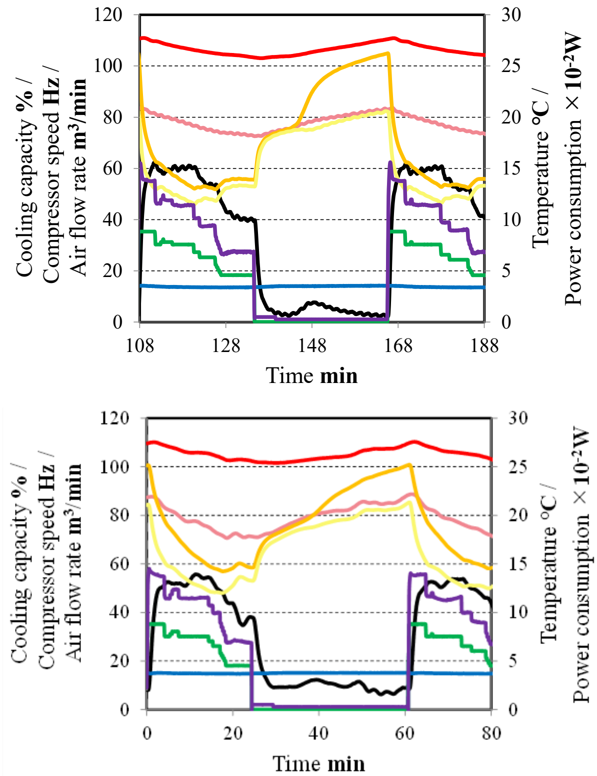


Fig.4 Test results with FFC at 25% PLR and 29°C outdoor temperature (top) Waseda University (bottom) Company A.

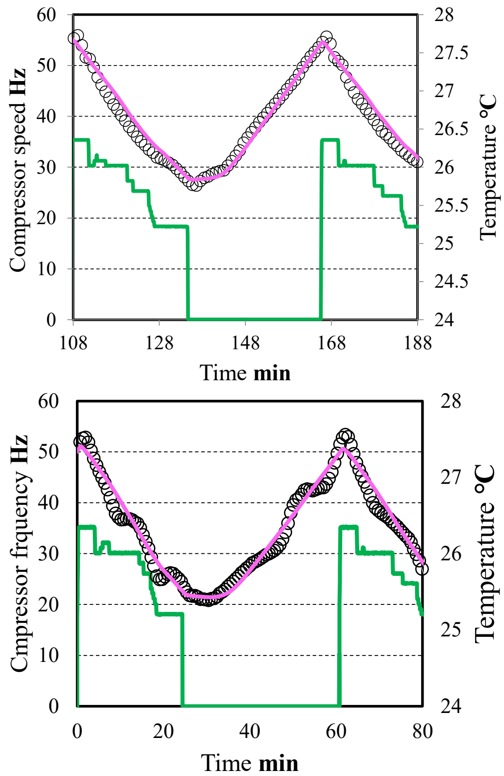


Fig.5 Emulator room temperature (purple line), measured room temperature (black markers), and compressor frequency (green line) results with FFC (top)

Waseda University (bottom) Company A.

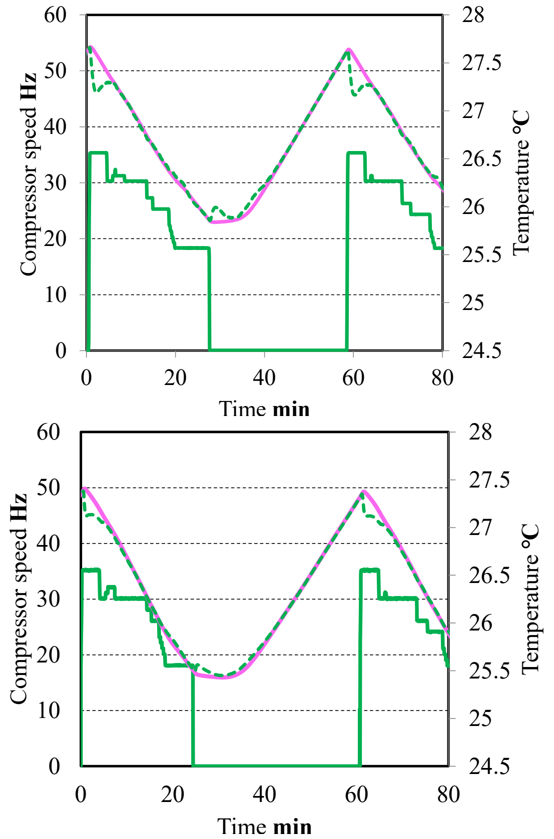


Fig.6 Emulator room temperature (purple line) and FFC compensated value (green dashed line); (top) Waseda University (bottom) Company A.

Temperature was lowered more intensely when the actual indoor temperature reached its peak and sharply raised when it hit the minimum. This compensated operation mitigated temperature overshoots and undershoots, effectively reducing the delay between the actual indoor temperature and the emulator's target.

As one key factor affecting the accuracy of air conditioner evaluations is the inherent delay between the emulator's control targets for indoor temperature and humidity and the values actually produced by the condition generator, the incorporation of FFC into the emulator system effectively addresses this delay, making it a valuable method for accurately measuring the dynamic performance of air conditioners.

## CONCLUSIONS

This study aimed to evaluate the dynamic performance of air conditioners with a focus on ensuring test repeatability and reproducibility under defined building load conditions. The developed "emulator-type load-based testing methodology," combines dynamic measurements performed in an air-enthalpy test setup with an emulator capable of replicating various building load scenarios. To validate test reproducibility, we conducted interlaboratory tests in two different testing environments. Results showed that, depending on the testing conditions, discrepancies in evaluation accuracy could reach approximately 5% when different testing equipment was used in cooling operation (even larger deviations were recorded in other round robin tests conducted worldwide [9]). This variation was attributed to delays and discrepancies between the emulator's target values and the actual indoor conditions generated by the test system's condition generator.

To resolve this challenge, we proposed a linear model representing the delay characteristics and developed a feedforward compensation (FFC) technique based on this model. A second round-robin test was then conducted using the same air conditioner and integrating FFC-enhanced measurements in the testing methodology. Key findings include:

1. Without FFC, the COP difference exceeded 4% at a 25% partial load rate, where intermittent operation occurs.
2. With FFC, the delay between emulator-indicated and actual indoor temperature was compensated, improving temperature tracking and reducing COP variation to under 2% at the same load rate. This demonstrates that result reproducibility levels comparable to that of current testing standards are achievable in characterizing dynamic operation through load-based testing procedures.
3. These results demonstrate that FFC significantly improves the reproducibility of test results by enhancing indoor temperature and humidity tracking relative to emulator targets.

In summary, the use of the developed emulator-type load testing device with FFC successfully validated test reproducibility and confirmed the need for emulator-based dynamic performance evaluation. The proposed FFC method does not require additional equipment and is therefore proposed for enhancing the capability of current testing equipment in conducting precise dynamic tests.

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